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A Continuous Flow Elevator to Lift Ore Vertically for Deep Mine Haulage using a Cable Disc Elevator

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ABSTRACT

Vertical continuous ore haulage with elevators in mining for deep haulage is virtually non-existent. In this, research investigations concentrated on a cable disc elevator. The problem of using a cable disc elevator is the friction between the elevator fixed tube and the moving ore on the disc.

This research establishes the friction forces existing as the elevator cable and discs are elevated up a stationary tube. Then the focus is to find a way to eliminate that friction. The method involved developing three test rigs:

Test Rig 1 measures static friction with the ore placed on a disc in a tube mounted on load cells to measure the resistance with the ore on the disc lifted by a counterweight. This is relevant for an elevator that has stopped under load.

Test Rig 2 measures the dynamic friction in an operational 5-inch elevator with the tube on the lifting side held stationary by load cells when the cable discs are lifting the ore.

Test Rig 3 eliminates friction in the lifting tube by using a pipe conveyor that travels vertically at the same speed as the cable disc elevator to contain the ore on the cable disc elevator. The cable disc elevator does all the ore lifting.

The research generated results for static and dynamic friction for gravel, granite and coal. Cable tension required for ore lift of 1000 metres and the maximum hoisting distance for some existing cables are calculated.

Implications of this research are that the cable disc elevator has the potential to haul from depths greater than existing elevators, has a small footprint in a mine, and with some further development could eliminate the need for truck haulage in open cut and underground mining from the mine.

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This project had many difficulties with equipment supply and reliability, funding and getting engineering services to dedicate time and resources. The following companies deserve to be thanked and positively acknowledged. In no particular order.

Pipe conveyor manufacturer: Beijing Huacheng Transition Technology Co. LTD.
www.hscdtech.com

Rubber conveyor belt for the pipe conveyor: Huacheng Rubber Co. LTD.
www.huachengrubberbelt.com

Load cells, displays and integrated computer software: Gedge Weighing Systems and Australian Weighing. www.gedgeweighingsystems.com.au

Technical advice in the early stages of the project from Fenner Dunlop and Contitech.

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Manufacture of the discs. E-Plas Manufacturing.

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Dr D Moates. Librarian.

Statement of Authorship and Originality

Except where explicit reference is made in the text of the thesis, this thesis contains no material published elsewhere or extracted in whole or in part from a thesis by which I have qualified for or been awarded another degree or diploma. No other person's work has been relied upon or used without due acknowledgment in the main text and bibliography of the thesis. No editorial assistance has been received in the production of the thesis without due acknowledgement. Except where duly referred to, the thesis does not include material with copyright provisions or requiring copyright approvals.

Signed; Colin Webb, date; 18/12/2019

DEDICATION

This research thesis is dedicated to the mining industry in the hope that it stimulates the engineers to develop a forward-looking approach to ore haulage from deep mining.

Deep mine continuous ore flow elevator haulage in still in its infancy. The focus has been on further development of the rubber belt elevator with steel wire ropes embedded in the rubber. The rubber belt technology may have a lot more potential for deep haulage, however one should not be blindsided by this traditional elevator method. There is potential to move forward with new methods.

I would greatly encourage the industry to take a leap of faith to develop and move onto new and effective technology that can advance hauling ore on a continuous operation, reduce costs of haulage, and improve air quality by replacing diesel haul trucks.

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Conveyor belt structure is described in the next table is taken from the Fenner Dunlop conveyor belting technical manual (Fenner Dunlop, 2009.). This gives a brief

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GLOSSARY OF TERMS

Aero mechanical conveyor	A Drag conveyor travelling at a speed that allows the product being transported to become fluidised. Suitable for low density mediums.
AS	Australian standards.
ATSM.	American Society for Testing Materials.
Axial stiffness	Maximum force to produce axial deformation- elongation due to tension.
Breakfree force	Static friction force that starts first movement
Bridon or Bridon-Bekaert	Steel wire rope manufacturing company.
Beumer	Manufacture of steel wire rope rubber conveying belting for overland conveyors and elevators.
BS	British Standards.
Cable	Steel wire rope.
Cable hoist	Winder system for hauling up a steel wire rope cable with an ore skip attached to the end of the cable.
Characteristic Length	The maximum length of the cable or elevator belt in a vertical attitude carrying its own weight with no other load.
Contitech.	Manufacture of steel wire rope rubber conveying belting for overland conveyors and elevators.
Cord.	The structural component of a rubber belt that runs longitudinally in a conveyor belt. Provides the main belt strength.
Covers	Material matting added to the top and underside of a conveyor belt to add drive friction and abrasive protection.
DIN	Deutsches Institute fur Normung. (German National organization for standardization).
Dynamic Friction	The resistance to movement between two surfaces in contact with each other when moving at different velocities.
Drag conveyor	Product is pulled through a duct by mechanical plates attached by a cable or chain/s.
Drive roller/ sheave	Supplies the mechanical force to a conveyor belt from the motor. For an elevator this is the top drive.
Endecott sieve	A standardised wire mesh used for separation of ore for particular ore size selection.
Fenner Dunlop	Manufacture of steel wire rope rubber conveying belting for overland conveyors and elevators.
Floveyor	A manufacturer of aero mechanical elevators.
Gedge	Manufacture of the load cells, weighing systems and displays.

GLOSSARY OF TERMS

Hao Sheng Transmission Technology	China based company in Shandong manufacturer of tube conveyors and overland conveyors. Manufacturer of the tube conveyor used in this research.
Hoisting Skip	Large container hanging at the bottom of a steel wire cable in a mine shaft for carrying ore.
Huacheng Rubber	China based company in Shandong manufacturer of steel wire rope rubber conveying belting for overland conveyors and elevators.
Idle roller	Roller that is not driven by a motor but rotates with the belt travelling around it. Usually at the bottom of an elevator.
Idle sheave Bottom sheave	Sheave that is not driven by a motor but rotates with the cable travelling around it. Usually at the bottom of an elevator.
ISO	International Organisation for Standardisation.
Kinder	Manufacturer of elevator buckets.
Load cells	Weighing transducer.
Minimum Breaking Force	Minimum force or load that will break the cable.
Nylacast, Nylube	Cast nylon polymers used to manufacture the cable discs.
Phoenix Conveyors	Manufacture of steel wire rope rubber conveying belting for overland conveyors and elevators.
Polymer	For conveyor and elevator rubber belts this is a rubber based medium for bonding the steel wire rope components and other matting materials together.
Skims	Polymer fillings between the cord’s weft, and belt covers.
Static Friction	The minimum force required to start movement between two surfaces that are in contact with each other.
Torque meter	Measures torque. Force by distance, a force that causes rotation.
Weft materials	Laterally fit across a conveyor belt to give structural strength to the conveyor belt width.

ABREVIATIONS

GENERAL

Symbol	Description	Unit of Measure
α	Coefficient of expansion of the steel rope. Dimensionless.	none
θ	Arc of contact.	radians
ρ	Density.	g/cm^3
A	Metallic cross-sectional area of the steel wire cable.	mm^2
a	Acceleration.	m/s^2
AR	Anti-rotation (description of cable characteristic).	none
Avg.	Average.	a number
BS	breaking strength.	
Cb	Cable weight per metre.	kg
C	Circumference.	cm
d	Steel wire rope diameter.	mm
D	Sheave diameter.	cm
D^n	Number of discs per metre.	none
D^w	Weight of one disc.	kg
DPM	Diesel particulate matter.	mg/m^3
EIPS	Extra improved plowed steel.	
E	Elastic modulus.	N/mm^2
e	Napierian Logarithm.	
F	Acceleration force.	N
FoS	Factor of safety.	

ABREVIATIONS

g	Acceleration due to gravity = 9.81	m/s^2
h	Height of ore on one disc.	cm
ID	Internal diameter.	mm, cm
l	Distance.	m
L	Steel wire rope length.	m
LD	Vertical lifting distance.	m
LR	Low rotation in steel wire rope.	
ΔL	Change in cable length due to thermal expansion.	mm
m	Length measurement	metres
N	Newton.	
p	Pressure.	kg/cm^2
P	Power.	kW
R or r	Radius.	cm
RPM	Revolutions per minute.	
SA	Surface area.	cm^2
t	Time	Seconds, minutes, hours
T	Temperature.	^oC
ΔT	Temperature change.	^oC
μ	Coefficient of friction.	dimensionless
V	Velocity.	m/s
V_1	Cable starting velocity.	m/s
V_2	Cable operating velocity.	m/s
V_{ore}	Volume of the ore.	cm^3

ABREVIATIONS

W	Work done.	Nm
W	Load applied.	kN
M, m	Mass of ore on one disc.	g, kg,

CABLE TENSIONS

Symbol	Description	Unit of Measure
T_1	Cable tension on the lifting side at the top of the elevator.	N, kN
T_2	Cable tension at the top of the elevator for the return/downward side relates only to the assembled cable.	N, kN
T_3	Cable tension at the bottom of the elevator on the return side.	N, kN
T_4	Cable tension at the bottom of the elevator at the lifting side.	N, kN
T_e	Working load due to lifting the ore.	N, kN
T_{max}	Maximum elevator cable tensions exist on the lifting side.	N, kN
T_e^L	Tension relating to ore weight.	N, kN
T_e^a	Tension for acceleration.	N, kN
T_e^f	Tension relating to friction.	N, kN

ABREVIATIONS

FRICTION FORCES

Symbol	Description	Unit of Measure
Force symbol	$\mathrm{Force}_{\mathrm{type\ of\ ore}}^{\mathrm{ore\ size}}$	
$A\mathrm{BF}_{\mathrm{ore}}^{\mathrm{size}}$	Average breakfree force	N, kN
$\mathrm{BF}_{\mathrm{ore}}^{\mathrm{size}}$	Break free force	N, kN
BS	Breaking strength	N, kN
$M\mathrm{BF}_{\mathrm{ore}}^{\mathrm{size}}$	Maximum breakfree force	N, kN
$W\mathrm{BF}_{\mathrm{ore}}^{\mathrm{size}}$	Wet ore breakfree force	N, kN
$W\mathrm{ABF}_{\mathrm{ore}}^{\mathrm{size}}$	Wet ore average breakfree force	N, kN
$W\mathrm{MBF}_{\mathrm{ore}}^{\mathrm{size}}$	Wet ore maximum breakfree force	N, kN
$\mathrm{DE}_{\mathrm{ore}}^{\mathrm{size}}$	Disc effect force	N, kN
DF	Dynamic friction force (Kinetic friction force)	N, kN
$\mathrm{SF}_{\mathrm{ore}}^{\mathrm{size}}$	Static friction force	N, kN
$\mathrm{J}_{\mathrm{ore}}^{\mathrm{size}}$	Jamming force	N, kN
$\mathrm{dE}_{\mathrm{ore}}^{\mathrm{size}}$	Disc effect friction	N/cm
df	Dynamic Friction (Kinetic friction)	$\mathrm{N/cm^2}$
$\mathrm{sf}_{\mathrm{ore}}^{\mathrm{size}}$	Static friction.	$\mathrm{N/cm^2}$
$\mathrm{j}_{\mathrm{ore}}^{\mathrm{size}}$	Jamming friction	$\mathrm{N/cm^2}$
size	Sieve aperture that the ore has been sieved through	Less than mm
Gn	Granite	
Gv	Gravel	
coal	Coal	

CONVERSION TABLES

CONVERSION FACTORS, S.I. UNITS

FORCE			
1 kN	=0.101972 Mp	1 UK tonf	= 9964.02 N
1 N	= 0.101972 kgf	1 lbf	= 4.44822N
1 kgf	=9.80665 N	1 lbf	= 0.453592 kgf
1 kN	= 0.101972 tonne		
MASS			
1 kg	= 2.20462 lb.	1 lb.	= 0.453592 kg
1 tonne (t)	= 1000kg		
1 kg/m	= 0.671970 lb/ft	1 lb/ft	= 1.488 kg/m
1 kg	= 1000 g		
1 tonne (t)	= 9.80665kN		
LENGTH			
1 m	= 3.28084 ft	1 ft	= 0.3048 m
1 km	=0.621371 miles	1 mile	=1.609344 km
VOLUME			
1 cm^3	= 0.061023 in^3	1 in^3	= 16.3871 cm^3
1 litre (l)	= 61.0255 in^3	1 in^3	= 16.38866 ml
1 m^3	= $6.10237 \times 10^4 in^3$	1 yd^3	= 0.764555 m^3
DENSITY			
1lb/ft^3	0.0160 g/cm^3	1 g/cm^3	62.428lb/ft^3
1kg/m^3	0.001 g/cm^3	1 g/cm^3	1000 kg/m^3

1.0 Introduction

1.0 Introduction

This research examines the cable disc elevator and its potential for use in mining as a vertical lift elevator for long ore haul to even 1000metres. The thesis aims to assess the capabilities of this style of elevator when it comes to lift distances by using a vertical cable disc elevator in a fixed tube and as a hybrid elevator where the fixed tube is replaced with a pipe conveyor.

The specific focus of the research is to establish the knowledge of friction for static and dynamic friction dragging ore up inside a fixed tube has friction resistance for the ore in contact with the tube. The friction force has to be overcome by the lifting force being applied by the cable in the elevator that is dragging the discs and ore up. The static friction and the dynamic friction are measures in two test rigs, Test Rig 1 for the static friction being measured on one disc, and Test Rig 2 is a fully operational cable disc elevator designed to measure the dynamic friction of the ore sliding in the tube.

A third test rig uses a pipe conveyor at the lifting tube pipe in Test Rig 3 so that the cable disc elevator and the pipe conveyor travel at the same speed, hence during the vertical lift there is no friction between these the cable disc elevator and the pipe conveyor. However, the ore entering and leaving the pipe conveyor section travels in a short-fixed tube section that has the same friction characteristics as in Test Rig 1 and 2. In the test rigs the lifting is done by the cable. The fixed tube and the pipe convey service the purpose of blocking the ore from falling off the discs.

The data from this research is then used to extrapolate to calculate the forces required to lift ore from 1000m and after selecting 3 commercial cable sizes then to calculate the depth that these cables could lift from based on their tension specification. The most important knowledge required to build a cable disc elevator is the tension requirement of the lifting cable. The tension require is the sum of the cable tensions for the elevator is shown in the equation:

$$T_1 = T_e^f + T_e^L + T_e^a + T_2 \qquad (1.0) \quad \text{(Metlikovic, 2009)}$$

Where T_1 is the total tension required by the cable, the tension to overcome gravity for the ore weight is T^L, for ore acceleration T^a, plus the tension required to overcome friction T^f.and the tension effect of the cable weight is T_2. Cable tensions are displayed in Figure 1. The forces for lift, acceleration and the cable weight are known, to then establish the total tension the force required to overcome friction is needed and is the key focus of the experiments in this research.

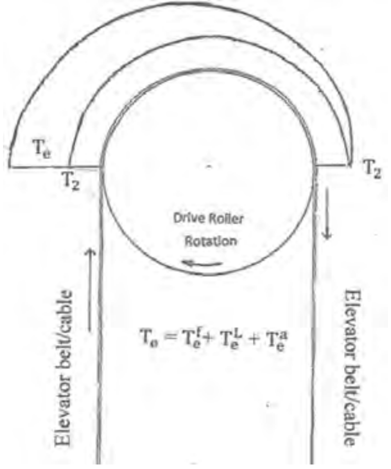
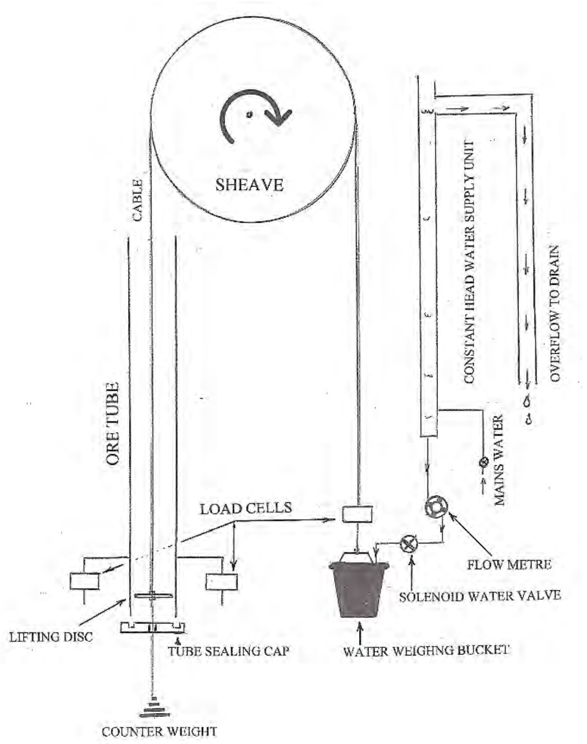
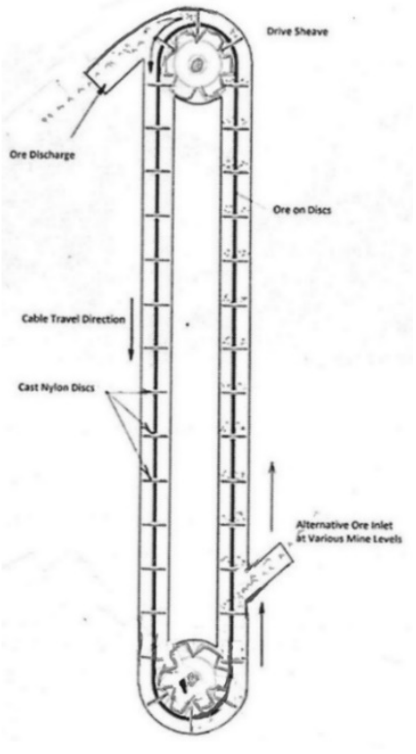


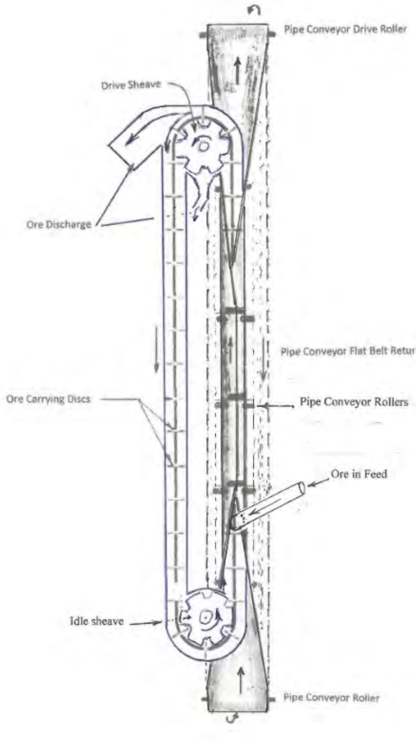
Figure 1. Elevator head cable tensions (Metlikovic, 2009)



Test Rig 1 for static friction measurement



Test Rig 2 for dynamic friction measurement



Test Rig 3 the combined elevators

Figure 2. The three test rigs used in this research

This research examined the cable disc elevator and measured the friction between the ore and the tube. Establishing the friction force allows this to be added to the forces of ore weight and gravity, cable weight, and acceleration to calculate the total weight that is on the lifting cable (Walker, 1988).

The rocks selected for testing were gravel, granite and coal. These were from local mining operations within a short travel distance from the university.

1.1 Deep Mines

According to the National Mining Association (based in Washington), demand for mined products will grow alongside the global population as demands for higher standard of living continue to expand (NMA, 1998). Currently the only source of minerals and fossil fuel resources is from mining for these and the only known place that these resources are currently available is from the sub-surface of the earth. These minerals at present can only be obtained through surface mining, underground mining and from underwater deposits. All technical developments and all human endeavours depend on the products of mining. (Ramani, 2011).

Based on historical precedent, mining in future is likely to become more difficult, and governed by new laws, new regulations, permit conditions, and new health and safety, environmental, and social issues, all of which will impact the way in which mines will operate. As mines exhaust the high and most economical ore, those in the future will have to extract ore of lower grades, mine deeper and operate under more severe conditions. Lower cost extraction and production can only be achieved by continued improvement.

The mining cycle is comprised of repetitive operations including drilling, blasting, loading, and hauling waste and ore to a dump site, a processing plant, or stockpile. Hauling is a batch process that involves the use of a haul truck or cable hoist or can be done continuously using an overland conveyor belt. The choice of equipment depends on the characteristics of the strata to be mined and contributes to the viability of the mine and the prices for the minerals.

This thesis is concerned with the haulage element of the mining cycle and investigates vertical continuous ore lifting using a cable disc elevator. The most popular methods for mine haulage are briefly explored. All mine haulage systems have engineering limitations, some of which are briefly discussed. For a continuous vertical lift, the only options are various types of bucket elevators and the cable disc elevator. Some of these limitations are explored in the literature search.

The underlying objective of this research was to find a continuous flow vertical elevator that could lift ore from 1000metres. The research choice is the cable disc elevator which is demonstrated that this elevator could achieve that objective under specific controlled conditions and selection of ore particle size. Ore size is important and some underground crushing is required.

The total amount of a resource in the earth that may be accessible, is limited to the ability of the current mining methods that allow economic extraction. Not all resources have been identified, some minerals are close to the surface, and many are deeper. Once the easy to extract minerals are mined the mining must go deeper. However, deep mining occurs in a very technical and challenging environment, in which significant innovative solutions and best practice are required, and additional safety standards must be implemented in order to overcome the challenges and reap huge economic gains. Mining deeper economically increases the amount of resources that may be available as reserves for mining and mineral recovery (Pathagam, 2017).

An increased global supply of minerals is essential to meet the needs and expectations of a rapidly rising world population. This implies extraction from greater depths (Fairhurst, 2017).

Research in this thesis demonstrates there is potential for the cable disc elevator to lift ore from 500m, 1000m and for some ores at further depths. The deepest elevator in the World to date is at 276m lifting coal at the White County Coal mine in USA (Contitech, 2013). The cable disc elevator in this research can go deeper.

The list of mines below show some of the depths that mines are operating at.

1	AngloGold Ashanti -Mponeng gold mine operating at depths	2400 to 3900m
2	Tua Tona gold mine operating at depths	1850 to 3450m
3	Savuaka gold mine operating at depths m	3100 to 3700m
4	Gold Fields Driefontein mine with ore reserves to	3400m
5	Kusasalethu Gold Mine operating at	3276m
6	Great Noligwa Gold Mine	2400 to 2600m
7	South Deep Gold Mine operated by Gold Fields	2995m
8	Moad Khotsong Gold Mine is operating at depths	2600-3054m
9	Creighton mine is the World's deepest nickel mine	2500m
10	Kidd Creek Copper and Zinc Mine (Xstrata)mining USA	2927m
11	Resolution Copper mine with shaft number 10	2116m
12	Cheremoukhovskaya-Gloubokaya bauxite mine in the North Urals.	1550m
13	Gwalia Gold Mine Leonora Western Australia	1660m

The above list is taken from, Miningtechnology.com, (Rio Tinto 2008), (UC Rusal 2015).

Deep mines in Australia are mostly metalliferous mines. Coal mines are essentially mining old vegetation growth that was once at the surface. The deepest coal mine was the Balmain Mine which operated from 1897-1931 at a depth of approximately 860 metres. (NSW Dept. of Industry, 2007).

According to Mining Technology (2013), the deepest underground mine in Australia is the Enterprise mine at Mount Isa. The main shaft extends to 1900m below the surface. Ore extraction is reported to be approximately 3.4 million tonnes per year. There are ore bodies at 1100m where current production is, plus ore bodies at 1900m, 3000m, and 3500m. Leinster Nickel mine operates 700km North East of Perth at between 1100 and 1400 metres. (Thiess, 2018).

The above discussion demonstrates there is opportunity for a continuous elevator to lift from significant depths.

1.2 Mine Haulage Systems

The selection of the ore haulage system is one of the most major decisions made in the development of an underground mine, and once selected, the haulage system defines the mines ability to respond to changes in mining inventories and market conditions for its products. Commonly applied haulage systems in modern mining in Australia include.

- Shaft hoisting
- Conveyor haulage
- Truck haulage
- Vertical conveyors
- Bucket elevators

Other haulage methods for underground mining are;

- Train haulage
- Hydraulic hoisting

Train haulage for underground mining is not used in Australia as there is little opportunity for relief to consider this. Train haulage is used in the mountainous regions in Norway where there is option haul ore out of the side of mountain where topographical relief is present. Due to the topography of Australia rail haulage from underground mines is not considered in this research introduction any further

Hydraulic hoisting has limited precedence. There are risks associated with the pump technology with the pump technology, wear rates on pump columns significant upfront costs and the courage to be the first are seen as the main sticking points for hydraulic hoisting (Francis, Turner and Larder, 2005). There is some precedence at the McArthur River Uranium mine in Canada which produces approximately 250.000 t/a from 640m. Pratt (2008). Hydraulic hoisting is only acknowledged here and not considered further as the coal selected, if slurried, would be difficult to separate from the water.

The most common methods for hauling from underground are the first three of, shaft hoisting, conveyor belt haulage, and haul truck haulage. Each of these systems have recognised advantages and disadvantages as described by Bloss, Harvey, Gant and Routley (2011), and Tilley (2011).

An analysis by Pratt (2005) and Spreadborough and Pratt (2008) of the main three haul methods of shaft hoisting, haul trucks and conveyors have been presented as shown in Figure 3. Of interest here is the operating ranges.

Other haulage methods exist which include the bucket elevators which lift vertically ore of various particle size that has been reduced to size suitable for the elevator buckets. These elevators can consist of ore buckets attached to one elevator belt or two belts with buckets suspended between the belts. The limitation of these bucket elevators is the weight of the belts. The strongest belts are structured with a series of steel wire cables that determine the belt strength but adversely increase the weight load the belt has to carry. This belt weight is a limiting factor for these elevators.

Bucket elevators are operated successfully in the grain and flour industry, in mineral processing plants, extensively for lifting superphosphate lime, cement coal, and mineral ores from crushing plants. Figures 4 shows these elevators.

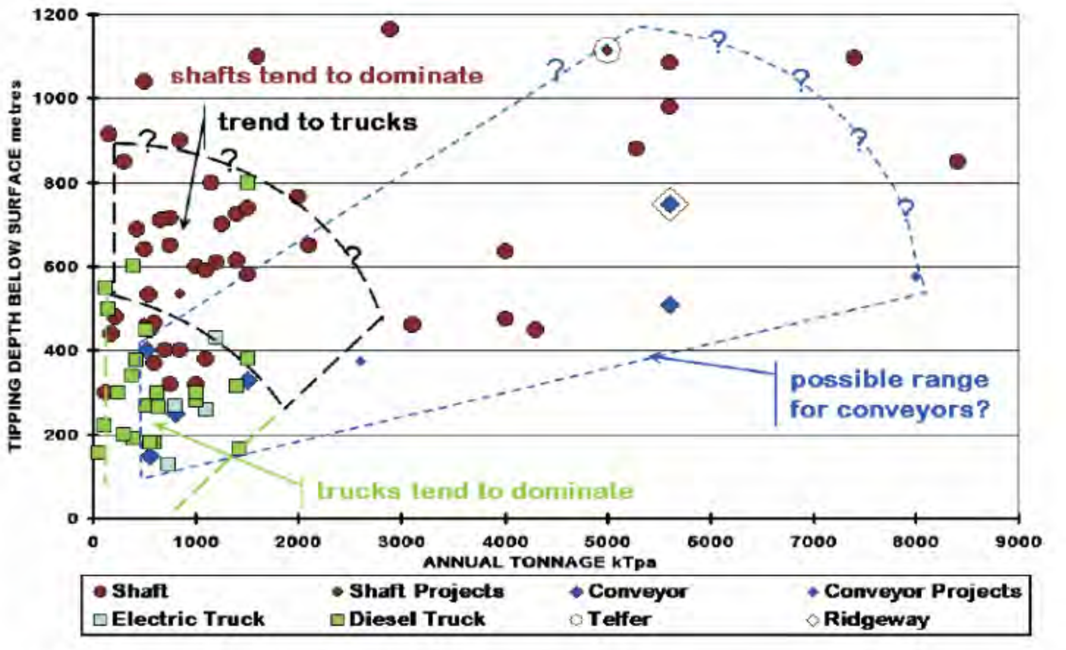


Figure 3: Operating ranges for underground haulage systems (Pratt, 2005) and (Spreadborough and Pratt 2008)

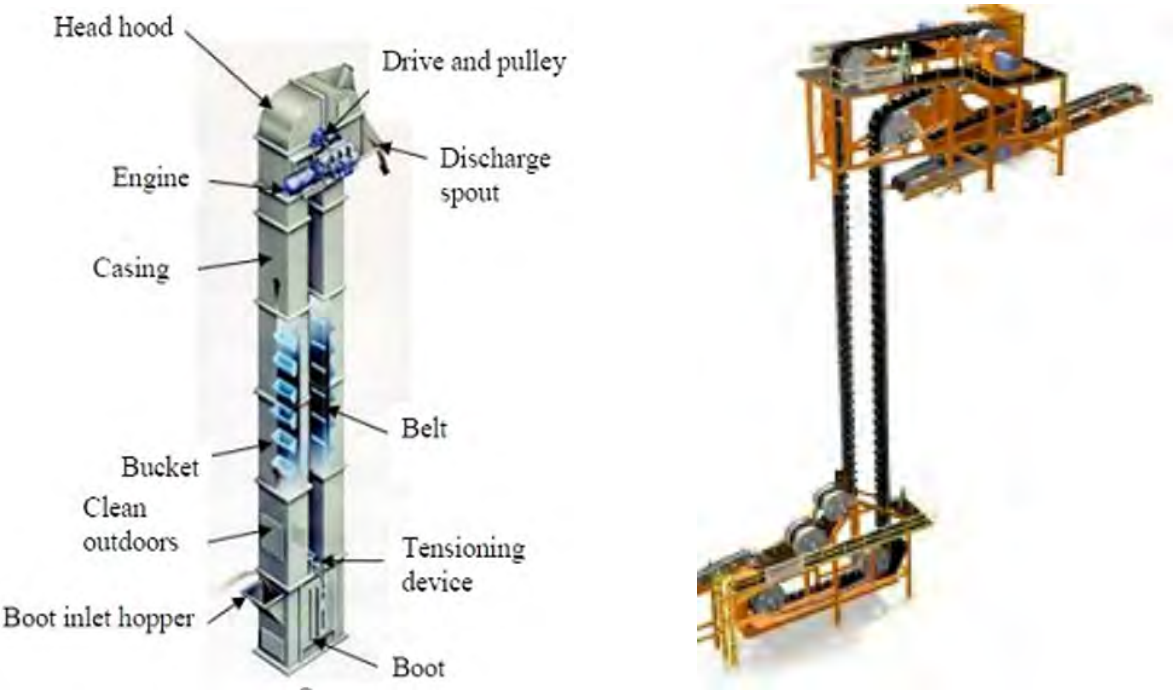


Figure 4: Typical Universal Bucket (Ramakrishna, 2018) and a Pocket lift twin belt elevator (Beumer, 2015)

These elevators are efficient and reliable for the industries they serve. The universal bucket elevator using a single belt with the buckets attached to the belt. The largest is at the Indian Quest ACC cement company (Holcim, 2015), and is built by The Beumer Group. It is 1250mm wide and there is 173.5 m between the roller centres. This elevator operates at 600 tonnes per hour lifting cement. A bucket elevator has many advantages for hauling ore:

The largest twin belt bucket elevator in the World is at White County Coal Mine in Carmi Illinois USA; the gap between the centres of its rollers is 276 metres. This elevator has twin belts and the pocket buckets carrying the coal are suspended between the belts. The pocket brackets are vulcanized to the inner top side of the belt edge. Referred to as a pocket lift elevator, it operates at 1815 tonnes per hour with a belt weight of 100 tonnes. Energy consumption is at 0.3kWh/t of ore per 100m of lift (Contitech, 2013). This elevator was built by Contitech, who claim to have designs for 700 - 1000-metre-long lifts that use a series of multiple elevators.

Bucket elevators convey bulk materials on a vertical or a very steep inclined path. These consist of an endless belt with buckets attached. There are two main rollers for the belt, one head roller, which is the powered roller, and an idle roller at the bottom. There is significant tension between the two rollers such that the bucket elevator belt has enough frictional attachment to the drive roller to transfer power to the elevator belt. Material is loaded into the buckets at the bottom of the elevator and lifted to the top where the elevator buckets discharge their load. For the long elevator belts the cord providing the main belt strength. Typically for the examples referred to in Figures 5 and 6 the belts weighs 86kg per metre of length, hence the longer the lift the longer the belt and the higher weight at the top that the belt has to carry. Hence, an increase with belt length reduces its capacity to carry ore. It is difficult to increase the cable size in the belt structure as there are many cables that have to be equally tensioned. These belt structures strengths and limiting factors are discussed in the Literature Search.

However, elevators form part of the inspiration for this research and to find a way that vertical lift with elevators can go further.

1.3 The Cable Disc Elevator.

A cable disc elevator as shown in Test Rig 2 in Figure 1 and 8, plus a section of the elevator demonstrated in Figure 5 has a single cable that travels around a loop like a bucket elevator. There is a top powered sheave and a bottom idle sheave. The ore is feed into the bottom of the cable disc elevator and is dragged up the elevator then centrifugally discharged at the elevator top. The advantage of this elevator is the single cable that can be selected to match the ore lifting required tension.

The test rig had discs that were 5mm less in diameter than the tube leaving an all round gap between the disc and the tube of 2.5mm.

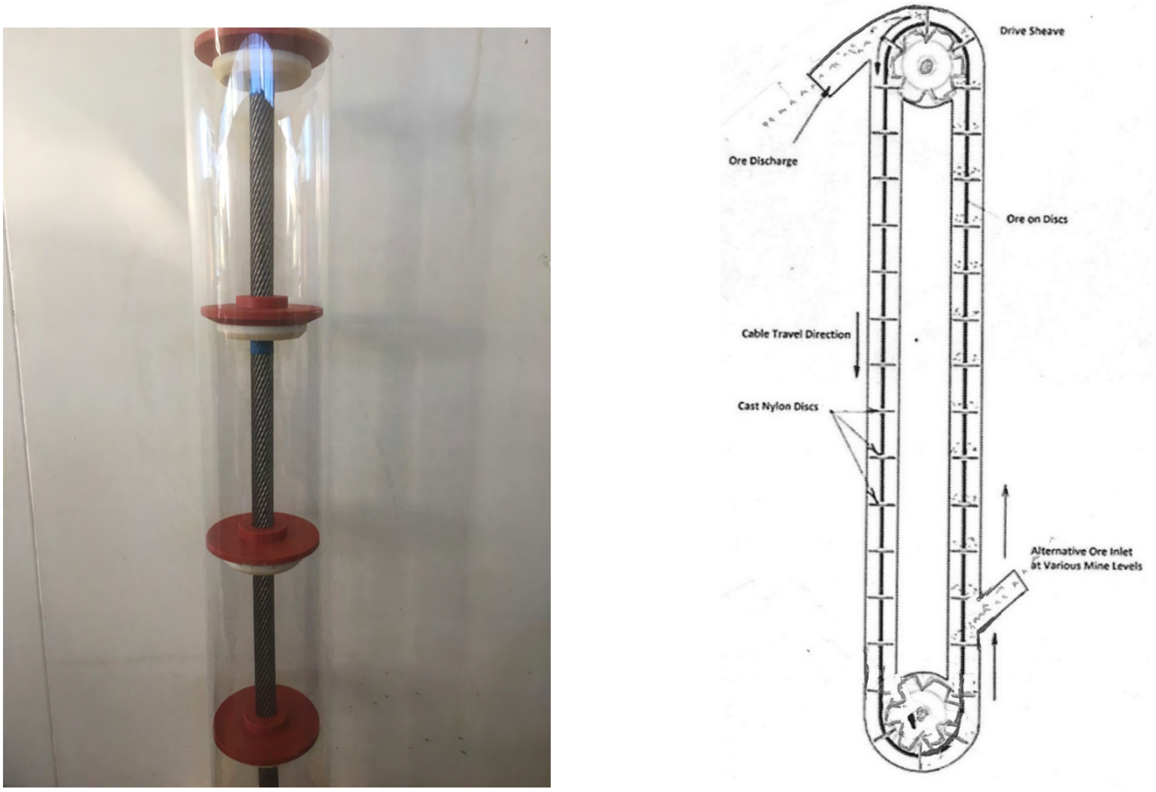


Figure 5: The cable disc elevator sketch as in figure 2 and a clear view of the cable disc elevator section in a plastic tube.

1.3.1 The Cable Disc Elevator as a Drag Conveyor.

Vertical and horizontal draglines made from a steel wire cable, chain with discs or bars to drag product along have been in use for a long time. Indeed, vertical lift using this technique has been used for smaller production units since the 1950s. Typically, the vertical lift has seen success in the grain and powder industry for heights up to 20 metres, and using a 6 – 9 mm steel wire cable with tubes up to 5-inches in diameter.

Despite an extensive review of the literature, no standards exist for these elevators. However, standards for lifting cables exist, and could be adapted and have some relevance for such operations. One of the restrictions in design for the vertical lift is the friction that develops between the product on the discs and the sidewall of the elevator. The product that is being lifted starts to compact on the disc and gravity brings the product over the side of the disc to the tubed wall of the elevator and is dragged up the tube which creates friction. This friction can be large enough to increase power requirements and lead to forces large enough to cause cable failure. Research with Test Rig 2 is used to measure that dynamic friction when the cable disc elevator is in operation. Whereas Test Rig 1 shown in Figure 1 is used to measure the static friction for one disc.

There are other variants of the cable disc elevator where the gap between the disc and the tube can be 12 to 20mm. Such elevators haul for short distances and for low-density products and often referred to as aeromechanical elevators. They are not relevant for this research.

The most important knowledge required to build a cable disc elevator is the tension requirement of the lifting cable T_1. The tension ability of the cable is the sum of all the tension requirements of the ability to lift the cable, the tension to overcome gravity of the ore and the tension required to overcome dynamic friction is;

$$T_1 = T_e^f + T_e^L + T_e^a + T_2 \qquad (1.0)$$ (Metlikovic, 2009)

For static friction there is no acceleration and the Metlikovic equation is then:

$$T_1 = T_e^f + T_e^L + T_2 \qquad (1.1)$$

Whichever tension requirement is the greater between T_1 for static friction or T_1 for dynamic friction is then the tension used as the elevator design tension.

1.4 The Cable Disc Elevator with a Pipe Conveyor

Test Rig 3 shown in Figure 1 has a rubber textile cord belt pipe conveyor that replaces the tube in the cable disc elevator shown in Figure 2. The pipe conveyor travels at the same velocity as the cable disc elevator but does not lift the ore. All the ore lifting is done by the cable disc elevator, leaving the only duty of the pipe conveyor is to stop ore falling off the discs.

As the pipe conveyor only carries its one weight the pipe belt can be light, thin and have a textile cord structure and hence can hang vertically for large distances, it is not carrying ore weight. However, to get the ore into the pipe conveyor section and to leave that section the cable disc elevator has a small section of fixed steel tube and those sections are the same as for Test Rig 2 then the friction in the in feed and exit should be the same as that of for Test Rig 2.

1.5 The Research Questions

The research questions were developed to collect the primary knowledge of static and dynamic friction between the ore and the elevator tube. There is an underlying theme for this elevator to be able to lift ore from depths of 1000 metres.

There are five research questions that this research answers. To answer the questions and obtain the required knowledge, three test rigs were built:

- Test Rig 1 measures the static friction.
- Test Rig 2 measures the dynamic friction.
- Test Rig 3 combines cable disc elevator inside a pipe conveyor.

1.5.1 Test Rig 1 Static Friction

Test Rig 1 is designed to measure static friction. The importance of static friction knowledge is to simulate the event where the mine has a unplanned stoppage that may occur due to an electrical failure, and the elevator has to be restarted. Tests were conducted using the three selected ore of different particle sizes, less than 2mm, 2-5mm, 5-9.5mm, above 9.5mm and ore ungraded containing the natural mix of these sizes. Further tests for static friction were done to measure the effect of added water in the ore.

Tests were undertaken with different amount of ore on the discs.

Friction was determined as Newtons per square centimetre at the surface contact between the ore and the elevator tube, between the disc and the tube and for larger particles that jammed between the disc and the tube.

Research question 1: What is the static friction between the ore being elevated and the tube of the cable disc elevator and what different friction forces are interacting in the tube?

1.5.2 Test Rig 2 Dynamic Friction

Test Rig 2 enabled the investigation of dynamic friction.

Dynamic friction is tested in Test Rig 2. This is an operational cable disc elevator as illustrated in Figure 8. The gap between the disc and the tube was 2.5mm. Ore was tested below 2mm particle size to avoid jamming that was experienced in Test Rig 1. Dynamic friction was measured with the elevator cable travelling at different velocities and at different ore loadings per disc. A test for static friction is also completed by stopping the elevator insitu loaded with ore and restarting the elevator. This test demonstrated the much higher friction for static over dynamic.

Research question 2: What are the friction forces that would be acting in a cable disc elevator for dynamic friction.

1.5.3 Test Rig 3. The Combined Cable Disc Elevator and the Pipe Conveyor Hybrid Elevator

Test Rig 3 has a pipe conveyor replacing the fixed lifting side tube of the cable disc elevator as illustrated in Figure 2. When the cable disc elevator and the pipe conveyor are travelling at the same velocity there is no relative movement between those parts and the ore, hence there is no friction. However, there is a fixed tube at each end of the elevator where there will be friction between the ore and the fixed tube.

Research question 3; What would be the impact of the frictional forces for a hybrid cable disc elevator combined with a pipe conveyor when used to replace the lifting tube?

Ore was tested at 2mm particle size and up to 10mm. For gravel and coal the larger particles disintegrated quickly then reduced to less than 2mm in size. Granite did not shear; however, the large particles did not jam in the cable disc elevator infeed of 250mm, and out feed conveyor short section of less than 750mm long Section

1.5.4 Projected Lifting Distances

Research question 4; What is the maximum distance that a cable disc elevator can lift from?

The total tensions required to lift the ore is calculated by adding the friction determined in this research and that required to overcome gravity, acceleration and lift the cable. This determines what capacity cable would be required for the application.

Lifting distance is dependent on the tension strength of a lifting cable. Three commercially available cables that could be used in a cable disc elevator are considered and the distances those cables could lift from is calculated.

Research question 5; What is the maximum distance that a hybrid elevator combined pipe elevator with a cable disc elevator can lift from?

In this testing the cable disc elevator cable did all the lifting. The only function of the pipe conveyor was to supply a pipe to stop the ore from falling off the discs.

This test rig had the lowest friction for dynamic and static friction resulting only from the infeed and out feed sections. The distance this combined elevator can lift from is strictly the strength of the pipe conveyor to carry its own weight and the size of the cable lifting the ore.

By selecting a suitable pipe conveyor structure and cable size continuous vertical ore lifting can be achieved from 1000metres. There are separate calculations for each test rig for static and dynamic friction.

1.6 Aims and Objectives

The aim of this thesis is to examine the cable disc elevator and the cable disc elevator combined with a pipe conveyor concept and idea, and to research these units with the focus towards the mining industry.

The Objective is to measure the friction between the ore and the tube. Engineering knowledge on power, shaft sizes, and cable technology is well developed and not researched here, they are calculated and added to the friction forces to determine the required cable strength required of the elevator (Walker, 1988). The decision to research the cable disc elevator becomes apparent as there is very few options available for continuous vertical long ore haulage for deeper mining.

The underlying objective of this research was to find a continuous flow vertical elevator that could lift ore from 1000metres and for the commercial cable examples selected, then predict the maximum distance these cables could lift from using this elevator. The research choice is the cable disc elevator which is demonstrated that this elevator could achieve that objective under specific controlled conditions and selection of ore particle size. Ore size is important and some underground crushing is required.

An important objective is to theoretically demonstrate from the data established in this research that a continuous flow ore haulage elevator can achieve ore lift for long distances.

The objective of friction knowledge between the ore and the elevator tubes establishes the following frictions for the three selected ores.

Static friction for each ore using Test Rig 1

- At different particle size
- Different weight of ore on each disc
- Ore with added water
- Static friction in Test Rig 2 by stop starting the rig when loaded in operation

Dynamic friction with Test Rig 2

- For each ore below 2mm particle size
- Different weight of ore on each disc
- Ore with water added

Friction removal using Test Rig 3 with a pipe conveyor. The knowledge of these frictions allow the lifting heights of the elevator to be calculated.

1.7 Methodology

In a research perspective this is an engineering project where the epistemology is experimental research methodology. The research was undertaken by using 3 test rigs as described in the introduction and Figure 1. By deduction calculations are extrapolated to predict the length of the elevator at the maximum strength of the selected cables and what strength of cable would be required to lift ore from 1000metres for a operating elevator of the same tube as the test rigs.

1.7.1 Literature Review

Secondary data was reviewed through the university library using a range of information sources which included academic and commercial abstracts, relevant standards, bibliographic data bases and internet search engines.

To aid with this research a list of key technical engineering terms was made and information that related to these established.

1.7.2 Data Collection

Data was collected from various manufactures of cable disc elevators and pipe conveyors. These companies supplied relevant engineering manuals of the products they make. This included conveyor belt manufactures, crane cable manufactures and plastics companies, from within Australia and overseas. This information was not collected by survey but instead personal communication and or visit with those companies.

This resulted in a collection of data of the manufacturing capability of the industry that then helped to direct the project onto a path that concepts developed here could be easily transitioned to larger scale in the future.

1.7.3 Data Analysis

Analysis of data collected from companies, research papers, standards to be analysed for the selection of what components and concepts that could be extracted from the literature to aid in the design of the test rigs.

1.7.4 Experimental Analysis

From the literature searches the experimental method was determined to build the test rigs and measure the friction between the ore and the elevator tubes. Then use this data to make relevant calculated deduction for elevator lifting depth.

1.8 Scope of the Research

The scope of the research is to test this idea and concept of the cable disc elevator and the cable disc elevator combined with a pipe conveyor for vertical continuous ore lift. This testing was undertaken with small limited scale test rigs that were designed to measure friction between the ore and the tube that the ore was lifted in.

The research was not aimed to create a full-size elevator in field conditions. This research was also limited to the selected ores. The ores selected for this research were granite, gravel, and coal. These ores were selected from local mines and are typical of mainstream mine ores.

There is no attempt to evaluate the economics of capital costs or operational costs.

Static friction measured was limited to defined conditions for the amount of ore on each disc, a range of ore particle size, any added water to the ore as described in the Test Rig 1 operation.

Dynamic friction was measured and limited to ore of particle size less than 2mm. Elevator conveyor speed was varied up to but not exceeding 3.5m/s, and various ore loadings per disc.

Predictions are limited by the test rig size and capacity and larger size elevators would require further validation; however, these test rigs form a part of knowledge that can be used for further research to help the concept more forward.

1.8.1 Scope of Test Rig 1 for Static Friction

The disc to tube gap was 2.5 mm for all static friction tests. Ore particle size tested where limited to less than 2mm, 2-5mm, 5-9.5mm, above 9.5mm and ungraded ore, and ore particle size with added water. Sample weights per disc varied from 500 grams to 7000 grams.

Movement of ore in the tube is observed from zero then at 500mm vertical movements to 1500mm and not beyond 1500mm for in a clear tube where the disc to tube gap is 2.5mm. Ungraded granite was lifted in the tube with a disc gap of 12.5mm and the lift limited to 250mm

1.8.2 Scope of Test Rig 2 for Dynamic Friction

The disc to tube gap was 2.5mm. The elevator velocity was varied between 1.0 to 4.0 m/s. Ore weight loading on the discs is up to 3.5 kg per disc.

The test rig was constructed in a building that had the maximum height of 8.2 metres. When the top and bottom of the elevator and framework was subtracted the length of the straight tube of the elevator where testing took place was 4 metres long. The cable travelling in this section then had 16 discs in the tube at any one time.

1.8.3 Scope for the Hybrid Combined Cable Disc Elevator and the Pipe Conveyor

The pipe conveyor belt was a textile belt in order to have a minimum belt pipe forming section and deforming section of 2 metres each. The conveyor pipe section that was formed for the cable disc elevator was 6.25 metres. The overall height of the test rig was 11.25 metres with the base frame. This test rig was mounted on a concrete slab outside of the testing building. To have doubled the height would have been desirable however in the time period for this project and budget constraints this size was selected and was adequate to test for friction and demonstrate the idea and concept.

Testing velocities went to 3.5 m/s. A decision was made not to exceed this velocity or find a velocity were failure might occur with the cold glued join of the pipe belt. The research was focused on measuring friction and not mechanical designs and limitations.

This elevator had a gravity ore feed. No wet ore was tested in this rig as the ore feed required a smooth sliding ore that flowed consistently, free moisture would have changed the ore feed rate to the elevator for this test rig and further complicated and extended the research time limits.

1.9 Overview and Brief Outline of the Thesis

This is a brief summary of each chapter of the thesis from Chapters 2 to 9.

1.9.1 Chapter 2 Literature review.

The main focus is materials that are relevant to the components that would be used in the cable disc elevator and the pipe conveyor. This includes the structure and manufacture of overland conveyor belts of various types and including pipe conveyors. Belt types including those with textile and steel wire cable cords

Steel wire ropes/cable data literature types in particular those associated with mining hoist applications

1.9.2 Chapter 3 Methodology

The epistemology of this thesis is by experimentation and builds knowledge that under the same circumstances can be validated by measurement and experiment.
this chapter brief outlines the experiments for each test rig

1.9.3 Chapter 4 Ore Selected

This chapter describes the ores selected for use in this research. Where the ore came from.

For each ore the particle size distribution is determined. Tests that are operated in the test rigs use ore that has been separated with the sieve sizes specified here.the density of the ore is determined and this result is used to determine for different ore weights on the elevator disc the surface area contact

1.9.4 Chapter 5 Test Rig 1 Static Friction

Test Rig 1 is used to determine the static friction between the selected ore and the elevator fixed steel tube. Tube sizes used are 5-inch and 8-inch diameter. Ore samples vary in weight and hence surface area contact with the tube. Sample of different size is used and the effect that the sizes have with friction including jamming. Tests are also done with 2mm ore and added water.

1.9.5 Chapter 6 Test Rig 2 Dynamic Friction

Test Rig2 is used to determine the dynamic friction between the ore and a 5-inch tube when the elevator is operating at different speeds and different weight of ore is on each disc. This is a fully operational elevator. For each of the ores only the 2mm size is used.

1.9.6 Chapter 7 Test Rig 3 Combined Elevator

Test Rig 3 is a combined elevator where a pipe conveyor replaces the fixed tube of the cable disc elevator. This elevator uses a range of ore sizes and successfully the ungraded ore as defined by the sieve analysis in Chapter 4.
The elevator is divided up into 3 zones. Zone one is a fixed tube section where the ore is feed into the elevator and has contact with the ore for 250mm.
Zone 2 has the pipe conveyor and the cable disc elevator combined and operating at the same

velocity. Zone 3 is where the ore departs from the pipe conveyor section to enter the elevator head and is discharged.

The friction areas between the tube and the ore is in Zone 1 and 3.

1.9.7 Chapter 8 Discussion

This is a brief summary of results for frictions determined in this research. It also provides a summary of the predicted depths these elevators could lift from under defined condition based on the research conducted

1.9.8 Chapter 9 Conclusion

Highlights the issues and suggests further research.

2.0 Literature Review

2.1 Literature Introduction

This research focuses on acquiring the knowledge of friction for a cable disc elevator hauling mine ore and predicting the total friction and lifting force required for lifting ore from 1000m. Despite extensive searching there was no research or commercial knowledge found, for a cable disc elevator used in the mining industry, nor is there any information found for a pipe conveyor that operates vertically or is made from a textile cord conveyor belt.

An extensive literature search has been undertaken; a process that continued as the research progressed. As well as traditional sources of literature contact was also made with the two of the world's largest conveyor belt and elevator manufactures in Australia, Contitech and Fenner-Dunlop. This included meetings with technical managers who made various technical manuals and other information available. The author also contacted steel wire rope manufacturer Bridon, rubber belt manufacture Huacheng Rubber based in Shandong China, and Hao Sheng Transmission Technology Beijing China.

The literature review drew on insights from discussions with those companies included the above as well as journal and conference papers, textbooks, and web pages. The search concentrated on; raw materials used for belt manufacture including the type of rubber used; steel cable technology, synthetic materials and different designs of elevator systems that are in currently use.

A major component of the literature review was focused on examining and obtaining copies of relevant standards from ISO (International Standards Organisation), AS (Australian Standards), ATSM (ATSM Society), and BS (British Standards), these comprise of a considerable body of knowledge which has been useful in this research. Those standards and many other relevant papers are listed in the Bibliography. Other industry associations have very strong research and practical knowledge which was drawn on and contributed to this research including the Conveyors Equipment Manufacturers Association (CEMA 2017), and the Association for Rubber Products Manufacturers (ARPM, 2011). There were no standards found for cable disc elevators.

After reviewing the literature on various elevators and mine ore lift, there is very little information on long haul for continuous lift systems from 1000m or for cable disc elevators. However, the breadth of knowledge on cables and overland conveyor belts is enormous and much of this success of the industry stands on the huge shoulders of those researchers, companies, and industry associations, who have developed this industry for more than 100 years to the high level and the sophisticated products and engineering that exist today. In searching existing knowledge for bucket elevators, overland conveyor belts and mine hoist there is no single piece of information for friction of cable disc elevators.

Components of the cable disc elevator are common with mine hoist cables and cables used in overland conveyor belts. In this research, the pipe conveyor has many similarities with overland conveyor pipe belts except it is used vertically and uses a textile belt. There were no examples found where a pipe conveyor belt is used vertically or has a textile belt. Much of the literature review was directed at understanding various products that on the market, including mine trucks, elevator lifts, overland conveyor belts, crane lifts, lift elevators, and mine winders. Mine trucks, and cable hoisting systems haul ore and overland conveyor belts lifting ore from 1000m. Continuous vertical lift bucket elevator shown in Figures 4 and 5 have lifts for 276m (Contitech, 2013) and 173m (Holcim).

Materials used in the construction of conveyor belts and the main properties of steel wire elevator cable are reviewed. The literature suggests that the cable disc elevator existence in its present form provides little evidence of what this elevator maybe capable of. Literature relating to mine hoist cables and overland conveyor belt cords that are relevant for a future cable disc elevator are discussed for the physical engineering properties. The literature search discovered that bucket elevators structure is an adaption of the overland conveyor belt technology, with one exception of the chain driven bucket elevator.

Vertical continuous flow elevators are used in many applications for material handling for large tonnage movement of commodities such as wheat for ship loading in grain silo systems (Schmid,2016). The success of the cable disc elevator use is in non-mining industries is encouraging for the mining industry that these technologies can be adequately adapted for ore haulage from 1000metres, because there is potential for such an elevator to replace diesel haul trucks with continuous flow elevators. The operating ranges for haul trucks is shown in Section 1.2 Figure 3. In summary, the literature review describes some of the knowledge of products, and science and industry, relevant to elevators and in particular the cable disc elevator and pipe conveyors.

2.2 Current Ore Haul Methods

This part of the literature review selects the most popular ore haulage methods and briefly discusses the adverse components of these operations in mining.

2.2.1 Diesel Powered Haul Trucks

The benefit of replacing diesel powered haul trucks is the removal of emissions and reduced ventilation requirements for exhaust gas removal. Haul truck manufactures have done much to improve their product to reduce emissions, however the removal of the diesel engine underground removes the emissions issues. Trucks can be replaced with vertical elevators Below is a summary of the reason’s diesel needs to be eliminated from underground.

- The World Health Organisation (WHO) on the 12th July 2012 declaring diesel emissions as a Class 1 carcinogen placing these emissions in the same category as cigarette smoking and asbestos (IRAC, 2015).
- There are currently no national exposure standards for diesel particulate matter (DPM) for non-road diesel engines in Australia. The Western Australian Government ‘Management of diesel emissions in Western Australian mining operations-guidelines’ (Department of Mines and Petroleum 2013). The Australian Institute of Occupational Hygienists (AIOH) suggest an exposure limit of 0.1mg/m^3 of DPM.
- Improvements in regulation and engine design in the United States (EPA Tier 4) and the European Union (Stage IV) have by default resulted in better engine design.
- Diluting and removal of diesel emissions in the underground mine is achieved by the mine ventilation system where ventilation and control of the emissions are managed to meet the requirements of a breathable air (QGN21, 2014). This is a cost to mine operations.

In reviewing these documents; it can be concluded that diesel emissions can best be removed by eliminating diesel engines from underground mining.

2.2.2 Hydro-hoisting

There are many situations where hydro hoisting is used, for example the Vaal Reef No1 shaft in South Africa uses a Mitsubishi-mars pump to lift gold bearing or of 2mm particle size from 2200m in seven stages (Berg, 2004).
Another example is the Hansa Mine in Dortmund, Germany has brought ore from 850m to the surface hydraulically since 1977. Horizontal coal reserves had been mined out, then extraction of coal from the remaining steep deposits was extracted by high pressure water blasting (Jordan,1980). Dewatering of the pumped slurries adds another process to the mining operation in particular the dewatering of fine coal (Parekh, 2009).

On reviewing these publications, a decision was made for this research to use a cable disc elevator which does not require the extra step of ore to be slurried and dewatered.

2.2.3 Mag-Lev hoisting

Mag-lev engineering has been applied for high speed trains in Japan, South Korea and China. The idea for vertical lift has been a concept that has attracted a lot of attention at various times. Otis Lifts took patents out in the 1950's, and today the system is used in small component production lines with the benefit of combined vertical and horizontal movements. The concept of mine haulage at any level with Mag-Lev continues to attract reader interest, however, little has been done other that some laboratory research for the mining industry (Bhowmick, 2015).

2.2.4 Mine Hoist Elevators and Cable Winders

The technical knowledge of hoist elevator cables contributes much to type of cables that could be available for a cable disc elevator at 1000m. That knowledge assists in predicting the depth a vertical pipe conveyor may be able to reach

There are two common types of hoists: the drum hoist or the friction hoist (Koepe hoist). Friction hoists have steel wire rope passing over a wheel/sheave, with an ore skip conveyance on one end of the rope and a counterweight on the other. The drum hoist has a conveyance at each end of the rope using the skip as a counterweight. (Lowrie, 2002).

There are 6 main types of hoists, single drum, double drum, friction (Koepe) drum, Blair-multi rope hoist, conical and the spiral drum hoist (De La Vergne, 2003). The only hoist system that has any common element with the cable disc elevator is the friction (Koepe) hoist which has two skips that balance each other, as one skip is hoisted up the other skip is going down. This balances out the weight of the skip and is driven by the power transferred from the drum by friction between the drum and the cable. A mine hoist can be energy efficient when two buckets are used because one is hauling while the other is lowering (Lowrie, 2002). For most deep mines, this has been a historically successful method. These mine haulers are a batch process much like mine trucks. Hoists have a small footprint and can fit in a multi-use shaft. Indeed, this technology is a proven mine ore haulage method for use in deep mines. (Regan, 2007). Hoisting ropes have a factor of safety that is usually stipulated by laws and regulations and are required to have a minimum load strength equal to the maximum suspended gross load multiplied by the factor of safety. (Lowrie, 2002). When the required cable lift capacity is determined, its capacity is multiplied by the factor of safety to determine the tension or lift capacity of the cable (Bise, 2003).

An example of a friction drive used for mine ore haulage is the Pyhasalmi Mine st North Ostrobothnia in Finland. The hoisting capacity is 275t/h at a hoisting distance of 1407m using a 44mm diameter steel wire rope (ABB, 2019).

According to the Bridon specification handbook (2011) a 45mm diameter Tiger Dyform 34LP/PI mine hoisting rope strength is 2460 N/mm^2, and rope mass of 10.2 kg/m. A cables characteristic length as defined in the Robertson lifting manual (2014) calculated by the following formula.

$$\text{Characteristic length } = \frac{\text{Breaking force}}{\text{Cable weight x 9.81}} \tag{2.1}$$

Where the cable weight is the weight for one metre. Using data of the 45mm diameter hoisting cable presented in Table 5;

$$\text{Characteristic length } = \frac{2{,}460{,}000}{10.2\ x\ 9.81}$$

$$\text{Characteristic length } = 24{,}584 \text{ m}$$

Then applying a factor of safety of 15% the cable lifting length is then 3688m. For this cable to lift ore from 1000m the weight of the ore it carries, the force for acceleration and the friction in the cable disc elevator cannot exceed the cable capacity.

2.3 Overland Conveyor Belts

2.3.1 Overland Conveyor belts

None of the literature indicates any significant use of conveyor belts for overland ore haulage. Much of the elevator industry appears to try to adapt these into vertical elevators with attachment of different designed ore buckets. Overland conveyor belts are very successful for what they achieve in carrying ore long horizontal distances. The technical knowledge of the conveyor belt structure and ability assists in predicting to what depth a vertical pipe conveyor may be able to reach. The relevance of these long-distance conveyor belts is that they are also used for elevator belts, have proven strength, are readily available from the belt manufactures, and have high resilience.

Long haul overland conveyor belts are achieving significant haul distances. The longest single flight belt is 21.7 miles (35km) and the longest system is 62 miles (100) km long of 11 flights with belt strengths of 7000kN/m width (CEMA, 2014). An example of an overland conveyor belt being used for ore haulage from underground for a 1000m lift is ST7500 Phoenix conveyor belt in Picture 2. The development tunnel also facilitates vehicle travel and other services. An example of a overland conveyor belt used in underground mining is the ore conveyor at the Prosper II mine which hauls ore from 1000metres and the belt is 8000m long. This belt is a Phoenocord ST7500 steel cable belt (Phoenix, 2018).

2.3.2 Conveyor Belt Structure

Belt structure consists of the following:

- Cord. This runs longitudinally in the belt and takes the belt tension and determines the overall strength of the belt. Typical materials for Cord structure have been, cotton, rayon, glass, nylon, polyester, aramid, and steel cable. Steel cable require brass or galvanize coating for rubber to adhere. (Peterson, 2009. Evans, 1997. Mark, 2013). Except for cotton which has many fibres to attach to skims (rubber) all the other materials require pre-treatment with a formaldehyde resin coating to get rubber skims to attach. Aramids such as Kevlar require a primer of epoxy prior before the formaldehyde application. (Kevlar, 2014).
- Steel wire cords are polymer filled. This polymer filling stops water travelling along the cord should ore rocks damage the covers and expose the cord. Polymer filling also serves the purpose of lubrication between the steel wires and stops and ingress of ore where the cover may be damaged (Changwoon 2002, Peterson 2009).
- Skims are used to tie the layer of the cords together and bond the weft cords with the cord's components together (Fenner, 2009).
- Polymer fillings between the cord materials and the covers is usually a rubber polymer that also bonds the conveyor components together (Fenner, 2009).
- Weft materials are shown laid laterally, hold the width of the belt together. For the example above, smaller woven steel wire rope, weft is laid across the belt (Fenner, 2009).
- Covers are added into the belt structure to improve grip on the drive roller, and provide protection to the belt from impact, oil, sunlight and other hostile environments (Fenner Dunlop, 2009).

Conveyor belt structure is described in the next table is taken from the Fenner Dunlop conveyor belting technical manual (Fenner Dunlop, 2009.). This gives a brief detail of the materials used for the manufacture of conveyor belt and elevator belt materials and structure.

Table 1. Conveyor belt Cord strengths for various materials (Fenner, 2009).

Carcass	Carcass materials		Strength range	Features and applications
	Warp Longitudinal	Weft transverse	Kilo Newtons per metre width	
PN Plain weave (DIN code EP)	Polyester	Nylon	315 to 2000 kN/m (150 to 400 kN/m/ply)	Low elongation, very good impact resistance, good fastener holding, an excellent general-purpose fabric.
PN Crow's foot weave	Polyester	Nylon	630 to 2500kN/m (315 to 500 kN/m/ply)	Low elongation, good impact resistance, very good fastener holding, excellent rip resistance, for high abuse installations.
PN double weave	Polyester	Nylon	900 to 1350kN/m (400 kN/m/ply)	Low elongation, excellent impact resistance, excellent fastener holding, for high abuse installations
PP plain weave	Polyester	Polyester	Up to 500kN/m (120 & 450 kN/m/ply)	Used in special applications where acid resistance is needed.
NN plain weave	Nylon	Nylon	Up to 2000kN/m (150 & 450 kN/m/ply)	High elongation mostly replaced by polyester-nylon. Used in special applications where low modulus needed or in high pH environment.
CC plain weave	Cotton	Cotton	Up to 400kN/m (65 & 70 kN/m/ply)	Used in special applications such as plaster board belting and hot pellet handling.
SW solid woven	Nylon/cotton or Polyester/cotton	Nylon/ Cotton	600 to 1800kN/m	Main use in underground coal mining. Good fastener holding and impact resistance. Used for bucket elevators.
ST steel cord	Steel cord	None (special reinforcement available)	500 to 7000kN/m	Very Low elongation and high strength. Used for long haul and high-tension applications.
AN aramid nylon (Kevlar)	Polyaramide	Nylon	630 to 2000kN/m	Low elongation, high strength, low weight. Used in high tension applications and on equipment conveyors.

In Figure 6 the belt shown has a textile cord structure. The belt shown in Figure 9 the cord structure is made up from longitudinal steel cable that have brass or galvanize coating for rubber to adhere

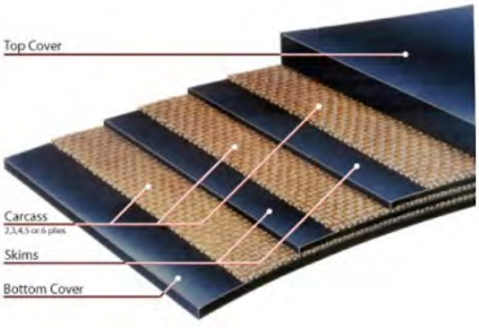


Figure 6. Typical belt structure using woven material for the carcass. (Phoenix, 2004)

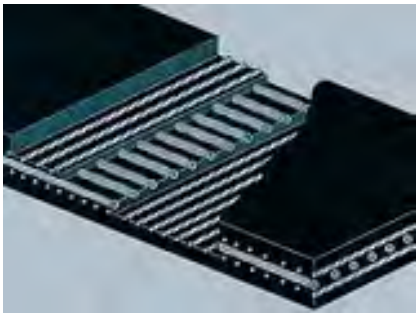


Figure 7. Steel wire cable cord belt (Phoenix, 2007).

Wire used in the cable structure has been galvanised or brass coated as there is a chemical reaction during vulcanization where sulphur in the polymer compound chemically react and form a metal sulphide adhesive interface connecting the steel and the polymer materials as shown in Figure 10. Textile belts using polyester require the polyester to be coated with a formaldehyde coating, and Kevlar textiles are precoated with epoxy resin then formaldehyde before the rubber polymer is used (Kevlar, 2014). This is like many other adhesive bonding applications. (Peterson 2009, Evans 1997, Mark 2013).

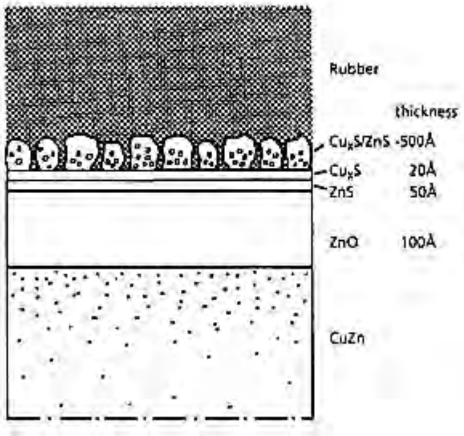


Figure 8. Interfacial Copper Sulphide Film in Rubber-brass Bonding (Mark, 2013, Gough, 1968)

The strength of any conveyor belt comes from the carcass, for steel wire conveyor belts this is from the cords. Calculations for strength of the overland conveyor belts are only based on the strength contribution from the steel wire rope cables. Characteristics of steel wire cords that make these most suitable are the very high strength, very low elongation, excellent heat resistance, good fatigue and abrasion resistance (CEMA, 2014).

For bucket belt elevators the most common belt structure has the fabric carcass as drilling holes to bolt on elevator buckets because this does the least damage to the belt. Steel cord belts cannot have a hole drilled that breaks a cord, hence these belts when used for elevators have the buckets or bucket mounts glued or vulcanized onto the belt however the two elevators shown in Figure 5 have cable steel wire cords (Continental, 2013 and Beumer, 2015)

2.3.3 Overland Conveyor with Separate Belt and Cable

In this type of overland conveyor belt the belt structure and the driving cables are not bonded together. A cable belt conveyor differs from the conventional conveyor belt in that there is almost no tension induced in the belt. The belt simply rides on the two large endless wire ropes at the sides of the belt. The belt design is different in that there is some preformed dip in the middle of the cross section of the belt to maximize the volume of ore on the belt. The belt weight is supported by the two cables. At the discharge and tail or loading ends, the cables and the belt separate where they wrap around the respective return pulleys and drum. At the drive end the cable wraps around the friction drum drive. Intermediate friction drum drives for the cable can be placed along the belt to achieve a longer conveying system, and there is no requirement for the cables cord inside the rubber conveyor belt to match the strength of the outer cable. Hence the outer cables can have a large diameter (Overland, 2019).

Picture 1 Cable belt. Metso MRC Cable belt conveyor (Metso, 2019).

An example of this type of conveyor belt hauling coal from underground was at the Selby mining complex, (now closed) in England from various depths including from 990 metres underground hauling 1830 t/h and length 14923m (Thomson, 2002).

No literature was found showing this design operating vertically or at steep angles, however this has a concept of being able to select large cables for the duty that are not restricted to the manufacturing capability of the conveyor belt structure. This implies that separating the belt structure and the cable allows for stronger cables.

Shown in Table 1, the steel cord conveyor belt has the highest strength, for long distance vertical lift steel cord belts are used. White County Coal mine pocket lift belt is 276m (Contitech, 2013) and uses a steel wire cord belt structure.

Table 2. Steel wire rope strengths, Dyform 34LR PI Series used in rubber belt conveyors. (Bridon, 2011)

Steel wire rope diameter mm	Approx. nominal length mass kg/m	Min. Breaking Force E 1960 grade kN
10	0.50	92
11	0.61	111
12	0.72	133
13	0.85	156

Australian Standard AS1333-1994 shows the belt strength standards for Australian belts to ST6300 and refers to ST 7500. Cable strength as minimum breaking strength of 133kN. Table 3 below also shows that for a 1000mm wide belt of ST6300 strength there are 48 cables. Conveyor belt construction requires the cables to be of even tension so that all the cables pull together in the conveyor belt. Any cable that is tensioned tighter will be working more than those of lower tension and is susceptible to being overloaded. Pre-tensioning the cables requires significant manufacturing machine strength.

Siempelkamp, one of the major equipment manufactures for belt making machinery built the Fenner Dunlop plant in Kwinana Western Australia claim that cable tension equalization is within +/- 2% over 520 cable drums. The cords are tensioned during belt manufacture with alternating S and Z twist cords (Fenner Dunlop, 2013).

Conveyor belt construction with 12mm diameter cables or less, are achieving the long-distance overland travel as per the examples above. For the manufactures to increase the cable size in the belt carcass requires stronger manufacturing machinery in order to equal tension in all the cables. This would be commercially difficult to justify given the current distances overland belts can haul ore using the existing size cables, plus the market demand in mining for such belts is for overland haulage. Some cable minimum breaking strengths are listed in the Table 4. This results in the high strength belts available for bucket elevator construction need to be selected from the range of conveyor belt products that can be made by the overland conveyor belt machinery.

Limitations of construction of belts to approximately ST7000 does not stop the opportunity for continuous vertical lift for 1000m in multiple steps. Such a lift with bucket elevators of various types will then need to be constructed with a number of elevators in series with transfers between each elevator. Using a multiple step of elevators in a series could lead to a lighter cheaper belt construction and more elevator sections. Contitech's twin belt pocket lift elevator with buckets between the belts operating at 276metres at White County Coal design could achieve 1000metres in four steps.

2.4. Steel Wire Cable Sizes used in Overland Conveyor and Elevator Belts

The Australian Standards list a table of steel cord belting sizes and strengths in AS1333-1994. These show the basic strength data for these belts numbering the quantity of steel wire cores, their diameter, and strengths. This is shown in Table 4.

Table 3. Steel wire rope specifications for belt conveyor cords, (AS1333-1994)

Belting Designation	Steel cord belting reinforcement		Number of cables																
			Belt width mm																
	Cord (min) breaking force kN	Cord pitch mm	600	650	750	800	900	* 1000	1050	* 1200	* 1400	1500	* 1600	1800	2000	2200	2500	3000	3200
ST500	7.3	13.8	42	45	52	56	63	70	74	84	99	106	113	128	142	156	178	215	229
ST560	8.2	13.8	42	45	52	56	63	70	74	84	99	106	113	128	142	156	178	215	215
ST630	9.3	13.8	42	45	52	56	63	70	74	84	99	106	113	128	142	156	178	215	215
ST710	10.3	13.8	42	45	52	56	63	70	74	84	99	106	113	128	142	156	178	215	215
ST800	11.6	13.8	42	45	52	56	63	70	74	84	99	106	113	128	142	156	178	215	215
ST900	14.7	15.3	37	40	47	50	56	63	66	76	89	96	102	115	128	141	161	193	207
ST1000	16.5	15.3	37	40	47	50	56	63	66	76	89	96	102	115	128	141	161	193	207
ST1120	18.5	15.3	37	40	47	50	56	63	66	76	89	96	102	115	128	141	161	193	207
ST1250	20.6	15.3	37	40	47	50	56	63	66	76	89	96	102	115	128	141	161	193	207
ST1400	22.1	15.3	37	40	47	50	56	63	66	76	89	96	102	115	128	141	161	193	207
ST1600	29.1	17.3	33	36	42	45	50	56	59	67	79	85	90	102	113	124	142	171	183
ST1800	32.7	17.3	33	36	42	45	50	56	59	67	79	85	90	102	113	124	142	171	183
ST2000	36.4	17.3	33	36	42	45	50	56	59	67	79	85	90	102	113	124	142	171	183
ST2240	41.0	17.3	33	36	42	45	50	56	59	67	79	85	90	102	113	124	142	171	183
ST2500	51.1	19.4	30	32	37	40	45	50	52	60	70	75	81	91	101	111	127	152	163
ST2800	57.4	19.4	30	32	37	40	45	50	52	60	70	75	81	91	101	111	127	152	163
ST3150	64.6	19.4	30	32	37	40	45	50	52	60	70	75	81	91	101	111	127	152	163
ST3550	72.8	19.4	30	32	377	40	45	50	52	60	70	75	81	91	101	111	127	152	163
ST4000	82.0	19.4	30	32	37	40	45	50	52	60	70	75	81	91	101	111	127	152	163
ST4500	92.3	19.4	30	32	37	40	45	50	52	60	70	75	81	91	101	111	127	152	163
ST5000	102.0	19.4	-	-	-	-	45	50	52	60	70	75	81	91	101	111	127	152	163
ST5600	113.5	19.4	-	-	-	-	45	50	52	60	70	75	81	91	101	111	127	152	163
ST6300	133.0	20.0-	-	--	-	-	43	48	50	58	68	73	78	88	98	108	123	148	158
ST7500	-				-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

2.5 The Pipe Conveyor.

As can be seen by the previous discussion, pipe conveyors are an important extension of the science and technology of overland conveyor belts. The first pipe conveyor concept was developed by the Japanese Pipe Conveyor (JPC) in 1978 and patented on the basis that it formed a trough into a pipe shape using unique construction involving rollers to guide the belt into a tubular shape. These conveyors use an overland conveyor belt with some modifications of the belt structure. The concept is shown in Figure 12 and 13. The belts have a cord structure of steel wire cable which improves the belts longitudinal strength to hold the ore weight, and provides shape stiffness which reduces roller resistance (Zang, 2012). The pipe conveyor structure varies to the overland conveyor belt design is no wefts are only textiles and no weft cables as shown in Figure 10

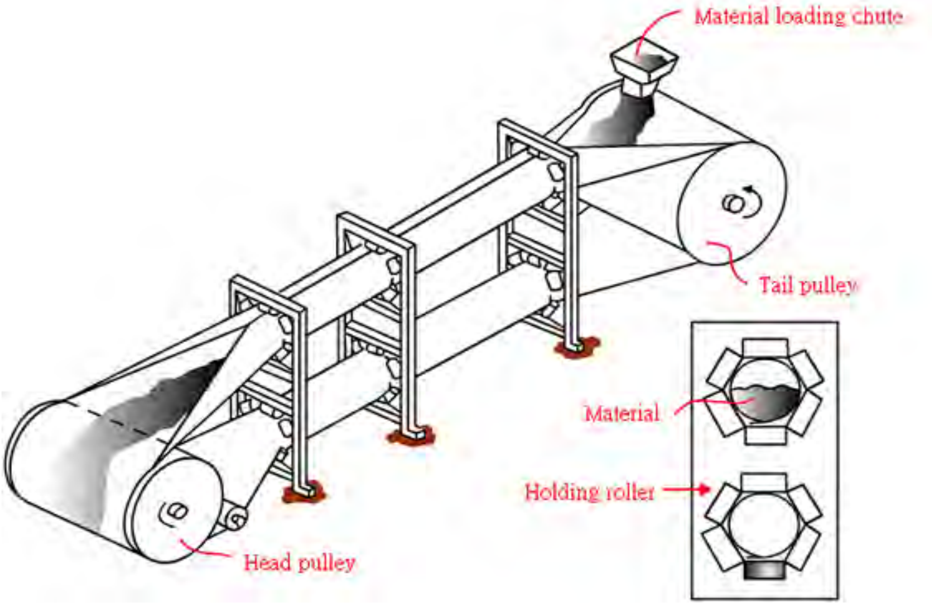


Figure 9. Pipe conveyor drawing concept (Probelt, 2018).

Figure 10. Cutaway section of a steel cord pipe conveyor, showing some variation in the cable configuration. (Bridgestone, 2018).

This technology has developed significantly since the JPC patents have expired and considerable interest has resulted in more than 160km of pipe conveyors being built for over 700 installations

(Staples, 2002). Typical lengths pipe conveyors exist range from 0.340 to 4.390km (Conti Pipe, 2016)

Their attraction for this research is that the pipe conveyor offers the necessary shape and dynamics for a cable disc elevator to have a dynamic vertical tube which is frictionless between the cable carrying the ore, and the tube conveyor, when travelling at the same speed. After an extensive search of literature, there is no application present where a pipe conveyor is used vertically or in tandem with a cable conveyor. Any information, therefore, relies on company specifications and standards.

The features of a pipe conveyor are that the flat conveyor belt has been shaped into a tube by rollers. The tube conveyor design encloses the ore being transferred avoiding ore spillage and protecting the ore from the elements. These belts can also navigate terrain, can tolerate long sweeping bends and steep angles up to 30^{o} (Continental, 2016).Long haul pipe conveyor belts have longitude steel wire cable cord in a particular distribution to achieve a low rolling resistance for the belt tube shape to take place, weft strength is from the textile component (Zang, 2012).

Rollers used for the pipe conveyor consist of six rollers that form a hexagon shape through which the belt passes. Typically, the rollers are mounted on a panel with three rollers on one side and three on the other. Having three rollers on each side of the panels allows the rollers to be longer and effectively overlap the hexagonal plus avoid the belt edge getting jammed into a roller edge when smaller rollers are used on the one side. Larger rollers also have lower roller resistance and are less noisy (CEMA, 2017).

Load forces exerted by the rubber conveyor belt on the rollers depend on the mass of ore being transported, plus the mass and stiffness of the belt. Lodewijks (2012) calculates the load forces that uses a model with multiple Maxwell parameters incorporated with a Wrinkler foundation. However, these calculations are dependent on a horizontal pipe conveyor with various levels of ore fill resulting in a higher rolling resistance for the lower circumference of the pipe shape and lower resistance for the upper rollers where there is no ore. With no ore present the rolling resistance is brought on by the rollers keeping the pipe shape, and the rollers forcing the pipe formation (Zang, 2012).

Steel wire cables used in the overland conveyor belts have very low elasticity as calculated in the Bridon manual (2011), this leads to the flat belt to pipe transition usually taking place over 10 to 40 metres for steel wire cabled belts. The minimum transition is 60 x the pipe conveyor outer diameter (Continental, 2012).

Based on the information in this literature review for a pipe conveyor to replace the vertical tube of the cable disc elevator. it would not be practical for the rig to have a 10m belt forming inlet and a 10m outlet. Also, for a mine that may require a 40m in and 40 out for a steel wire cable belt cord structure, would require increased development for this length. For this test rig a textile belt is used which can have short belt forming sections. The textile belt could have a high enough strength of 2500 kN/m i.e. 400kN/m/ply which may have the strength for a 1000m vertical pipe conveyor when this does not have to carry and ore. The only effort the pipe conveyor belt has to carry is its own weight and the length it can achieve vertically which is the characteristic length as defined in 2.2.4 for cables.

The invention of pipe conveyors was a forward step for conveyor belt innovation and now have a presence in the mining industry with many conveyor belt manufacturers offering these as part of their product range. The literature review found no pipe conveyors in a vertical position or any made from textile belting or any description of the belt characteristic length. The use of the pipe conveyor as applied in Test Rig 3 is thought to be the first such application for a pipe conveyor.

2.6 Selection of Elevator Belt Types

Conveyor belts used for elevators need to have the ability to have buckets attached. Buckets are usually attached by vulcanising the rubber attachment to the belt or the buckets can be bolted to the belt. Bolting directly though the belt can damage the belt cord especially when the cord is cables.

2.6.1 Side wall rubber vulcanised belt

A Beltco (2012) elevator that has ore carrying buckets on this style of elevator are vulcanised or glued to the belt, in some belts there are bolted brackets. The side wall belt is shown in Figure 14.

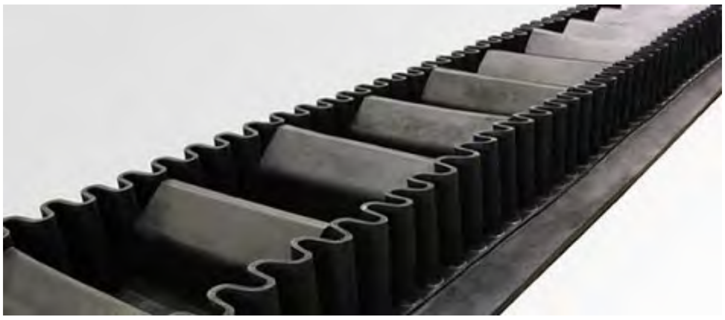


Figure 11 Speciality belting with sidewalls (Beltco, 12/2018).

2.6.2 Traditional Bucket Elevator.

The traditional universal bucket elevator as shown in Section 1.2, Figure 5 has buckets with mounting bolts though the belt. The most common style of belt for these applications has a fabric mesh cord as shown in Figure 8. The tallest elevator of this style is at India Cement Co, where the elevator belt at 173m high (Beumer, 2015). A typical traditional elevator bucket that is bolted onto the elevator belt is the one shown in Figure 13.

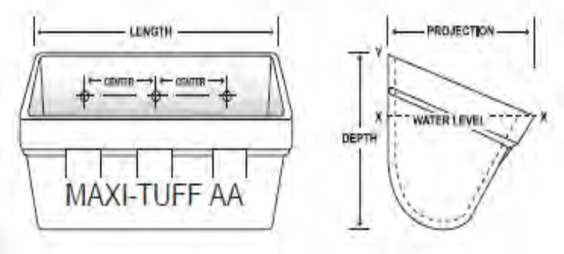


Figure 12. Kinder elevator bucket that is bolted onto an elevator belt (Kinder, 2015)

2.6.3 The Pocket Lift Bucket Elevator

This pocket lift elevator construction was used by Contitech (2013) for the White County Coal mine. The design of bucket elevator has the buckets suspended between two belts as shown in Section 1.2, Figure 6.

The pocket elevator has many advantages in the design. The brackets that buckets are mounted on are vulcanised or glued to elevator belt. Attaching brackets with this method allows the belt to be selected from the strongest belt steel wire cord belting.

- Twin belts allow for more cables per bucket width increasing the overall lifting strength, compared to a single belt where buckets of the same size can take up the full width of the belt for the traditional bucket elevator. The lifting capacity is a function of the number of cables and the cable size or tension specification for the cables. Cable capacities are listed in the Table 3 along with the number of cables per belt width.

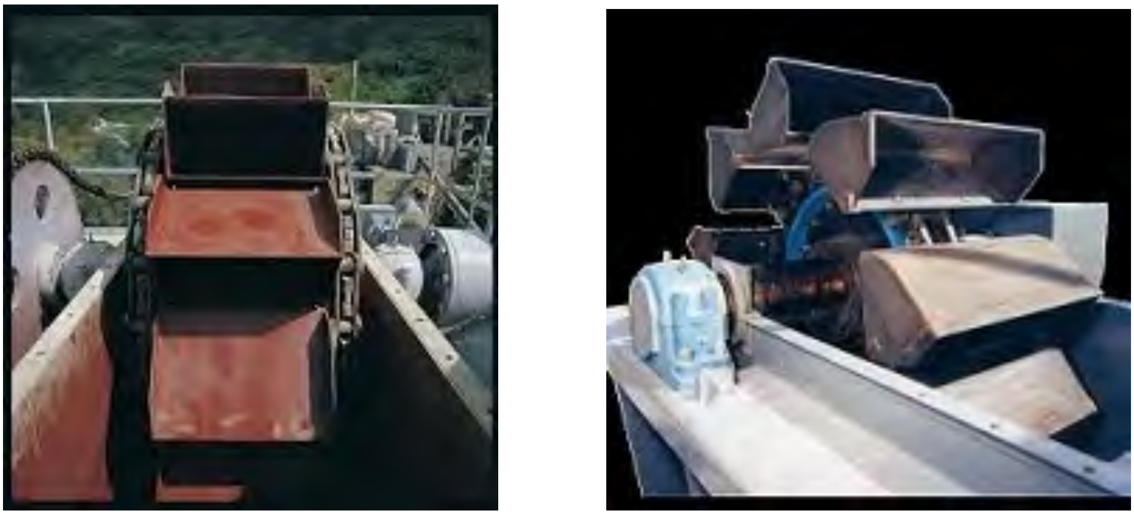
- Twin belts allow for the belt to be in an inverted position on separate rollers without interference from the buckets, hence, elevator unloading is not dependant on requiring ore throwing velocities for the buckets to unload the product. Plus, the drive head roller system can consist of a number of driven rollers drums.

- Perhaps the limitation of such elevators is cost. There are no publications or press release information on the cost, but sources inside Contitech have indicated to the author that to manufacture the same today (2018) would cost approximately $22m plus civil engineering costs for the 276m lift.

2.6.5 Chain Bucket Elevators

Chains used in elevators are usually made with flat leaf linked chains, with roller and pin linked joints or round link chains (Renold, 2018), (Bogaert, 2018).

These elevators are sprocket driven which makes the drive connection positive and not dependant on friction. Chain selection is critical to the correct functioning of bucket elevators. In most applications the chains can are straight side bar, hardened bushed rollerless type or hardened bushed roller chains. Less frequently, some chains are off set (CEMA, 2017). Single chain elevators are usually limited to a bucket width that does not exceed five times the width of the chain (CEMA, 2017). An example of the single chain and double chain elevators is shown in Picture 7.. Typically, they operate at speeds of up to 2 m/s, and the distance between shafts centres is 70 metres. They can carry up to 400t/h. (CEMA 2017).



Picture 2. A twin chain and single chain bucket elevators (Renold, 2018)

2.7 The Cable Disc Elevator

The cable disc elevator is the chosen elevator system for research in this thesis. Cable disc elevators have been in production since the 1950’s (Floveyor, 2015). There are a small number of manufactures producing the two types of these elevators, the drag conveyor elevator and an aero mechanical elevator. Connection between the discs either uses a chain (Hapman, 2018), or steel wire cable. For the cable type disc elevator, the cable rarely exceeds a diameter of 10 mm and lift over 20 metres. During an extensive literature review only one research paper was found which discusses this type of elevators (Webb, 1968), and that was the aero mechanical elevator. This study does not have much relevance for this thesis, as the gap between the discs and the lifting tube were large and the bulk density of the medium being lifted was in the order of 450-650 grams per litre, compared to granite’s density of 3600grams per litre.

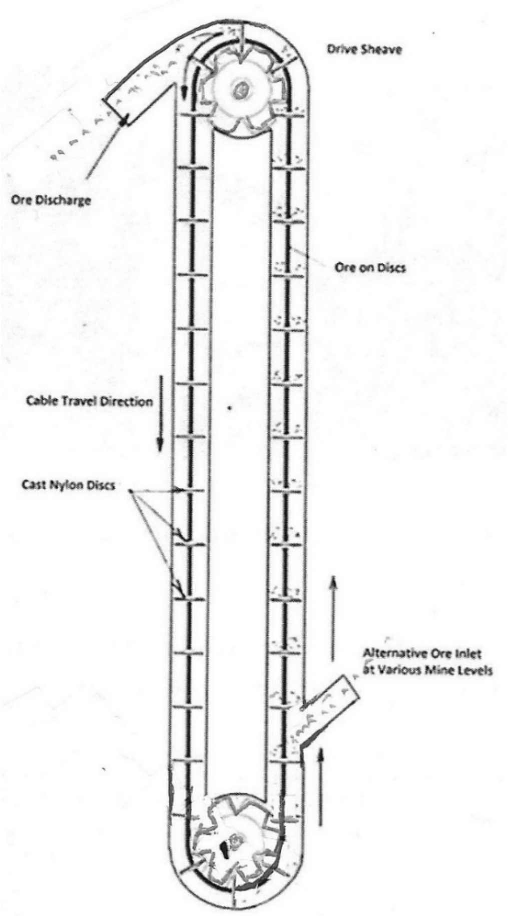


Figure 13. Open drawing of the cable disc elevator from Figure 1 (Adapted from Floveyor, 2015)

Literature searches were undertaken but information for this type of elevator being used for mine ore haulage was not found. However, with large diameter cables of 40+mm there may be potential to use this design and could be capable lifting ore from depths of 1000metres or greater. The unknown variable is the friction, between the ore and the tube when the ore is being dragged up the tube. This friction resistance would contribute to the tension requirement of the lifting cable, however, the magnitude of the friction is unknown. This thesis seeks out some of that knowledge of friction.

2.8 Steel Wire Cable Characteristics

As noted in the previous discussions steel cables are essential for overland conveyor belts and mine hoists. Steel wire cables react to temperature, high tension that causes twisting/rotation, and fatigue. Some of these characteristics are discussed below.

2.8.1 Steel Wire Rope Extension

Bedding down of the assembled wires for a steel wire rope occurs when the rope is loaded for the first time. The extended length results in a corresponding reduction in rope diameter. This results in an extended length of the helical lay. Mechanical extension stops when sufficiently large forces have settled onto the bearing surfaces of adjacent wires. This extension has no elastic properties and is difficult to determine (Bridon, 2011)

Elastic extension of the rope extends in a manner outlined in Hooke's law until the 'Limit of Proportionality of Elastic Limit' is reached. Young's Modulus of Elasticity is not a characteristic in wire ropes. An apparent modulus can be determined between two different loads. This varies depending on the rope shape and make up rather than just the diameter. Modulus of Elasticity increases as the cross-sectional area increases. Rope length also changes with twisting of the rope, Glushko, (1996) calculated and measured the rotary angles of wire ropes in mining shafts The change in rope length was calculated for wire ropes with one strand layer and a fibre core where the strand length is constant and the strand winding radius r remains constant. (Hankus, 1993, 1997).

Glushko and Hankus Feyrer (2015) demonstrated that for a wire rope of cross-sectional area 100.5 mm^2, rope length 245m, elasticity modulus E_s=93,000N/mm^2, and preloaded rope σ_z=0 and 400N/mm^2.the extension was 21.4mm. They also provide an approximation is given by the formula below. For accurate analysis a modulus test needs to be carried out on the samples of wire rope.

$$\text{Elastic Extension} = \frac{\mathrm{W \, x \, L}}{\mathrm{E \, x \, A}} \ \text{mm} \tag{2.18}$$

Where W is the load applied kN, L is the rope length in mm, E is the elastic modulus kN/mm^2 and A is the metallic cross-sectional area mm^2.

If the load exceeds the Limit of Proportionality, then the rate of extension will accelerate as the load is increased until a loading is reached where continuous extension occurs causing the rope to fracture without any further load. (Bridon, 2011)

2.8.2 Thermal Expansion and Expansion and Contraction of the Cable

According to Bridon (2011), the coefficient of linear expansion of steel wire rope in 12.5 x 10^{-6} per degree Celsius. For the change in length of rope:

$$\Delta \mathrm{L} = \alpha \, x \, \mathrm{L} \, x \, \mathrm{T} \tag{2.19}$$

Where L is the rope length m, Δ T is the change in temperature $^{\mathrm{o}}\mathrm{C}$, and α is the coefficient of expansion. For a 10-degree change in temperature this would represent the following cable extension for 1000m.

$$\Delta \mathrm{L} = 12.5 \, x \, 10^{-6} \text{ x } 1000 \text{ x } 10$$
$$\Delta \mathrm{L} = 12.5 \, x \, 10^{-2}$$
$$\Delta \mathrm{L} = 125\mathrm{mm}$$

The cable also needs to be polymer filled for lubrication, to reduce wear between the wires and to eliminate the inclusion of fine ore dust entering the cable matrix which could create abrasion. This should also reduce external wear. Bridon (2011), Feyrer (2015), demonstrate there is very little stretch in steel wire ropes.

2.8.3 Pressure on the Head Drive

As the rope goes over the head roll sheave it is subjected to a radial pressure which sets up shearing stresses in the wires. At this point the rope structure is distorted. For cranes and lift wires cables are lubricated with petroleum products such as grease. For mining where there can be significant ore dust which is abrasive, rubber infill between the wires is necessary to remove abrasive contact and rubbing, spread the load between the wires and hold the wires together when the cable is under pressure going over the drive sheave. As the cable passes over the sheave, the sheave receives tension from the rope in the angle of contact. This is independent of the diameter of the drive sheave.

$$\text{Load on the bearing} = 2\,T_1 \sin\frac{\theta}{2} \tag{2.20}$$

Θ is the cable contact angle of arc

If the rope is fitted well into the sheave grove, then the pressure between the rope and the groove is dependent on the tension T_1 and the diameter but is independent of the angle of arc.

$$\text{Pressure } p = \frac{2 . T_1}{D\, x\, d} \tag{2.21}$$

Where p is the pressure kg/cm^2 , T_1 is the rope tension in kg, D is the diameter of the sheave cm, and d is the diameter of the rope cm.

This formula used in the cable crane industry assumes that the pressure is constant over the sheave contact area. Pressure varies from the nip point and increases rapidly as contact between the sheave and the cable starts then reduces as the cable moves to depart the sheave. (Bridon 2011)

2.8.4 Bend Fatigue

Bend fatigue for a steel wire cable usually requires cycling the duty that it will be used for over a sheave of the size that will be used and under constant tension, because the ISO4309 standard for fatigue has some relevance. However very few ropes operate under the conditions outlined in the standard.

Bend fatigue is related to the diameter of the sheave, the number of cycles, wire rope style and diameter, and the speed of the cable traveling over the sheave. Manufacturers have recommendations for the sheave diameter which range between 100 and 120 times of the cable diameter.

2.8.5 Double Layer of Wire in Conveyor Belts

The longitudinal strength of a conveyor belt is determined mainly by the strength of the core, in long belts. This the strength of the steel wire rope design. Increasing the size of the cables in theory may seem an answer for the development of longer lifting elevators, however this is not a manufacturing option. The pocket lift elevator using 2 belts clearly demonstrates that doubling the number of cables by supporting the buckets between the belts has been an effective way of achieving greater lift distance (Contitech, 2013).

Doubling the cables in the belt core with a second layer over the warp (using cross cables or matting) between the cables is not an alternative as the cables have a different diameter path over the drive roller. This is because of the lack of elasticity of the steel wire rope. A cable in a second layer going over a drum roller would be required to travel a distance greater than the cable closest to the drive or idle drum. This is calculated below.

Where the drum diameter is 2000mm, cable diameter 12mm, and warp cables at 8mm, rubber skims between each layer of 5mm, then considering the diameter travel of the closest cable to the drum with skims and matting under this of 10mm then skims warp and skim separating the next layer of cable the cable radius for the first cable would be 1016mm, and the second cable 1046mm. The sketch drawn by the author in Figure 17 shows the concept of one row of cables above another

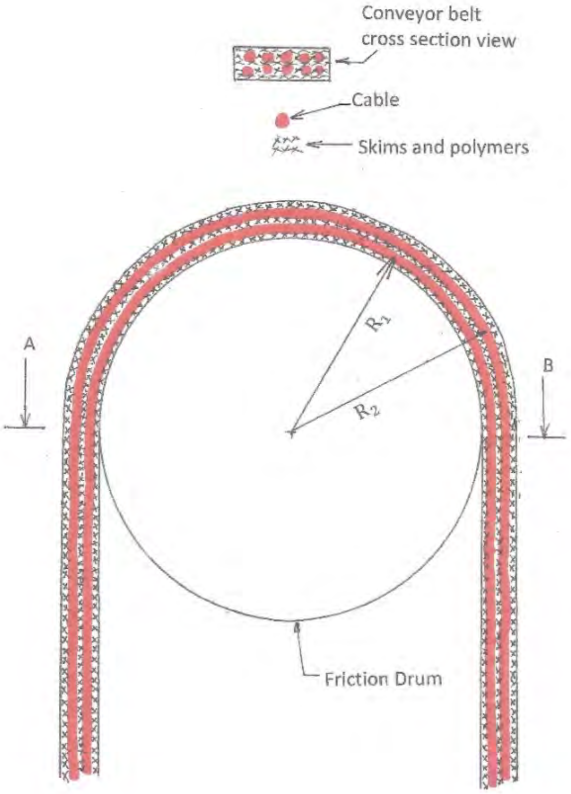


Figure 14.A theoretical double cable layer belt (Authors sketch)

R_1 is the radius at the centre of the first cable (and equals the drum radius + distance to the centre of the cable) and C is the circumference of the friction drum.

R_1 = 2000/2mm + 10mm (Skims and matting) + 6mm (Half cable dia.)

R_1 = 1016mm

The length of the first cable over the drum from point A to B is half the circumference 0.5C

$$0.5C = \frac{Diameter}{2}\pi \qquad (2.22)$$

$$0.5C = 1016\,\pi$$
$$0.5C = 3191.9mm$$

For R_2,the radius for the second layer of cables, the increase in radius is half the first cable diameter 6mm, plus the skim layer 5mm, plus the weft layer of 8mm cable, plus the skim layer of 5mm, plus half the thickness of the second layer of the cable 6mm.

$$R_2, = R_1 + 6 + 5 + 8 + 5 + 6 \text{ mm} = 1046\text{mm}$$

Point A to B length of the second cable is then

$$0.5C = 1046\,\pi \text{ mm}$$

$$0.5C = 3286.1\text{mm}$$

$$\Delta 0.5\ C = 3286.1\text{-}3191.9\text{mm}$$

$$\Delta 0.5C= 94.2\text{mm}$$

The length of elasticity required of the second cable is then 94.2mm over a distance of 3191.9 mm or 3 percent elasticity. As calculated using the formula from Bridon, and from Feyrer, it is reasonable to accept that such elasticity is not possible.

Pressure applied from the top layer of cables can be calculated from equation (2.2) above would have the top cable layer cut into the lower level cable damaging the belt.

The conclusion from the above discussion is that steel wire rope core conveyor belts can only be used in a single plane of rope in the core.

2.8.6 A Bucket Elevator with Cables and No Belt

There may be many potential applications that could be applied for mine ore lift. The author's objective of wanting to stimulate the mining industry to develop continuous vertical ore lift leads to many possibilities that have not been explored. This is one of those concepts.

The concept of this elevator has the rubber of the elevator belt removed and the buckets attached directly to the elevator cable. The buckets and brackets act as weft links between the cables and aid positive drive on the friction drive roller. The sketches below are purely conceptual. There are no such elevators and no literature were found that discusses real-world application of such concepts. Apart from the chain elevator, all the belt bucket elevators are developed as a step further on from the belt conveyor with buckets attached. Why such a design does not exist is discussed in section 2.13, but broadly it concerns the physical characteristics of thermal expansion, cable rotation twist, and the difficulty of evenly tensioning the cables that have to work in tandem with each other.

This raises the criticism of the industry that it is focused on the rubber conveyor belt. It raises the question 'Is the elevator industry blinded by their success with using belts from the beginning, e.g. leather belts to rubber and today's sophisticated cable belts. Are rubber belts really needed to hold the bucket structure together and provide drive friction? However, the weight of the rubber cable conveyor belt self-inflicts its own limitation by reaching the maximum tension by its own weight as vertical distance increases.

Can the elevator industry be unlocked in its thinking to develop long vertical haul without the rubber? The sketch in Figure 18 is the authors concept of a cable elevator without rubber and cables connected laterally by the ore bucket structure.

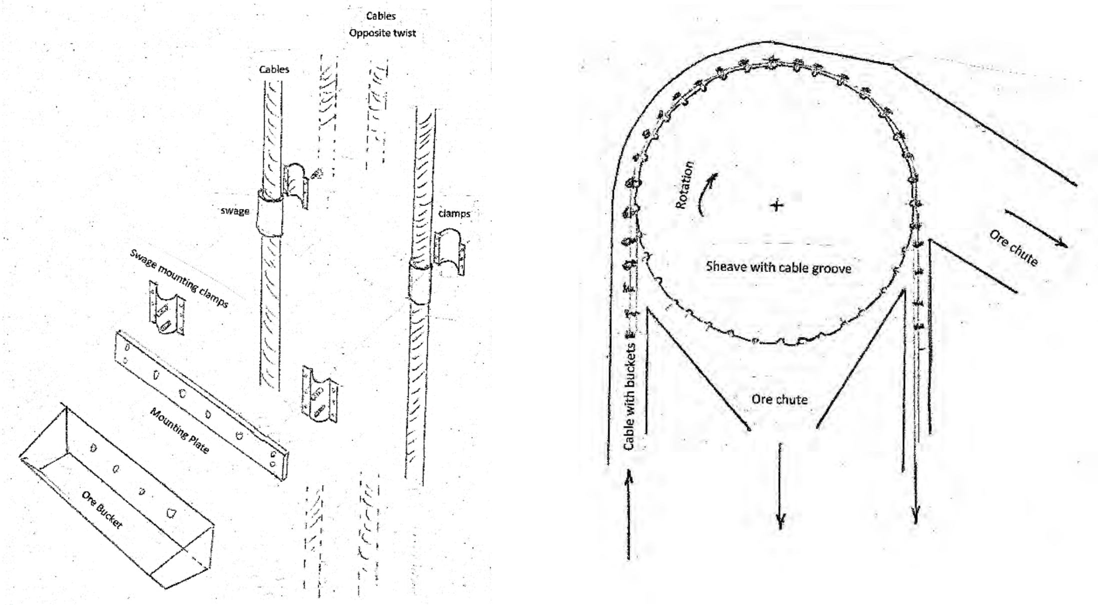


Figure 15. Twin cable elevator. Sketch of what components may appear like, with a geared friction drive (Authors sketch).

The concept is simple, with a bridging bar between the two or more cables clamped onto the cable swages. Ore buckets are bolted onto the bridging bar. Each cable could have the tension capacity necessary to carry the designed weight of the whole elevator. Adding more cables perhaps so that they total to 3 or 4 could reduce the overall effect of any one cable's specification variance. However, no such elevators are found in the literature, but the knowledge of cables, buckets and drive sheave are well advanced.

2.9 Discussion and Summary of the Literature Review

The literature search demonstrates some of the limitations that exist for the traditional bucket elevator adapting and using belt technology. Steel wire rope cables in the overland conveyor belts limit the core strength ability as the production capability requires even tensioning. Components of the cable belts burden the belt with non-lifting weight, such as the weft, skims and polymer. Cable strength are shown to be significant when larger cables are used even as a single unit. The elevator industry is very focused on the use of overland conveyor belt adaption.

As can be seen from this review there is very limited information about the use of the cable disc elevator in mining. Thus, no specifications about friction in cable disc elevators exists. Neither has the subject of using Cable disc elevators for hauling from large depths been adequately explored.

The next chapter discusses the method used in this research.

3.0 Research Methodology

To think of using a cable disc elevator for the purpose of ore lifting has required a step of faith in this research and literature review that this finds a new way for the mining industry to move forward with a innovative ore haulage from underground. To move forward with the test rigs and what they may discover is a step into the abyss of what may unfold and is done with some belief that there is knowledge to discover and apply, that in itself is rewarding.

3.1 Epistemology

The purpose of this research is to investigate the idea from a particular perspective that would help in the development of a cable disc elevator for deep ore haulage for 1000m with the opinion that this knowledge has potential to bring about change and advancement in mining. The radical perspective (Clough and Nutbrown, 2012) attempts to question the familiar concepts of overland conveyor belts being used for elevators by moving away from the conventual rubber overland conveyor belt, whether steel wire cable cord or for shorter lengths polyester cord based, then positioning the research without the conveyor belt structure.

It is necessary for the purpose of this research to be critical of the current manufactures for staying with the overland conveyor belt concept for so long. These manufactures are adapting their current products to elevator design as this can give them larger market for the conveyor belts, therefore they already have manufacturing capability. This thesis diverts from the current direction of using conveyor belts as a medium to hold elevator buckets, it also deviates by using a pipe conveyor being used in a hybrid combination to have the first vertical pipe conveyor as part of a vertical elevator.

3.2 Research Methods

Methods used in this thesis are constructed for the particular purpose to measure ore static and dynamic friction in the cable disc elevator lifting tube, and then predict lifting distance.

This research attempts to prove that a cable disc elevator is worth considering for deep mine ore haulage, is more importantly about investigating the research question of friction in the cable disc elevator and explore the possibilities of the phenomena that this elevator could lift ore from the depth of 1000metres. Variables are controlled in the research in order to eliminate undesirable consequences and select ore and ore size, and elevator design that makes predictions possible to allow success of the cable disc elevator. This is a method of positivism that seeks to explain the events in the research to extract the underlying knowledge that allows success of the objectives (Carr and Kemmis, 1986).

What is not known is the knowledge of friction between the ore and the tube in the cable disc elevator. The methods and test rigs are designed to uncover that data. This data is then used to calculate lifting cable tension requirements for the continuous vertical lifting of ore in the cable disc elevator with a fixed steel tube and a dynamic pipe conveyor tube.

The cable disc elevator is unique as its has a single cable of that can be selected of any size for the application and is not reliant on the strength to pair with other cables. Discs and swages that lift the ore attached to a cable are a small percentage of the cable weight. A cable disc elevator could drag ore vertically up the tube which would result in friction between the ore and the tube. By having an elevator with a very strong single cable reduces complicated calculations down to determining the elevator cable tension capability verses the opposing forces of friction, and gravity. The gravitational forces of lifting and acceleration are well known. Calculations for cable tension requirements in these elevators to lift any vertical distance the forces of gravity (acting on the ore and the cable) and friction need to be combined.

Two test rigs used in this research have been specifically designed to measure friction between the ore and the tube for static and dynamic friction. These test rigs were limited in size to fit within the building structure and budget. The experiments attempt to collect data in a way that can be expanded for greater lifting heights for the diameter tubes which were selected.

The third test rig is a hybrid, built with a cable disc elevator lifting side tube replaced with a vertical pipe conveyor and its purpose is to examine a method that eliminates ore friction in the combined section. This test rig uses a rubber belt with a polyester cord textile mesh that will allow the tube forming sections to be short (at 3m) This is selected to reduce the overall height of the test rig to be under 14 metres vertically due to site and budget constraints. However, as a result of the short pipe tube forming section there is a higher force required for belt tube forming than a steel wire cord belt at a mine where the belt forming section could be 40 metres long. Never the less the test rigs can produce good data that could be a forward step for future elevator development.

All test rigs are prototypes that have been specifically built for this research to measure the required knowledge of friction that answers the research questions. Components used for construction are listed in each test rig chapter description. There is some expansion and description in the relevant test rig chapters however the emphasis is on answering the research questions which contribute to the knowledge gap and are vital for future development of these types of elevators. The knowledge from this thesis is relevant for these test rigs but would have wider implications for this type of elevator if developed further for ore lifting.

3.3 Friction Measurement – Tribology

Bharat (2002) says that tribology is the science and technology of interacting surfaces in a relative motion and of related subjects and practices. In this research, meaning that as well as this is the equivalent of friction, the nature and consequence of the interactions that take place at the interface control its friction. During movement between the two surfaces, ore and the tube, interactions forces are transmitted, mechanical energy is converted, and surface topography alters at the interacting material interface. The methods applied in this research are focused on measuring static, and dynamic frictions. Rolling friction between the particles of ore are not measured but the change in topography is observed and its impact is photographed and observed.

The most important dimension measured in this research, is friction force resulting from the reaction between two surfaces, one a solid tube and the other loose ore. Other dimensions measured are done to define friction between ore and the tube in which the ore is lifted in. This is the principle of tribology where all results measured as the resistance to movement or the results contribute to the single dimension (Wang, 2013). In this case the resistance resulting from the relative movement between the ore and tube.

Friction is used to measure the resistance of relative motion between two bodies (Blau, 2013). In this research, the two bodies are the ore and the lifting side tube of the cable disc elevator. In principle, friction is measured by direct measurement of the forces holding the lifting tube in place. These resist the relative motion of the ore being dragged up the tube by the cable disc elevator. Resistance to movement in this thesis is measured by weigh load cells, which hold the stationary tube in place, or by weigh load cells, on the motor torque arm, which measures the force of the cable when lifting the ore through the tube. The friction between the ore and the tube is calculated from the friction force and the ore contact surface area and is reported as Newtons per square centimetre.

All weigh load cells, data displays and recording programs are manufactured to meet ISO 9000 standards for weight measurement. Load cells are used here in tension and compression as a force transducer supplying an electrical signal that has been standardised which is measured. These are standardised to measure weight shown on digital displays. All the weight systems are validated for calibration prior to each test run (Blau, 2008).

This research identifies some areas of failure and then concentrates on the requirement of ore selection that has the best chance of the cable disc elevator being successful. Tests are done with ore of different particle size. Photographic observations are shown where ore topography at the interface of the ore and the tube, and how this can lead to failure. The research does not go further into limits of failure in detail, rather shows where it can demonstrate success and what to avoid.

3.4 Cable Tensions and Lifting Distance.

To calculate lifting distance the required cable tension capacity is required. The relevant equation from Metlikovic (2006) is:

$$T_1 = T_e + T_2 \qquad 3.01$$

Where T_e is the working tension resulting from the force of gravity for lift and acceleration and the tension required to overcome friction. The cable tensions are shown in Figure 19.

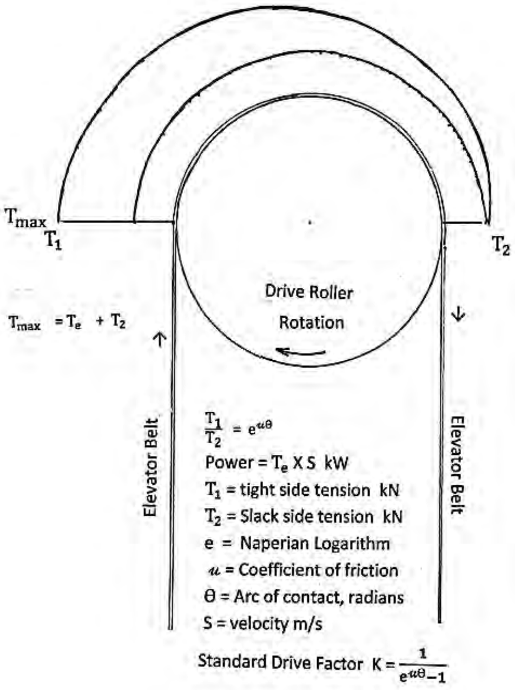


Figure 16 Cable dynamics (Metlikovic 2006)

From equation 1.0 $$T_e = T_e^f + T_e^l + T_e^a \qquad 3.02$$

Where T_e^f tension required to overcome friction.
T_e^l tension required to overcome gravity for lift.
T_e^a tension required for acceleration.

To calculate the tensions required per metre of cable for the test rigs, a projection is made for the tensions associated with greater lifting distances. This then determines the tension specification for a cable for that lifting distance. The projection of cable capabilities is also examined for three selected existing commercial cables.

The measurement of friction is required to find T_e^f.

3.5 Research Materials

Ores selected for this research are coal, gravel and granite. These have been sourced from local resources and are described in some detail in Chapter 4

3.6 Test Rigs Data

Experiments are designed to measure the static and dynamic frictions of ore in the tube of a cable disc elevator and for a combined cable disc elevator with a pipe conveyor.

3.7 Test Rig Methods

There are 3 test rigs used in the experiments. These test rigs measure the static, and the dynamic friction of the ore in the lifting tube. The third test rig aims to remove the friction in the lifting tube. Each of these test rigs use a single cable.

3.7.1 Static Friction Test Rig 1

This test rig measures static friction for selected ore. Static friction is measured for different weight of ore on the lifting disc. For an increase in the weight of ore on the disc, the volume of ore increases, which results in an increase in surface area (SA) contact between the ore and the tube. An exact amount of ore is placed on one disc in the fixed tube. Under precisely controlled conditions the disc is subjected to an increasing lifting force until the breakfree point is reached. Which is the point where the ore first starts to move upward. This force is then the static friction force (SF_{ore}). For each weight of ore used the height of ore in the tube is measured and the surface area of ore in contact with the tube is calculated. The weight of the disc and the ore is counterbalanced to eliminate the effect of gravity. From the surface area and the static friction force the static friction (sf_{ore}) can be calculated, measured in Newton's per square centimetre of ore contact. Predictions can then be made for larger surface area contacts in longer elevators. The static friction force is also referred to as the breakfree force (BF_{ore}).

Further testing is repeated for the above static friction force with ore containing added water of different particle sizes. The results are used to establish the static friction for the various ore samples per square centimetre of ore contact with the lifting tube, measured as N/cm^2.Knowledge of static friction becomes relevant for an operational elevator that has stopped fully loaded. This will determine the cable strength required for the elevator to be restarted without cable failure and the cable design can operate within the selected factor of safety of 6.67.Further calculations are taken to determine the potential lifting distance for 3 selected cables described further in this chapter. Figure 20 is a sketch of the components for Test Rig 1.

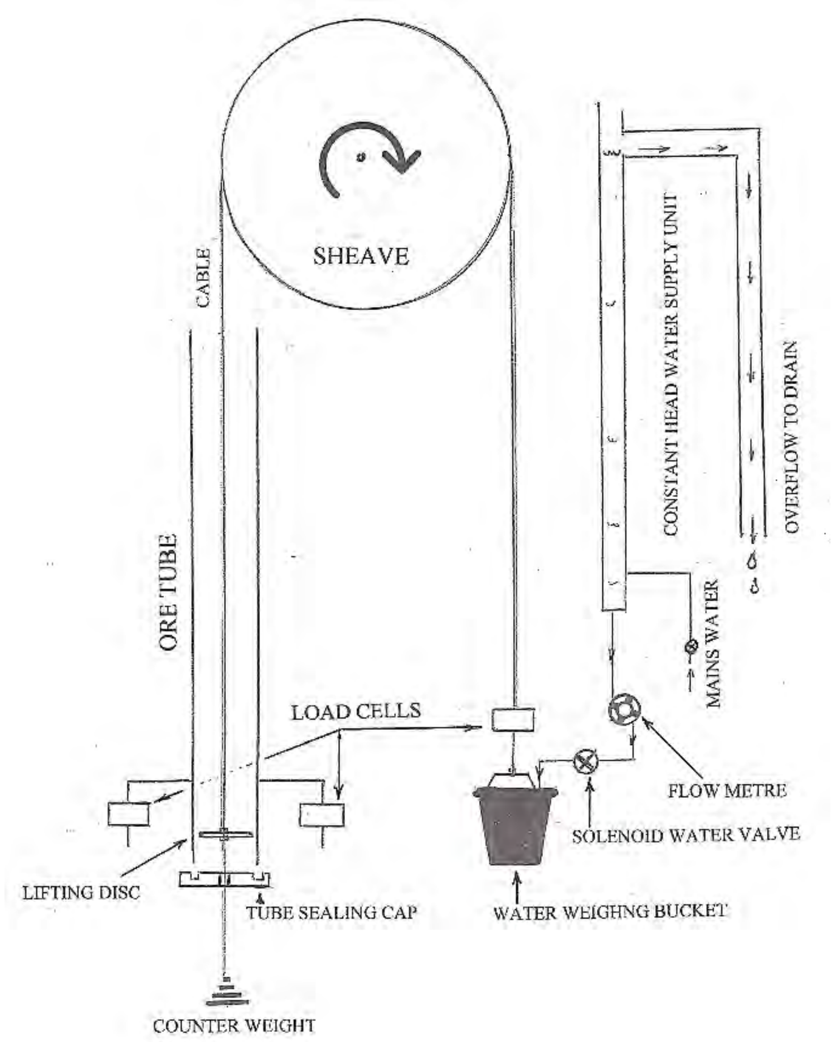


Figure 17. Sketch of Test Rig 1 used for determining static friction (Figure 1)

3.7.2 Dynamic Friction- Test Rig 2

This test rig is designed to measure the friction between the ore being transported vertically in the elevator and the steel tube of the elevator itself, with ore of different weights travelling at different velocities. The height of the ore on the disc for each ore weight has been determined for the first test rig and used here to calculate the ore to tube contact surface area. The test rig tube is independently mounted on load cells to measure the force of the ore dragging up the tube. There are 16 discs in the lifting side tube at any one time. The force on the tube is the dynamic friction force and when this is divided by 16, the dynamic friction force (DF) for one disc is calculated. By applying the weight of ore on the disc and calculating the surface contact area the dynamic friction can be calculated (df) as Newton's per square centimetre of contact area.

This test is repeated for different ore weights per disc and for different velocities. The results are used to establish the dynamic friction for selected ore samples per square centimetre of ore contact with the lifting tube (measured as N/cm^2) for various lifting velocities.

If the dynamic friction is known for one disc, the dynamic friction force other projected vertical lengths can be calculated. To calculate the total tension required of the cable disc elevator cable, the force of gravity acting on the ore and the cable, as well as the force of acceleration are added to the friction force. The amount of ore in the elevator is calculated from the ore bin weights and divided by 19 as there are 19 discs in the total elevator, of which 16 discs are in the steel tube mounted on load cells. Figure 21 is a diagram of this test rig.

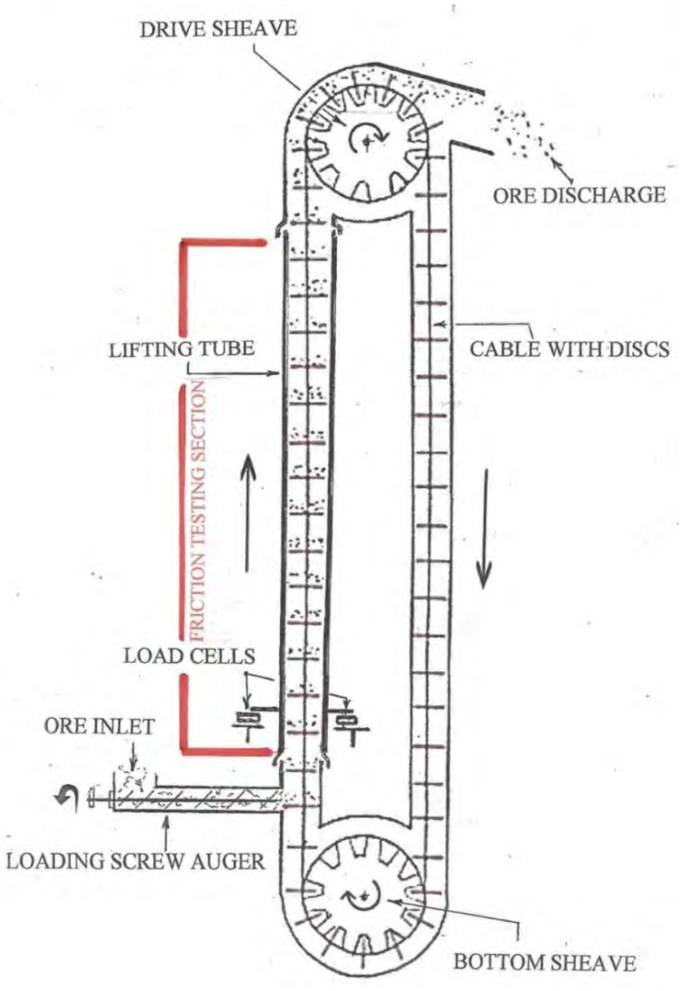


Figure 18. Sketch of Test Rig 2 used to determine dynamic friction (Figure 1)

3.7.3. Test Rig 3, A Hybrid elevator

In Test Rig 3, the lifting tube of the cable disc elevator is replaced with a pipe conveyor travelling at the same speed as the cable disc. Both components operate together at the same contact speed in the vertical position. Where the cable disc elevator and the pipe conveyor are combined, they travel at the same velocity and there is no relative movement between them.

Friction occurs with the ore and the fixed tube of the cable disc elevator prior to entering and after leaving the combined section. This friction is the same as for ore in Test Rig 2.

The amount of ore in the elevator is calculated from the ore bin weights and divided by 26 as there are 26 discs in the total elevator of which 22 are in the pipe conveyor. Figure 22 is a diagram of the combined elevator and Figure 23 shows the relevant friction zones.

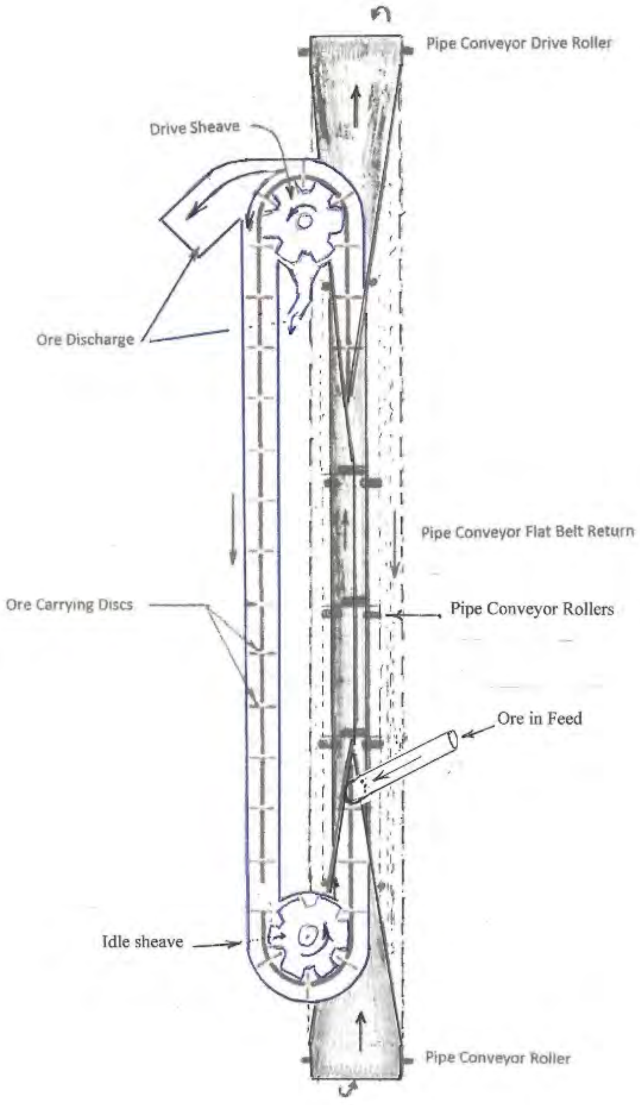


Figure 19. Sketch of Test Rig 3 where the vertical tube of Test Rig 1 has been replaced with a pipe conveyor

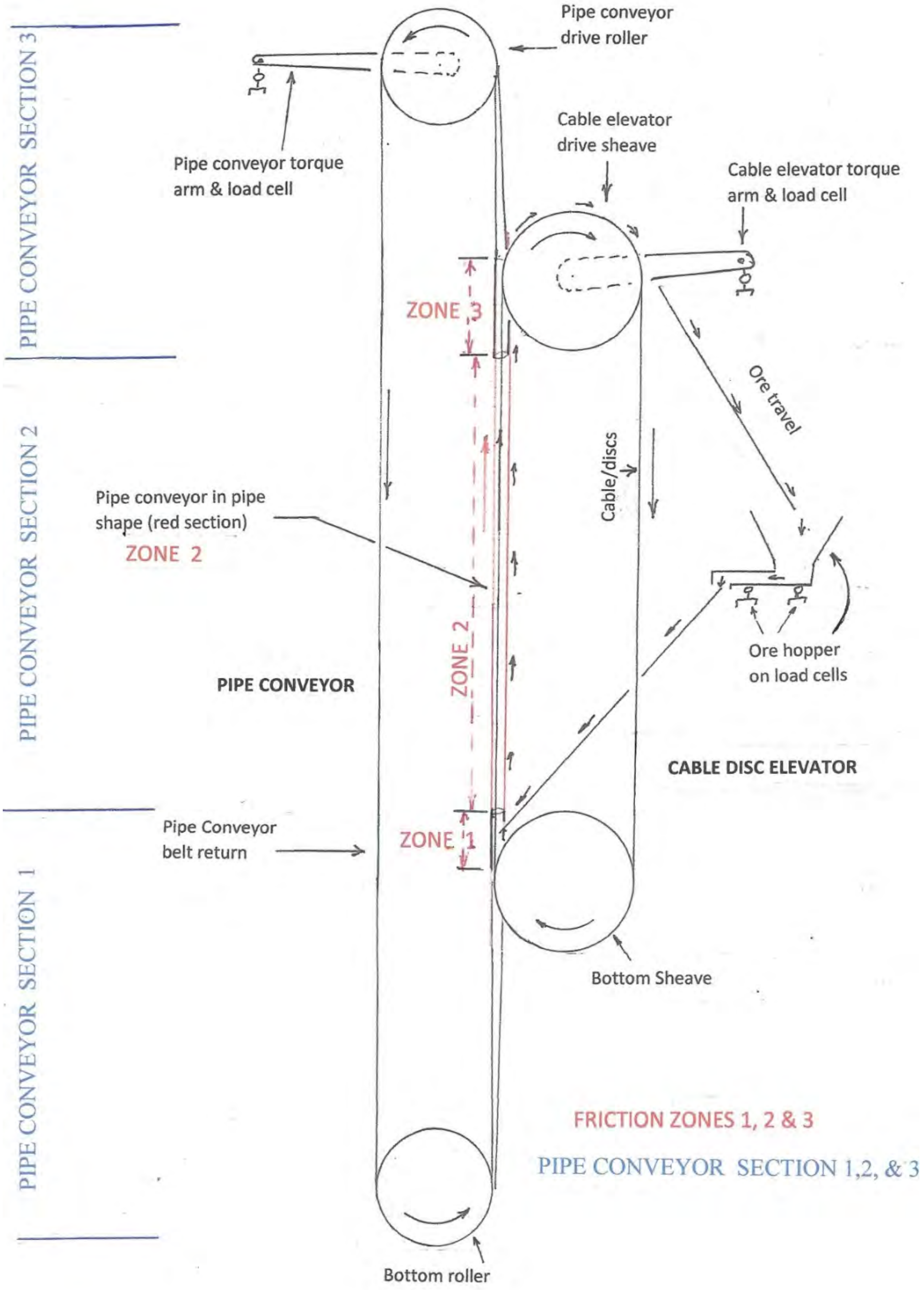


Figure 20. Test Rig 3 friction zones

3.8 Analysis of Results

Ores that are used are the same for all tests. The results are compared to the force required to lift ore against the force of gravity for the number of discs in the test rig and various elevator speeds. These results are then used to calculate the values for a cable disc elevator of known length with a selected number of discs and to calculate the total dynamic friction and the static friction from Test Rigs 1 and 2. The friction force can then be added to the effects of the cable weight and other factors to calculate the total tension requirements for various lifting distances. The total required steel wire cable strength is then compared to a selection of commercially available lifting cables.

Test Rig 3 cable strength calculations are used to calculate the values for various lifting distances using a selection of commercially available lifting steel wire cables and pipe conveyor belts. There are two projected lifting distances calculated for each situation. These projections are based on expansion of the results taken as lineal when the same amount of ore is on all the discs in the elevator projected lifting distance. They are:

- The maximum lift distance for the selected cable

- Establish the cable strength is required to lift ore from 1000m

3.9 Wire Rope Data Examples used for Calculations in this Research

Data and research results for the required cable tension T_1 is compared to the following three commercial cables, selected for their potential ability to operate long depths up to 1000m. These conditions are determined in the research. When applied to these selected cables, data generated can tell us the depth of the elevator that could be achieved. There would be many other cables suitable for this elevator. The main criteria are: sufficient tension strength; the cable is polymer filled; and it is suitable for the sheaves that need to be used, where T_1 is the maximum cable tension required on the lifting side of the elevator.

3.9.1 Bridon 34 LR Cable

An example using a 40mm lifting rope (Bridon, 2011), is shown in Figure 24 and specifications are detailed in Table 4.A Bridon Crane Wire Rope '*Endurance Dyform 34 LR',* a commercially available proven lifting and working rope.

Figure 21 Endurance Dyform 34LR

Table 4. Specification for Endurance Dyform 34LD Steel Wire Rope

Cable diameter	40mm
Nominal length mass	8.00kg/m
Minimum	1468N
Axial stiffness at 20% load (MN)	92
Torque generated at 20% load ordinary, Nm	94
Lang's Nm	211
Metallic cross section, mm^2	930
Polymer filled rope	yes

The gross lifting capacity of this rope is 149 t. After applying the safety factor of 6.67 the effective working potential is a carry weight of 22.33 tonnes. In that case the total cable tension force T_1 would need to be 219.0 kN.

3.9.2 Bridon 6AR Hoisting Rope

Another cable example is the Bridon Crane *Wire Endurance Dyform 6AR* (Bridon 2001) shown in Figure 22 and cable specifications are listed in Table 5.

Figure 22. Endurance Dyform 6AR steel wire rope (Robertson, 2014)

Table 5. Specification for Dyform 6AR Steel Wire Rope (Robertson, 2014).

Diameter mm	50
Nominal Length mass kg/m	11.00
Minimum breaking force EIPS/1960 grade kN	2070
Axial stiffness at 20% load MN	136
Torque generated at 20% load ordinary Nm	1428
Lang's Nm	2255
Metallic cross section mm^2	1316
Polymer fill rope	yes

The gross lifting capacity of this rope is 210 tn. After applying the safety factor of 6.67 the effective working potential is a carry weight of 31.5 tonnes. The total cable tension force T_1 would is 308.9 kN.

3.9.3 Gold Strand Wire Rope 75mm Diameter

A higher strength cable considered is the Southwest Wire Rope Gold Strand, specifications are API 9A, 6x36 classification wire rope galvanized with independent wire core. This is specified in Table 7 and Figure26 (South West Ropes, 2015).

Figure 23. Southwest Wire Rope LP. Gold Strand
(South west wire, 2015)

Table 6. Gold Strand Specification (South West Ropes, 2015)

Diameter mm	76.2
Nominal Length mass kg/m	24.7
Minimum breaking force EIPS/1960 grade kN	4160
Axial stiffness at 20% load MN	Not specified
Torque generated at 20% load ordinary Nm	Not specified
Lang's Nm	Not specified
Metallic cross section mm^2	Not specified
Polymer fill rope	yes

The gross lifting capacity of this rope is 424.2 tn. Applying a safety factor of 6.67, the effective working potential is a weight of 63.6 tonnes. Then, the total cable tension force T_1 will be 623.7 kN.

3.10 Power Required for Lifting Ore to Overcome Gravity

These calculations do not take into consideration the effect of any friction that will be determined with the test rigs but refer only to the effect of gravity on the ore. These calculations are based on where the elevator travels at 5m/s, acceleration to this speed from 0 to 5m/s takes 10 minutes and the production lift is 144 tonnes per hour.

The formula used are derived from *The Cambridge Handbook of Physics Formula's* **(**Woan, 2014).

3.10.1 Power to Overcome Gravity

$$\text{Power} = \frac{\text{TONNES x 9.81 x DISTANCE LIFTED m x EFFICENCY}}{60^2} \qquad (3.03)$$

For 1000metre lift,

$$\text{Power per tonne} = \frac{9.81\ x\ 1000x\ 1}{60^2}\ \text{kW}$$

=2.725 kW at 100% efficiency

Formula 3.02 is used to calculate the power per tonne in 100t intervals for various depths and shown in Table 7.

Table 7. Power kW required to overcome gravity from 100m to 1000m for selected production rates

Production tonnes/hour	100m depth	200m depth	400m depth	600m depth	800m depth	1000m depth
10	2.73	5.46	8.19	16.38	21.8	27.3
50	13.65	27.30	54.60	81.9	109.2	136.3
100	27.25	54.5	109.0	163.5	218.0	272.5
250	68.13	136.26	272.52	408.78	545.04	681.3
500	136.35	272.7	545.4	818.1	1090.8	1363.5
750	204.38	408.76	817.52	1226.28	1635.04	2043.8

Alternatively, power can be calculated using:

$$\text{Power} = T_e \times \text{Speed} \ \text{kW} \tag{3.04}$$

Where T_e is the effective working tension

$$T_e = T_1 - T_2 \ \text{kN} \tag{3.05}$$

And speed is measured in metres per second.

3.10.1 Power to Accelerate Ore Over Gravity to 5 m/s

Acceleration

$$a = \frac{V_2 - V_1}{t} \tag{3.06}$$

Where a is acceleration in m/s^2

V_1 Starting velocity in m/s
V_2 Final velocity in m/s
t time in seconds

Distance to accelerate

$$a = \frac{2l}{t^2} \ \text{m/s}^2 \tag{3.07}$$

I is the distance moved. Metres

Acceleration force

$$F = m.a \tag{3.08}$$

Where F is the acceleration force Kilo Newton's
m mass being accelerated kg

Acceleration work done

$$W = F.I \tag{3.09}$$

Where;

W is the work done Nm

Acceleration power $P = \frac{W}{t}$ kW (3.10)

3.10.2 Selected Acceleration

For practical operational reasons, the start-up time for the elevator is selected as 10 minutes, and the operating final speed is 5m/s once is complete.

Applying equation (2.05)

$$a = \frac{V_2 - V_1}{t}$$

$V_1 = 0$ as the elevator is starting from a stationery position

$$a = \frac{5 - 0}{10 \text{ x } 60}$$

The acceleration of the ore and cable is calculated to be;

$$a = 0.0083 \text{ m/s}^2$$

3.10.3 Distance to Accelerate

Applying equation 2.6 and rearranging for distance moved:

$$l = \frac{at^2}{2} \tag{3.11}$$

$$l = \frac{0.0083 \text{ x } 600^2}{2}$$

$$l = 1{,}494 \text{ metres}$$

The elevator cable will have travelled 1494 metres to achieve an operating speed of 5m/s. Depending on the depth of the mine haul shaft the elevator may have completed several rotations.

3.10.4 Acceleration Force to Overcome Gravity

Using the example for a 1000 metre lift, a cable disc elevator will have discs 250mm apart and 4000 discs in total. When carrying 2kg/disc, the total weight of ore on the lifting side of the elevator belt is 8 tonnes which at 5m/s equates to 144tn/h.

Applying the equation of force 2.07:

F = ma

F = 144 x 0.0083

F = 1.20kN

3.10.5 Work Done Against Gravity

Using the same example, and
calculating work done using formula 2.08:

$$W = F \cdot l$$
$$W = 1.20 \, x \, 1494$$
$$W = 1786 \text{ kW}$$

3.10.6 Power to Accelerate Against Gravity

Using the same example and equation (2.09) for 1000m at 144 t/h, and acceleration time of 10 minutes:

$$P = \frac{W}{t}$$
$$P = \frac{1786}{600}$$

P = 3.0 kW

Consumed in 600 second relates to a power demand of:

3.0 x 600 = 1800 kW

3.10.7 Forces at the Cable Extremities. T_1, T_{MAX}, T_2, T_3, T_4, T_e (Figures 24 and 25):

- T_1, and T_{MAX} are the same and represent the maximum tension on the lifting side of the elevator or in the case of a conveyor belt, the maximum tension at the drive roller.
- T_2, is the tension resulting from the weight of the elevator on the return side. There is no ore present, so the buckets have unloaded.
- T_3, is the tension at the bottom of the elevator at the point of connecting with the lower idle roller or sheave. There should be no load on the elevator at this point unless there has been mechanical tension applied to gain friction at the drive roller/sheave.
- T_4, should like T_3, have the same loading unless ore is added at the base of the elevator and there is some digging required.
- T_e, is the working tension resulting from the effort to lift the ore.

Of the tension components T_1, T_{MAX}, T_2, T_3, T_4, T_e are shown in Figure 26 which includes the tensions for the cable at the idle sheave.

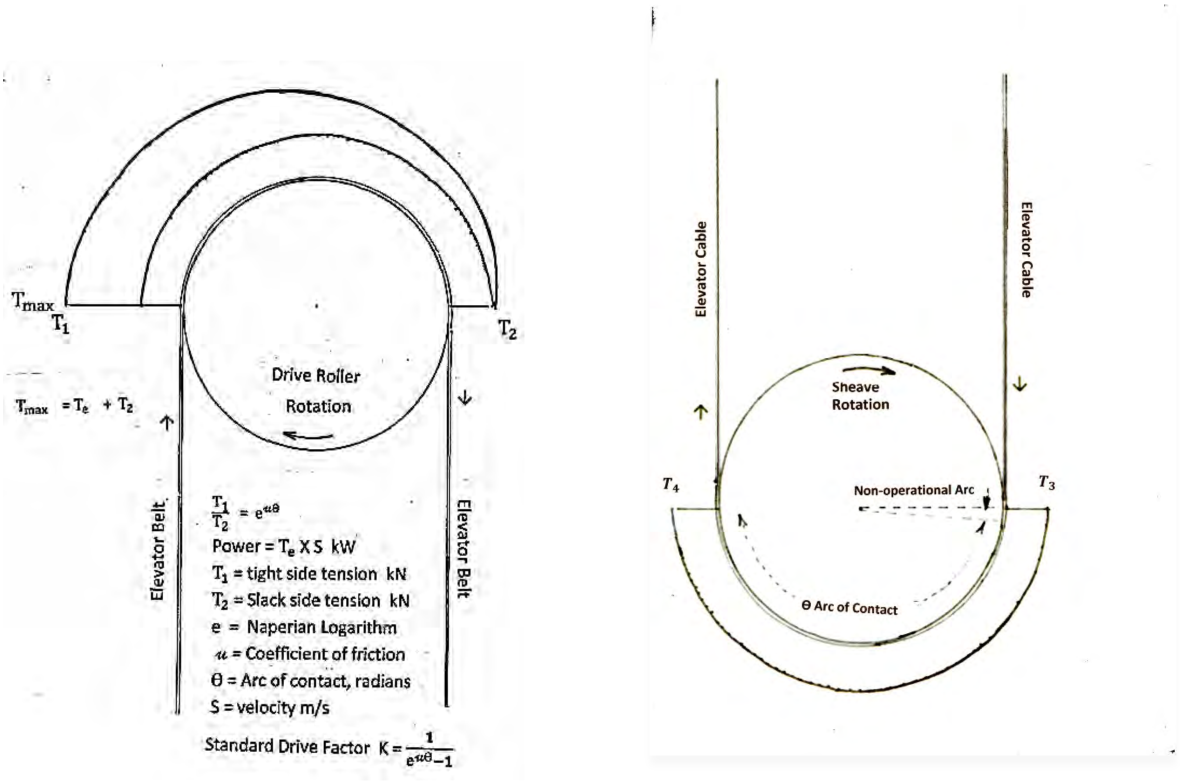


Figure 24. Elevator drive and idle roller tension dynamics (Metlikovic, 2006).

For a driven conveyor the belt or cable tensions required for transmission of the peripheral force are defined by the limiting condition such that:

$$\frac{T_1}{T_2} \le e^{\mu\theta} \tag{3.12}$$

$$\text{Power} = T_e \ x \ s \text{ kW} \tag{3.13}$$

3.11 Conveyor Belt Friction Components

Considerable amounts of design methods have been developed for conveyor belts and many companies have their own in-house design system and nomenclature. The two most popular design methods for the first order calculation of the working tension T_e are the Deutsches Institute Normung (DIN) Standard DIN 22101-3 (2015), and the Conveyor Belt Manufactures Association (CEMA) method.

Working tension T_e is defined as the sum of all forces resisting to motion to the drive. T_e=(T_1 - T_2) where T_1 is the belt tension entering the drive pulley and T_2 is the belt tension exiting the pulley. All forces in the conveyor of elevator belt are included in the total of T_e. (Harrison, 2009).

From Harrison $T_e = L.g\ (R + B + V) + Q.v' + P + O$ (3.14)

Where L = length of the conveyor (m)

G = gravitational acceleration 9.81 m/s^2

R = rotational resistance of all idler's kg/m

B = belting and material flexure resistance kg/m

V = material mass kg/m

$Q.v'$= Force to accelerate material (N)

P = force to accelerate all pulleys (N)

O = Forces for all other accessories.

CEMA and DIN and manufactures methods are similar but use different nomenclature to each other.

During this research the calculation of working tension T_e forms the critical criteria which must be calculated for all tensions.

3.12 Formula for Drive Roll Diameter

Sheave or roller diameter for steel wire lifting ropes vary considerable across various industries. The ratio of the diameter of the sheaves and drums to the diameter of the ropes should be at least those specified in AS 1418 and AS 2089. Cable manufactures specify the sheave size for their cables, and these range between a sheave diameter of 100 to 120 times the cable diameter.

3.13 Formula for Unloading the Bucket Elevator

When the ore is travelling up the elevator in the bucket at constant velocity it is acted upon by a constant force of gravity where:

$$P = m\ .\ g. \tag{3.15}$$

Where m is the mass of ore in the bucket in kg and g is the force of gravity 9.81 N/s^2. When the bucket reaches the top of the elevator and starts to turn then a centrifugal force on the ore (CEMA, 2017).

Then F becomes the centrifugal force for ejecting the ore from the elevator bucket

$$F= (m\ .V_0^2)/\ r \tag{3.16}$$

Where V is the velocity of the centre of gravity of the bucket load (m/s)
r is the radius of rotation from the centre of gravity.

A of the ore in the bucket to the centre on the pulley shaft O (m) m is the mass of ore in the pulley (kg)

F is the centrifugal force ejecting the ore.

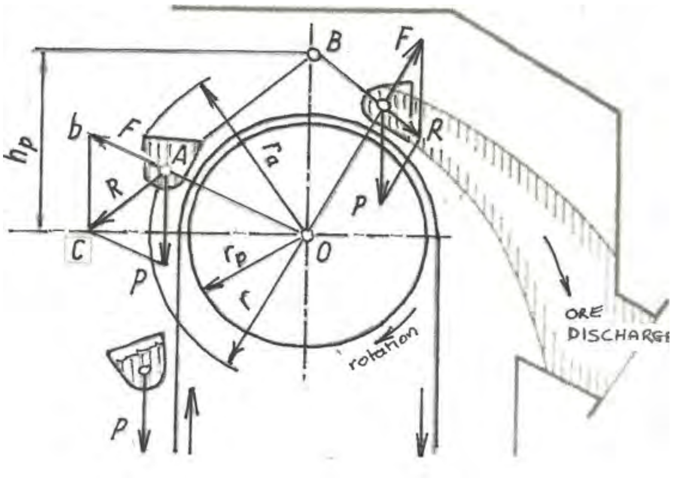


Figure 25. Ore throw from the elevator buckets (CEMA, 2015)

CEMA quote the work done by Kosmin and Fadeev (1929), Russian scientists, who developed a formula for throw by the pole distance hp.

$$hp = (g \cdot r^2) \times 30^2) / (\pi^2 r^2 . n^2) = 895/n^2 \tag{3.17}$$

where n is the rotational speed of the pulley.

There are 3 types of unloading: centrifugal force which is higher than the gravity force, and the ore is thrown over the external front wall of the bucket; where the gravity force is higher than the centrifugal force the buckets are unloaded by gravity over the back wall which is the closest wall to the elevator belt; and centrifugal and gravity unloading can take place simultaneously combined. Fadeev concludes that the method of elevator bucket unloading is determined by the ratio between the pole distance and the radius of the pulley.

$$A = \frac{hp}{r} \tag{3.18}$$

CEMA place the levels of A in four categories.
$A \leq 1$ for centrifugal unloading for high speed elevators.
A = 1 – 1.4 for high speed elevators with centrifugal and gravity unloading.
A = 1.5 – 3 for moderate speed elevators with combined unloading.
A > 3 for low speed elevators with gravity unloading.

3.14 Summary

Results of this research will provide comprehensive responses to the five research questions and the effectiveness of each rig.

The results for friction forces are determined for each test rig. These measurements are applied in predictive calculations that determine the potential lifting distance of a cable disc elevator and a hybrid cable disc elevator with a pipe conveyor, and under what conditions lift can take place.
To set the parameters for this research:

- Three ores are selected with a perspective of finding what ores and ore particle size will contribute to the success of this research.
- The test rig parameters are set to give the rig the best chance of success.
- Results are calculated for the cable tension required to lift ore from 1000m
- Using the specification data from the three commercial cables selected their depth capacity is calculated for lifting ore.

The next chapter starts with the basic material of ores that were selected for this research.

4.0 Ore Selected for Testing

There are many types of ore that could be used for this research if it were not for budgetary and time constraints other ores could have been added. The cable disc elevator in this thesis can be used for short distances however consideration was given, but not limited, to deep underground mining at depths of 1000metres. A decision was made to limit the research to three ores: gravel, granite, and coal. These ores represent different structures in their physical strengths e.g., for shear and compressive strengths. It is recognised that there are differing but similar physical structures within each of these ore groups. For example, variations exist between gravel, sandstone, and limestone ores, coal from brown coal, coking coal and high moisture coals, and granite. However, for the purpose of this thesis a selection of local materials is used. Samples of ore have been collected from the local mining area in and around Ballarat, Victoria, Australia. The ores are clearly defined as to the collection sites.

Samples of the ungraded ores were sieved and prepared for particle size distribution using Endecott's Sieves which comply with ISO 3310-1. Samples of different size ores were collected from the sieves.

4.1 Coal.

Coal used for this trial comes from the open cut Maddingley Brown Coal Mine. Coal is mined using excavators, then passed through a crushing plant at the mine base. All product from the mine is passed through a 10mm sieve. According to Maddingley the natural moisture content is 50%.

The Maddingley No. 2 open cut is the only brown coal mine currently operating in the Bacchus Marsh district. It extracts coal from a seam averaging 30 m thick under only 10 m of overburden in an area free from overlying lava flows. The coal is of lesser grade than La Trobe valley coal but is suitable as an industrial fuel. The coal is from the Early Miocene age, and overlies and is interbedded with the Werribee Formation. The seams are probably laterally continuous with those known to exist sub-surface at Altona. There are abundant plant remains in the coal including woody material and large trees. The coal seams are the third largest known in Victoria (after the La Trobe valley area and Anglesea deposits). They are a readily recognisable geological material and provide clear evidence of a terrestrial depositional environment. There is abundant plant material to allow detailed reconstruction of the species composition of the swamp forest communities that gave rise to the coal deposits. This open cut provides a clear view of the geological relationships between the coal and the overlying sediments (Rosengren, 1986).

The Maddingley Mine is 61 km North West of Melbourne and has the position coordinates of. 37^{0} $41' \; 11''$ South, 144^{0} $26' \; 01''$ East.

Picture 3. Google Map Open Cut Coal Mine, Maddingley Coal Mine (Google Maps, 2018).

Picture 4. Ungraded Coal prior to the crushing plant.

Picture.5. Course coal from the crushing plant**.**

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Picture.6. Coal fines from the crushing plant.

4.1.1 Coal Sieve Analysis.

The particle size of the coal was determined by using standard Endecott sieves. The data is in Tables 8 and 9 as retention on the sieve.

Table 8. Fine coal sieve particle size analysis.

Sieve aperture size mm	Retention % per sieve	Total Retention on the Sieve. %
9.5	0.0	0.0
5.0	12.1	12.1
2.5	19.6	31.7
2.0	6.5	38.2
1.0	17.1	55.2
Pan	44.7	

Table 9. Coarse coal sieve particle size analysis

Sieve aperture size mm	Retention % per sieve	Total Retention on the Sieve. %
9.5	5.0	5.0
5.0	11.5	16.5
2.5	47.0	63.5
2.0	12.5	76.0
1.0	17.5	93.5
Pan	6.5	

4.2 Granite

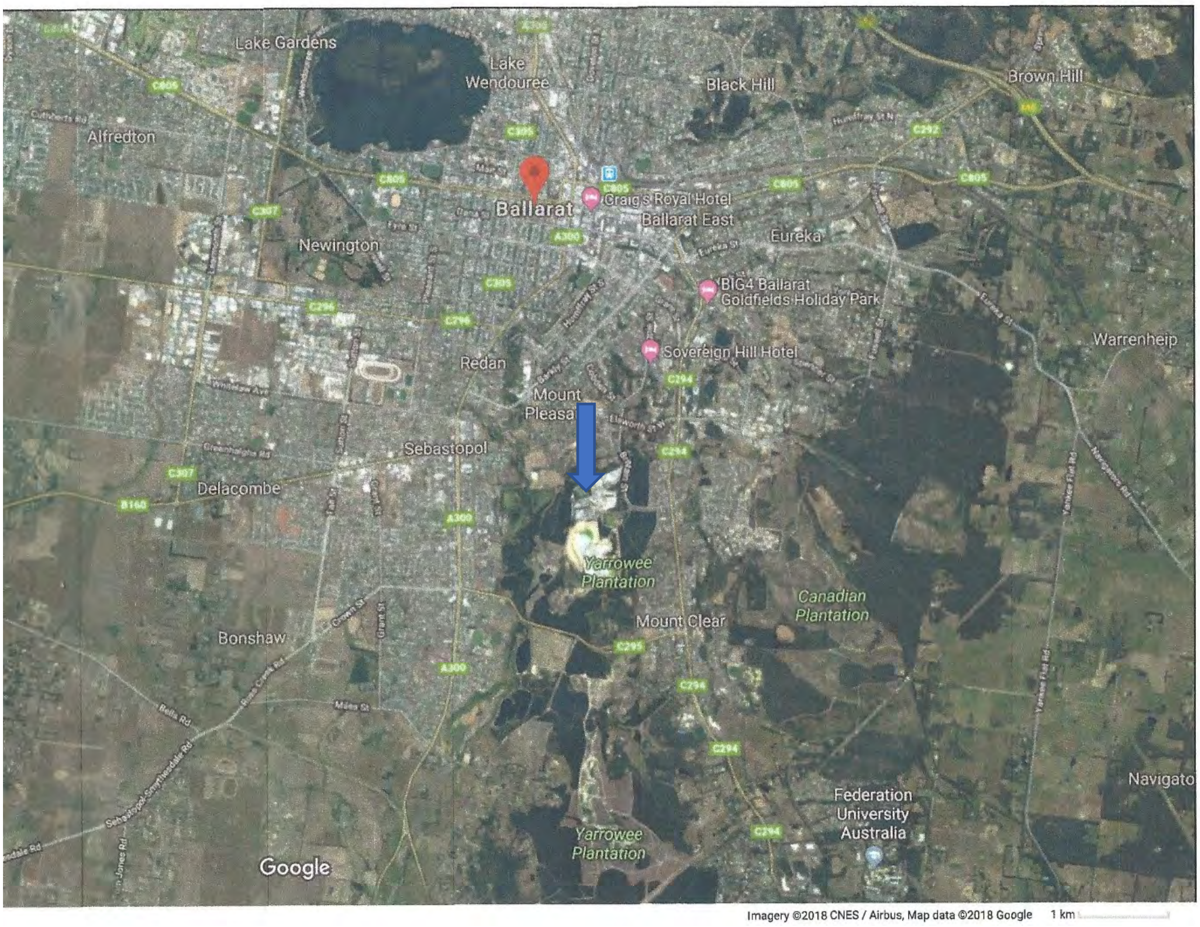
The crushed granite used in this research was collected from the Castlemaine Gold mine in Ballarat, 110km west of Melbourne.

The ore is hauled to the surface using mine trucks at Mt Clear via a decline. There is no underground crushing. Given that all crushing is above ground. The mine depth is varied but is typically at 500 metres from below the surface.

The ore is gold bearing and reduced in particle size for the mineralogy plant to extract gold. The particle size arriving at the above ground crushing plant is a result of fragmentation that takes place during blasting. Granite is also quarried at the Walsh Ballarat Quarries at Dunnstown and Learmonth, then crushed into various grades for road base, concrete production and other uses.

This granite is an igneous rock and is light coloured with visible grains throughout. It is formed through the slow crystallization of magna below the Earth’s surface. Analysis by the Ballarat

School of Mines showed this is mainly composed of quartz and feldspar with minor amounts of amphiboles, mica, and other minerals (Yates, 1953).



Picture 7. Google map of Ballarat Goldfields Mine site.

The Ballarat East Goldmine is marked with a blue arrow in Picture 7 above (Google maps Downloaded Dec. 2018). The mine is at Woolshed Gully Drive Mount Clear. The coordinates are $37^{0}\ 35'\ 29''$ South, $145^{0}\ 51'\ 23''$ East.

Picture 8. Ungraded granite after blasting.

Picture 9. Crushed Granite over 9.5mm.

Picture 10. Granite 5-9.5 mm.

Picture 11. Crushed Granite over 2mm less than 5mm.

Picture 12. Crushed granite less than 2mm**.**

4.2.1 Ungraded B Grade Crushed Granite Sieve Analysis

The granite consisted of a variety of particle size. Samples are separated using sieving by Endecott sieves. The results in Table 10 are the amount retained on the sieve.

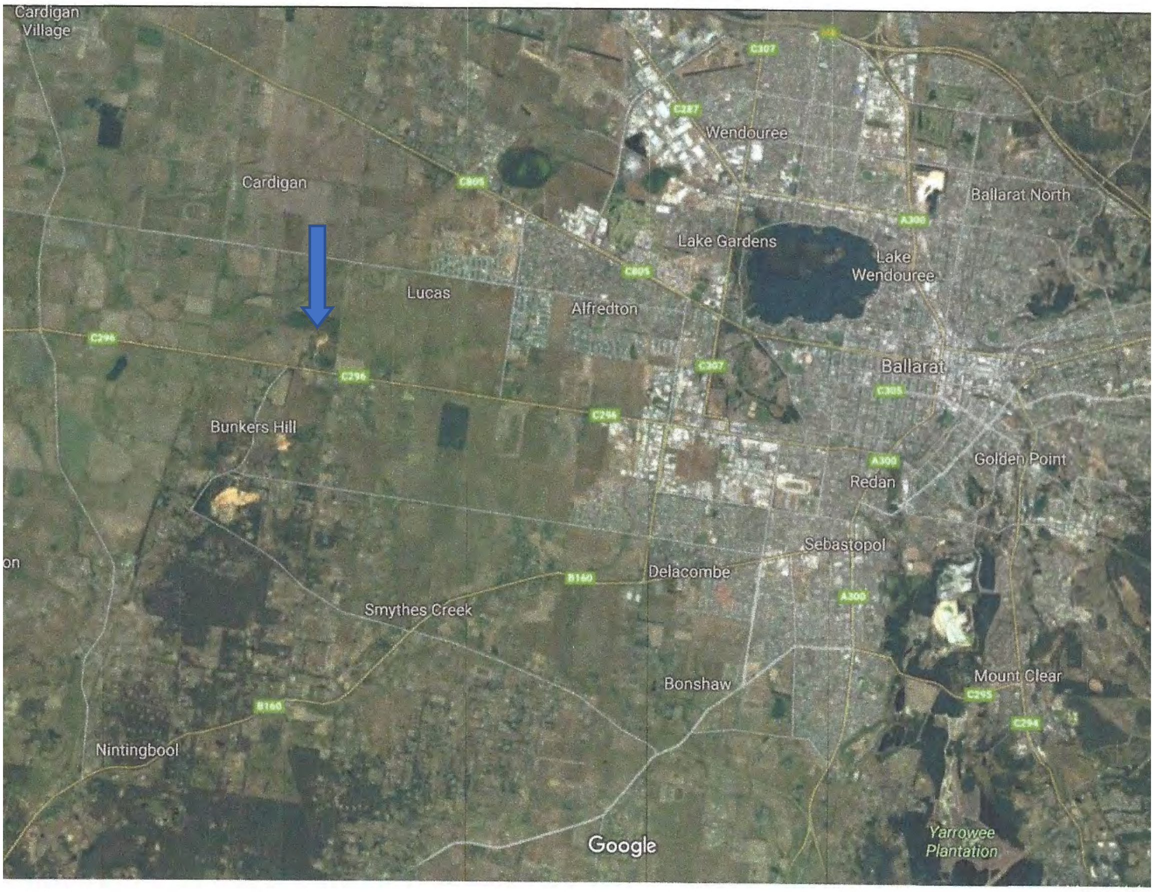
Table 10. Ungraded B grade crushed granite particle size distribution

Sieve aperture size mm	Retention % per sieve	Total retention above sieve %
12.5	0.0	0.0
9.5	20.7	20.7
5.0	23.4	44.1
2.5	23.5	67.6
2.0	4.2	71.8
1.0	14.3	86.1
Pan	13.9	13.9

4.3 Gravel.

The gravel selected for this research was collected from the Kopkes quarry and is typical of most gravels in the Ballarat district, which is 110 km West from Melbourne. There are other similar quarries at Sago Hill and Boral at Buninyong. The gravel has many uses, including as road base, fill under building foundations plus an ingredient for ready-mixed concrete production.

Gravel sample collection area is shown in Picture 13.



Picture 13. Google Map. Ballarat Kopkes Quarry.

The quarry site is marked with a blue arrow in Picture 26. Also visible are the pits at Bunkers Hill and Sago Hill. (Google maps Downloaded Dec 2018). The quarry is at Kopkes Road Haddon. The coordinates are, $37^0\ 50'\ 30''$ South, $145^0\ 0'\ 49''$ East.

Picture 14. Ungraded Gravel. Kopkees Quarry

Picture 15. Gravel 9.5mm +.

Picture 16. Gravel 5-9.5mm.

Picture 17. Gravel 2-5mm.

Picture 18. Gravel Below 2mm.

4.3.1 Gravel Sieve Analysis

The gravel consisted of a variety of particle size. Samples were sieved using standard Endecott sieves. The sieve separations are in Table 11.

Table 11. Ungraded Gravel particle size distribution

Sieve aperture size mm	Retention % per sieve	Retention above sieve %
12.0	0.0	0.0
9.5	1.0	1.0
5.0	1.5	2.5
2.5	7.3	9.8
2.0	7.9	17.7
Pan	82.3	82.3

Supply of this gravel varies in moisture content, as it is quarried from a open cut, and weather conditions thus influence its water content. For consistency, all the gravel is standardised for moisture to 5% unless stated otherwise. Samples for this research are graded by sieving the bulk gravel shown in Picture 27.

4.4 Ore Compaction and Ore Contact Surface area with the Elevator Tube

Ore is tested in test rigs for friction force at different weights on the elevator disc. In order to calculate the surface area of contact between the ore and the tube a simple drop test of different amounts of ore are dropped on the disc. Combined with the test rig forces, these surface area results are then used to calculate the friction force per square centimetre for each ore and for the selected particle size There are two tube sizes used in Test Rig 1, an 8-inch (203.2mm) diameter, and a 5-inch (127.0mm) diameter.

Ore compaction was measured on one disc after a 2.5 metre drop in the tube. The ore landed on the disc at 5m/s at impact. This method is designed to simulate the compaction that may exist when the ore is feed into the elevator. Ore height in the stationary tube is measured and the surface area of ore in contact with the tube is calculated and shown in Tables 13 and 14. Results described in this thesis are for ore that has passed through a 2mm Endecott sieve, unless specified by the particle size subscript or superscript. Testing for density was directed by ASTM D6683-19 and testing for particle size was directed by ASTM Designation E276-13 and E389-13. These results are then compared to those quoted in SME (2011) in Section 4.4.1 Table 15.

The symbols used for these calculations are shown in the Table 12.

Table 12. Measurement symbols

Symbol		Unit
SA	Surface area	cm^2
D	Tube diameter	cm
h	Ore height on the disc	cm
ρ	Ore density	g/cm^3
m	Mass of ore on the disc	grams
v	Ore volume	cm^3
R	Tube radius	cm
UG	Ungraded ore/ all sizes combined	No unit
superscript 9.5+	Particle are greater than	mm
superscript 5.0-9.5	Particle size range	mm
superscript 2.0-5.0	Particle size range	mm
If no superscript	Particle size is below 2mm	mm

The ore contact surface area with the tube is calculated as:

Contact area $$SA = D \cdot \pi \cdot h \quad cm^2 \tag{4.01}$$

For the 8-inch tube $$SA = 20.32 \cdot \pi \cdot h \quad cm^2$$

8-inch tube $SA = 63.84\ h \quad cm^2$ (4.02)

5-inch tube $SA = 39.90\ h \quad cm^2$ (4.03)

Calculating for ore density

Ore density $\rho = m/v \quad g/cm^3$ (4.04)

Volume of ore in the tube.

Ore volume $v = \pi R^2 . h \quad cm^3$ (4.05)

Calculating the ore density by substituting volume (v) into equation (4.04) the density is;

$$\rho = \frac{m}{\pi \text{ x } R^2 \text{ x h}} \quad g/cm^3 \qquad (4.06)$$

As π x R^2 are known for each tube equation (4.06) can be simplified for each tube.

8-inch tube $\rho = \frac{m}{324.29 \text{ x h}} \quad g/cm^3$ (4.07)

5-inch tube $\rho = \frac{m}{126.7 \text{ x h}} \quad g/cm^3$ (4.08)

Density of the ore on the disc allows projections of the ore height to be calculated when a larger diameter cable is used in the tube ore would be displaced further up the sides of the tube resulting in an increase in surface area contact between the ore and the tube. In Table 13 are the results for ore the compaction in the 8-inch tube and the compaction results for the 5-inch tube are shown in Table 14.

Table 13. Ore compaction on the disc in the 8-inch tube.

	Gravel			Granite			Coal		
ore wt. on one disc. g.	Ore height h mm	Ore Tube Contact Surface area SA cm^2	Ore Density ρ g/cm^3	Ore height h mm	Ore Tube Contact surface area SA cm^2	Ore Density ρ g/cm^3	Ore height h mm	Ore Tube Contact Surface area SA cm^2	Ore Density ρ g/cm^3
500	13	83.0	1.19	12	76.6	1.28	60	383.0	0.26
1000	26	166.0	1.19	24	153.2	1.28	90	574.6	0.34
1000^{UG}	28	178.8	1.10	25	159.6	1.14	110	701.8	0.28
$1000^{9.5+}$	26	166.0	1.19	30	191.5	1.03	80	510.7	0.39
$1000^{5.0-9.5}$	27	172.4	1.15	28	178.8	1.10	94	600.1	0.33
$1000^{2.0-5.0}$	30	191.5	1.03	26	166.0	1.19	87	555.4	0.35
1500	39	249.0	1.19	37	236.2	1.25	120	766.1	0.39
2000	52	332.0	1.19	49	312.8	1.26	150	957.6	0.41
2500	65	414.0	1.19	61	389.4	1.26	180	1149.1	0.43
3000	78	478.0	1.19	73	466.0	1.27	210	1340.6	0.44
3500							240	1532.2	0.45
4000							270	1723.7	0.46
5000							330	2106.7	0.47
6000							390	2498.8	0.47
7000							450	2872.8	0.48
Avg. per 1000 g for 2mm ore		164.0	1.19		155.6	1.27		441.8	0.44

Table 14. Ore compaction on one disc in the 5-inch tube

	Gravel			Granite			Coal		
Ore. Wt. on one disc. g.	Ore height h mm	Ore tube contact Surface area SA cm^2	Ore Density ρ g/cm^3	Ore height h mm	Ore tube contact Surface area SA cm^2	Ore Density ρ g/cm^3	Ore height h mm	Ore tube contact Surface area SA cm^2	Ore Density ρ g/cm^3
500	30	119.7	1.32	25	99.8	1.58	63	251.4	0.62
1000	58	231.4	1.36	40	159.6	1.97	125	498.8	0.63
1000^{UG}	71	283.3	1.11	63	251.4	1.25	274	1093.3	0.29
1500	90	359.1	1.32	65	259.4	1.82	210	837.9	0.56
2000	110	438.9	1.44	90	359.1	1.75	260	1037.4	0.61
2500	140	558.6	1.41	110	438.9	1.79	325	1296.8	0.61
3000	170	678.3	1.39	130	518.7	1.82	401	1600.0	0.59
Avg. per 1000 g of 2mm ore	56.9	227.3	1.37	43.8	174.8	1.79	131.8	525.9	0.60

4.4.1 Ore Densities

Comparing ore densities to bank and loose densities from standard industry texts. The locality of the ore selected for testing is precisely defined by the sample collection sites. Ore density is used to calculate the height of the ore on the elevator disc. Densities used are those determined, however in Table 15 these are compared to densities quoted in SME (2011). Densities for granite and gravel compare reasonable but the Maddingley coal has a lower density.

Table 15. Ore bank density, loose density and swell factor for selected ores. * donates data drawn from SME in imperial unites (SME, 2011)

Ore	Bank Bulk Density		Loose Density		Swell factor
	lb/ft^3	grams/cm^3	lb/ft^3	grams/cm^3	
*Gravel	91-120	1.46-1.92	46-107	0.74 – 1.71	0.51-0.89
*Granite	167	2.68	90-111	1.44 – 1.78	0.54-0.89
*Coal (Anthracite)	81-85	1.30-1.36	60-63	0.96 – 1.54	0.74
Gravel- Kopkees		1.49		1.37	0.27
Granite - Ball. Gold.		2.48.		1.79	0.44
Coal-Maddingley		0.65		0.60	0.08

4.4.2 Wet Ore Compaction in the 8- Inch Diameter Tube ID (203.2 mm).

Calculation of ore and tube contact surface area cm^2, and the ore density g/cm^2 in the compacted ore volume

Surface area is calculated using equation (4.02) $SA = 63.8\ h$ cm^2

Density is calculated using equation (4.07) $\rho = m/\ 324.3\ h$ g/cm^3

The purpose to test wet ore is do know what the effect of added water to the ore would have on the ore density and hence the surface area of ore contact in the elevator with the tube.in the elevator when that occurs on the mine. The measured ore height for various ore weights with a selection of added water is in Table 16 and the results for contact surface area with the tube has been calculated. This surface area is used in further calculations.

Table 16. Wet ore compaction and densities in the 8-inch tube

Ore Type	Ore weight (m) on the disc g.	Water added g	Ore height in Tube mm	Contact Surface Area cm^2	Ore compaction Density ρ g/cm^3	Average density ρ g/cm^3
Gravel	1000	100	31	197.8	1.03	
Gravel	2000	200	53	338.1	1.28	
Gravel	3000	300	79	504.0	1.13	
Gravel	4000	400	114	727.3	1.19	1.16
Gravel	1000	200	19	121.2	1.95	
Gravel	2000	400	42	268.0	1.76	
Gravel	3000	600	59	376.4	1.88	
Gravel	4000	800	85	542.3	1.74	1.83
Granite	1000	100	25	159.5	1.36	
Granite	2000	200	45	287.1	1.51	
Granite	3000	300	71	453.0	1.43	
Granite	4000	400	103	657.1	1.32	1.41
Granite	1000	200	slurry	N/A	N/A	
Granite	2000	400	slurry	N/A	N/A	
Granite	3000	600	slurry	N/A	N/A	
Granite	4000	800	slurry	N/A	N/A	
Coal	1000	100	60	382.8	0.57	
Coal	2000	200	115	733.7	0.59	
Coal	3000	300	169	1078.2	0.60	
Coal	4000	400	248	1582.2	0.55	0.58
Coal	1000	200	45	306..2	0.82	
Coal	2000	400	80	510.4	0.93	
Coal	3000	600	126	803.9	0.88	
Coal	4000	800	166	1059.1	0.89	0.88

4.5 Surface Topography between the Ore and the Cable Disc elevator Tube

Already discussed is the ore surface area between the ore and the elevator tube and the relationship to ore density. The physical differences in the topography of the ore at that surface of the tube is different for the ores and the ore particle size. The breakfree force is measured for the different particle sizes and the changes in the surface topography that take place when the ore travelling up the tube is observed. The changes at the tube surface that take place are by default resultant from the nature of the ore and its fragmentation rather than designer round balls like marbles- that would have a different outcome for friction.

The next chapter is chapter 5 which describes the tests for static friction in Test Rig 1 with the different ores, of selected ore particle sizes and ore with added water. The densities used in the following chapters are referred back to the densities in this Chapter 4.

5.0 Test Rig 1: Static Friction of the Cable Disc Elevator

5.1 Introduction

Test Rig 1 is designed to measure static friction in the cable disc elevator. Measurements detailed in this chapter are those of static friction between the ore on the disc and the steel tube. These measurements will be for ore of different particle size, ore with added water and ore of different weights on the disc. The data from these tests will help determine what ore has the lowest static friction for the cable disc elevator. Ores used are those selected in Chapter 4. Calculations then determine the static friction between the ore and the tube as Newton's per centimetre squared. Further calculations are made to determine maximum lifting depths.

Static friction is also referred to as the breakfree force that is required to get the ore on the disc to start sliding in the cable disc elevator lifting tube.

The reason this data is required is to know:

1. What implications exist for friction should an elevator stop insitu loaded with ore.
2. Determine which ores are favourable and unfavourable to the cable disc elevator.

There are many components of this elevator that could be researched. The most important data required is that of the static friction required to haul the ore up the lifting side tube. A decision was made to limit the scope of this research to advance the design and prove the feasibility of the cable disc elevator for application in mining.

For the three ores selected in Chapter 4 gravel, granite and coal, to test the level of static friction in the cable disc elevator, the following is explored:

- Two tube sizes are used for static friction tests, with diameters of 8 inches and 5 inches respectively.
- The lifting disc for Test Rig 1 is 5mm smaller in diameter compared to the tube. This leaves a gap between the tube and the disc of 2.5mm.
- The effect that ore with different particle size has on the static friction.
- Test the ways in which this causes the elevator to jam.
- Observe how the ore moves on the disc when the ore is lifted.
- Tests for static friction are completed with added free water. Water is added to simulate ore in the mine that has been wetted or flooded.
- The final analysis of the data for the lifting limits and cable tension requirements based on static friction.

These results are reported as average (avg.), maximum (max.) and minimum (min.) values. Average refers to the mean average which is the total of all results divided by the number of results. The maximum is the highest one-off result, and the minimum is the lowest one-off result.

5.2 Test Rig 1 Set Up

This test rig is specifically designed to collect data to measure the breakfree force of the ores in two steel tube sizes, an 8-inch diameter tube (203.2mm), and a 5-inch diameter tube (127mm).The critical data required is the static friction force the breakfree force that has to be overcome after the elevator has stopped during operation and needs to be restarted. In such a situation the elevator has to be restarted without an elevator cable failure. Test Rig 1 explores this in several ways.

5.2.1 Breakfree Force $\mathrm{BF_{ORE}}$ ($\mathrm{T_F}$) Testing for the Determination of Static Friction

Static friction acts between surfaces at rest with respect to each other. The value of static friction varies between zero and the smallest force needed to start motion. This force required to start motion, or to overcome static friction, is always greater than the force required to continue the motion, or to overcome kinetic friction. (Britannica downloaded, 12/2018*)*.

In this section for Test Rig 1, the terms used for static friction $\mathrm{sf_{ore}^{size}}$ and static friction force $\mathrm{SF_{ore}^{size}}$ are separated by surface area. The static friction force is known as the breakfree force $\mathrm{BF_{ore}^{size}}$ required to start movement where there is no ore wedged between the disc and the tube. Static friction is the static friction force divided by the surface area of the ore in contact with the lifting tube.

Static friction $\mathrm{sf_{ore}^{size}} = \mathrm{SF_{ore}^{size}}/\mathrm{SA}\ \mathrm{N/cm^2}$ or $(\mathrm{kN/m^2})$ (5.01)

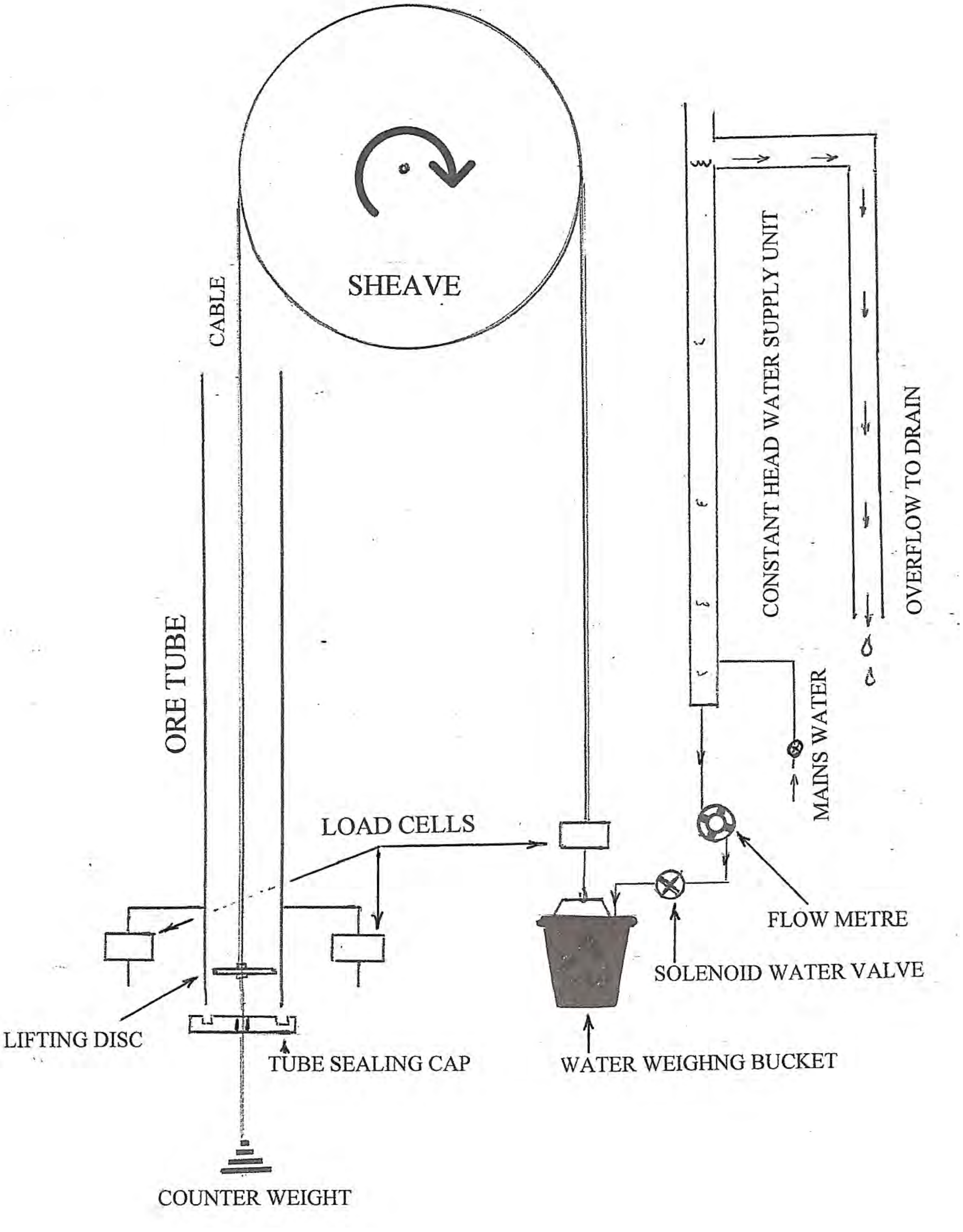


Figure 26. Test Rig 1 for testing the breakfree force.

To determine the maximum static friction for the ore, the ore is first tested for the breakfree force for various weights of ore on the test rig disc shown in Figures 26 and 27.

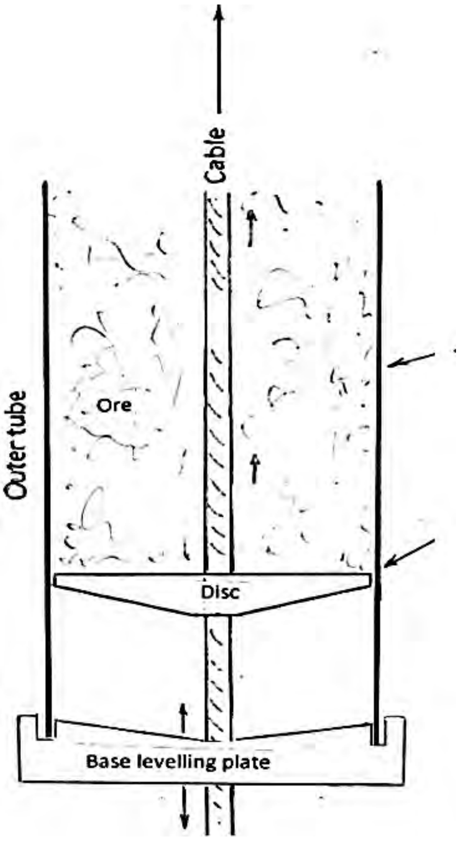


Figure 27. The cable loaded with ore. Test Rig 1

When using a fixed tube diameter an increase of ore weight on the disc increases the height of ore on the disc. Increasing the ore height then increases the surface area (SA) of ore contact with the tube.

Static friction ($\mathrm{sf_{ore}}$) is the force per unit area calculated as $\mathrm{N/cm^2}$

$$\mathrm{sf_{ore}} = \frac{\mathrm{BF_{ore}}}{\mathrm{ore\ SA}} \tag{5.02}$$

Substituting for the surface area with formula (5.01) the static friction can be determined by the following formula;

$$\mathrm{sf_{ore}} = \frac{\mathrm{BF_{ore}}}{\mathrm{D \times \pi \times h}}\ \mathrm{N/cm^2} \tag{5.03}$$

Where D is the tube diameter in cm, h is the height of the ore in the tube in cm, and $\mathrm{BF_{ore}}$ is the break free force for the sample in N.

5.2.2 Test Rig 1 Photo.

In Picture 19 the discs are in place, the lifting disc not visable as it is inside the tube resting on the lower base levelling plate. It is thus not visible in these pictures. Two of the three load cells supporting the ore tube are visible. An S shape load cell holding the counterweight bucket is in the background, whilst the bottom of the constant flow white water pipe is at the corner of the frame and the electric solenoid water valve. A water flow venturi indicator is mounted on the lefthand side frame leg.

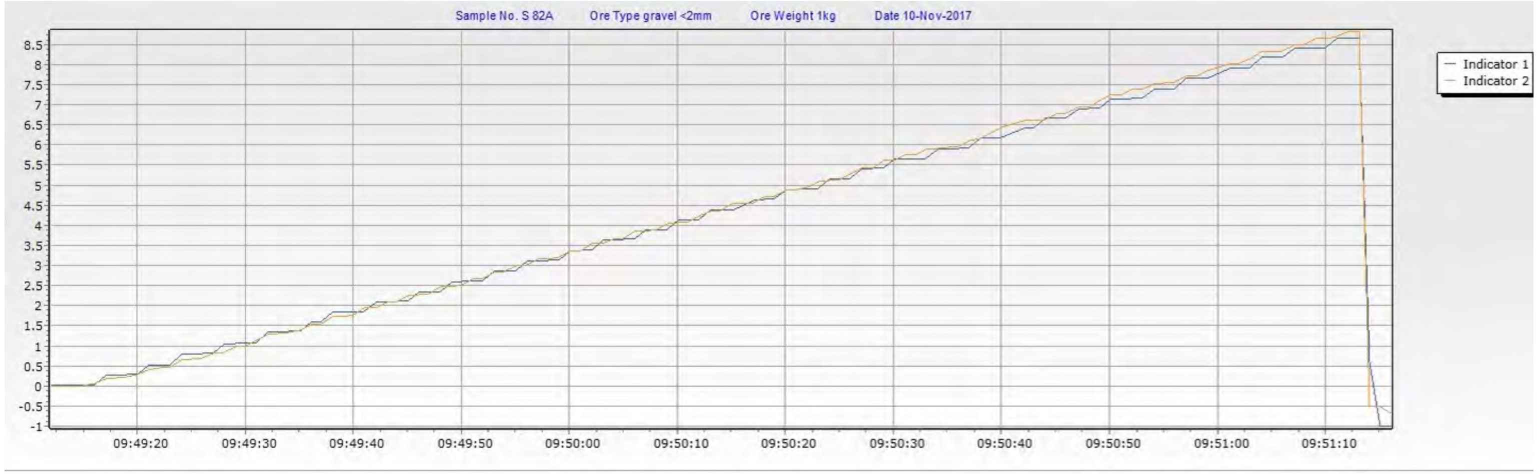
Ore is loaded into the top of the tube . The operator climbs the ladder and tips the pre-weighed quantity of sample in as evenly as possible. The tube length is 2.5 metres. This allows for a compaction of the ore resulting from a disc landing speed of 5 metres per second. The aim of this drop is to simulate the effect of ore entering a cable disc elevator where the cable is travelling at 5 metres per second. A constant head water supply fills the counterweight bucket at a fixed water flow rate of 2 l/min. Picture 19 shows the display data read-out for the water counterweight and the load cells holding the ore tube. Tare buttons for the load cell displays are on the right-hand side above the computer. The switch to turn the water on is above the power board. There is a further selection of pictures in Appendix 5.

Picture 19. Test Rig 1

5.3 Test Rig 1 Graph Examples

Results of the breakfree force are shown graphically and in a data table. Graphs 1 to 3 are examples of the graphs produced by Test Rig 1. The force countering the friction is that applied by water entering the counterweight bucket. The instant at which the breakfree force is reached is clearly defined on the graphs by the sudden drop in force. The breakfree force is the graph peak. These graphs show the instant the ore starts to slide. The breakfree force $\mathrm{BF}_{\mathrm{ore}}^{2}$ is the maximum reading at the graph peak.

The maximum force on the graph for Graphs 1, 2, and 3 are where the ore breaks free from the tube. The force is shown in pounds. For every test in Appendix 1 and 2 there is a graph of similar shape.



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Graph 1. Gravel 2mm particle size. Breakfree force test 1000 g. Water is added to the bucket at 2litres per minute

Graph 2. Granite 2mm particle size. Breakfree force test 1000g. Water is added to the bucket at 2litres per minute

Graph 3. Coal 2mm particle size. Breakfree force test 1000g. Water is added to the bucket at 2litres per minute

5.4 Test Rig 1 Equipment

Test Rig 1 is a purpose-built test rig as shown in Picture 19 and Figure 26. A 3mm steel wire cable passes over a sheave. On one side of the cable there is a load cell supporting the weight of the counterweight bucket and on the other side of the cable is a disc where ore is loaded onto that disc inside a tube holding load cells. Weights measured by the load cells are recorded through two displays, one for the counterweight and one for the tube. Water added for the counterweight flows from a constant head pipe at 2 litres per minute. The results are recorded on the computer.

5.5 Test Rig 1 Operation.

The test rig is operated in the following numbered sequence:

1. The test rig is clean, empty and dry.
2. The base levelling plate is secured into position and the lifting disc is lowered onto it.
3. Instruments are turned on, calibration using certified calibrated test weights for the bucket counterweight and the fixed tube load cells. When the test weights are removed the scales are set at zero.
4. A predetermined weight of ore is loaded onto the disc from the top of the tube (2.5m) and lands on the disc. The poring of ore down the tube is done evenly as possible to obtain a uniform height of ore around the disc.
5. Water is added to the counterweight bucket. The weight used is equal to the weight of the ore.
6. The weigh load cell displays are then tared to zero.
7. The scale readouts for the counterweight bucket and the tube load cells are then equal at zero and are in balance.
8. The computer program is turned on and the recording program started to record the load cell weights as displayed on the instrument panel over time.
9. The constant head water flow supply is started with the water turned on and overflowing at a low constant rate such that when the test rig is operating the overflow continues.
10. Data is then recorded onto the selected program page on the computer weighing program and graphs of the force are shown as in example in graphs 1, 2, and 3.
11. The computer program is allowed to run and the water from the constant head water supply to the counterweight bucket runs at a fixed 2 l/min.

12. The graph builds, then at the point where the static friction is overcome by the counter weight (the break free force $\mathrm{BF_{ore}}$) of water in the bucket, the disc slides rapidly and the friction is now much less than the breakfree force.
13. The water flowing into the bucket and the computer program is stopped. The data is the saved for analysis.
14. Ten samples are run each with the same ore and weight.

15 The ore height has been measured (Chapter 4) separately for the selected weight so that the ore contact surface area with the tube can be calculated. The data for the breakfree force $\mathrm{BF_{ore}}$is taken from the tools data page in the software.

5.6 Test Rig 1 Results

For each result in this section there were ten repeated tests. These are shown in Appendix 1 for the 8-inch tube and Appendix 2 for the 5-inch tube.

5.6.1 Break Free Force ($\mathrm{BF_{ore}}$)

Test Rig 1 results are taken at the maximum point on the graph where the disc with the ore starts to slide. For the example in Graph 1 sample 52 the breakfree force is taken at the maximum point and is 6.5 pounds. For each example tested there is an equivalent graph. Results for these maximums are recorded in Appendix 1 for the 8-inch tube and Appendix 2 for the 5-inch tube. These results are the breakfree force for each test.

5.6.2 Ore Tube Contact Surface Area

Ore surface area contact with the tube was measured separately in a drop test that measures the ore height in the tube. Afterwards, the surface area was then calculated. Results are shown in Tables 17, and 18, for the natural ore and Table 20 for ore containing added water.

5.7 Ore Movement in the Tube

Observing the movement of ore in the tube may help us understand the friction between the ore and the tube, the mixing of ore particles and particle stratification.

Friction between the ore and the tube resists ore movement up the tube. Observations at the top of the tube show that the ore has moved into a vertical position, with the ore in contact with the disc slowly rising through the centre to the top of the cell. As the disc continues to rise, the ore at the bottom of the sample rotates to the top of the disc. This caused by the ore coming into contact with the side of the tube experiences friction causing this ore at the tube surface to travel at a slower speed. The tube for these pictures is made from poly carbonate and its surface roughness is 0.0015 ε μm (Farshad, 2017). The tube is 196mm in diameter. This was the closest diameter and surface roughness to stretched steel tubes, whose Manning’s roughness (Manning’s, accessed 2018) coefficient is 0.012 ε µm used in the test rig, however the poly carbonate tube still allows for visual observation. The movement of the ore shown in Figure 31 is downward relative to the disc in the cell. Relative to the elevator tube the ore is still rising. Figure 28 was drawn from the observations in Pictures 20 to 28.

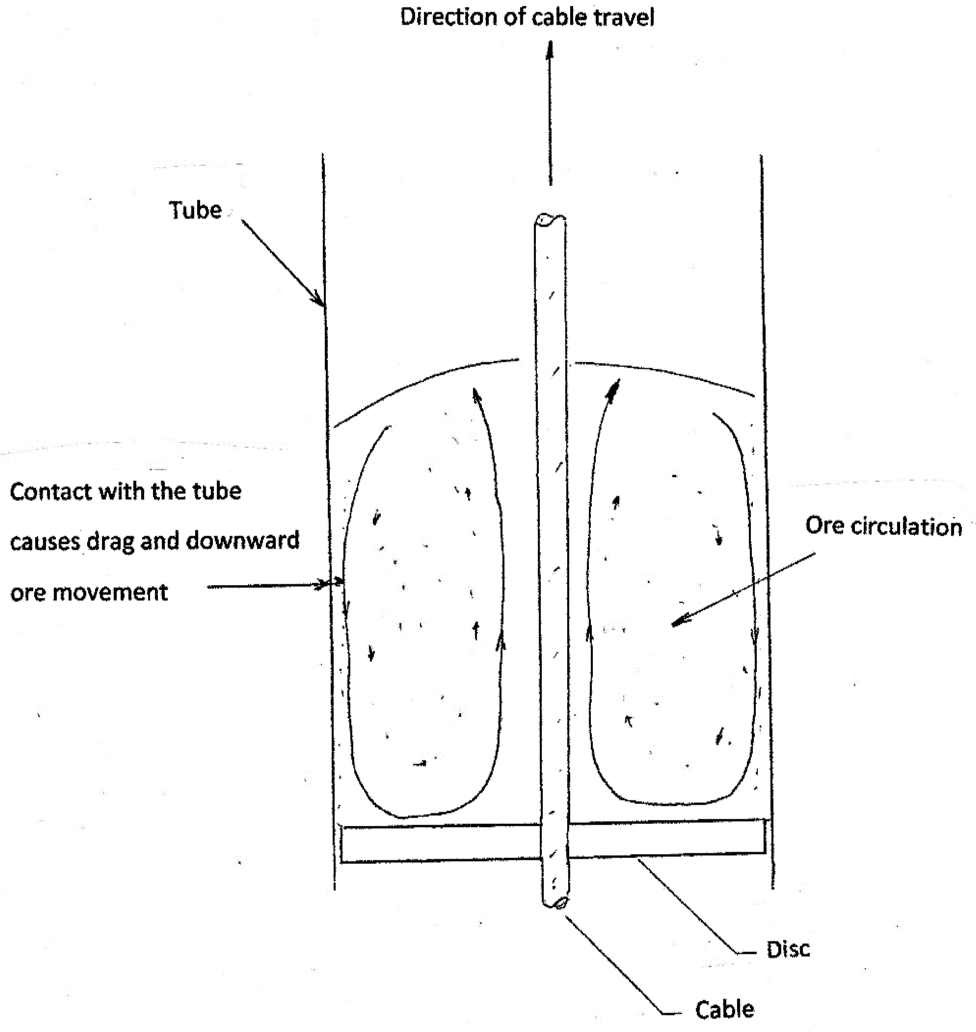


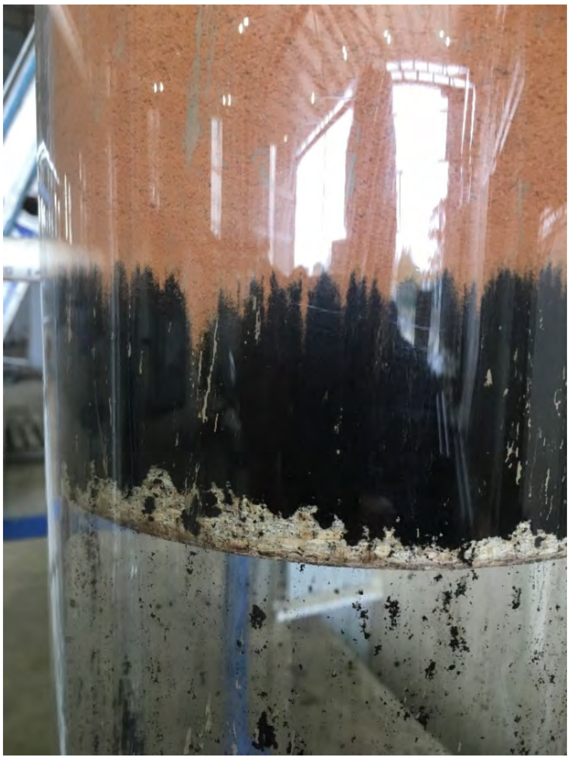
Figure 28. Ore movement observed in the tube.

5.7.1 Ore Movement in the Tube for 2mm ore

This test is done with 2mm ore and a disc to tube gap of 2.5mm. Pictures 20 to 28 are a series of photos taken after each 250mm of vertical movements. Visual movement of the ore is shown best with ores of different colours. 500 grams of 2mm coal is laid on the disc followed by 1000 grams of 2mm gravel. The weights were selected to achieve approximately the same volume and hence, visual tube contact surface area of ore. Gravel and coal were selected as the colour comparison allows easy visual observations of the ore movement.

Picture 20. Coal under gravel at point zero.

Picture 21. Coal under gravel after 250mm of movement.



Picture 22. Coal under gravel after 500mm of movement.

Picture 23. Coal under gravel after 750mm of movement.

Picture 24. Coal under gravel after 1000mm of movement.

Picture 25. Coal under gravel after 1250mm of movement.

Picture 26. Coal under gravel after 1500mm of movement.

Picture 27. Coal under gravel after 1500mm movement. Top View.

Picture 27 shows the coal coming up through the gravel demonstrating the vertical movement of the ore in the tube. Some of the gravel has been scrapped away to expose the first grains of coal that have started to move up into the gravel.

Picture 28. Coal under gravel after 1500mm movement with the upper layer of gravel removed.

5.7.2 Ungraded Ore Movement in the Tube for two Disc Gap Sizes

5.7.2.1 Ore Movement in the Tube for a disc gap of 2.5mm

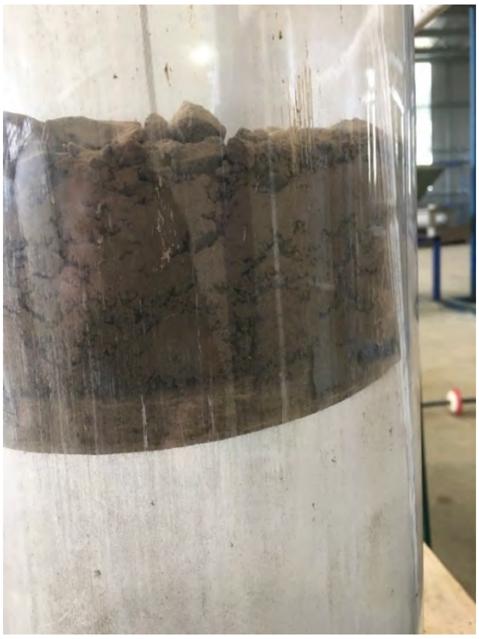
To seal the bottom of the ore on the disc a 500-gram layer of smaller than 2mm granite was loaded onto the disc, above which 1500 grams of ungraded granite ore is placed. The ungraded granite matches the particle size distribution shown in Table 14. During the movement of the ore the topography of the ore at the interface of the tube changes to larger pieces resulting in jamming. Picture 29, the fine granite below 2mm can be seen below the ungraded granite prior to any movement

Picture 29. Ungraded granite at zero movement.

After 250mm of vertical movement of the disc the upper layer of ore is moving down the side of the ore on the disc.

Picture 30. Ungraded Granite after 250mm of movement.

This disc was difficult to lift as the coarse ore from the ungraded ore started to move down the side of the fine ore and causing some jamming.



Picture 31. Ungraded Granite after 500mm of movement.

By 750 mm of or movement most of the fine layer has disappeared into the centre of the ungraded ore.

Picture 32. Ungraded granite after 750mm of movement.

The ore continues to separate as the disc is lifted. Larger ore pieces are accumulating at the sides.

Picture 33. Ungraded granite after 1000mm of movement.

Picture 34. Ungraded granite after 1250 mm of movement.

The topography of the ore at the tube surface has completely changed. At this distance 1500mm of movement, particles of ore have lodged between the disc and the tube resulting in the disc being jammed in the tube and the fines are in the centre of the disc.

Picture 35. Ungraded granite after 1500mm of movement.

5.7.2.2 Ore Movement in the Tube for a disc gap of 12.5mm

This lifting test was done with 4kg of ungraded granite of particle size distribution recorded in Table 14. The disc to tube gap is 12.5mm. The objective of this test is to simulate what would happen if the cable disc elevator was the aero mechanical cable disc elevator referred to in the Literature Review Section 2.7. Observation are that it would not be possible to measure any friction between the ore and the tube. The force measured was that required to pull the disc through a pile of ore. There is no ore sliding. This justifies the decision to select the disc to tube gape of 2.5mm.

Picture 36. Base with no ore.

Pictures 37 to 40 show the ore that has fallen off the disc in the first 500mm of the disc being lifted.

Picture 37. 4kg of granite before lifting.

Picture 38. After 250mm of travel.

Picture 39. After 500mm travel.

5.7.3 Ore Movement Visual Observations Discussion

There are many combinations of testing that could have been done with different ores and different disc to tube gaps, however the pictures shown here in Pictures 20 to 28 showed an reasonable example of ore movement that happens in in this research for fine less than 2mm ore.

5.7.3.1 Ore Movement Visual Observations Discussion where the Tube to Disc Gap is 2.5mm

In the clear tube the static friction between the ore and the tube is expected to be less than that of ore in a steel tube because of the lower coefficient of friction for the clear tube. Alas, there is no equipment that would allow the movement of the ore to be observed in the steel tube. Ore at the tube surface is exposed to surface friction, this ore is only being dragged upward by the next closest layer of ore. The resultant drag of the ore at the surface creates a vertical rotation of ore on the disc because the ore at the tube surface is traveling more slowly as shown in Figure 28.The ore starts to separate, with the fine grains moving into the centre of the disc and the larger particles moving towards the outer edges.

For ungraded granite, some difficulty was experienced getting the disc to lift and stay horizontal because of pieces of ore becoming wedged between the disc and the tube. With a vertical movement of 1500mm there are sufficiently large pieces of ore jamming between the disc and the tube to stop the disc from moving upward within the test rig. The 500 grams of 2mm fine granite that was on top of the disc but under the ungraded ore moved into the centre of the ore cell. Where the ore was ungraded i.e., of various particle size, the topography of the ore at the tube surface changed adversely.

The most significant observations during the movement of ore in the tube were:

- The rotation of the ore as per the sketch in Figure 28. Photographs 20 to 28 confirm that the ore friction retards the movement of the ore at the tube surface in the opposite direction of the disc.

- Ungraded ore particles of different size travelled at different rates and separated and the surface topography changes to larger particles that are left at the outer tube contact area.

- Larger wedge-shaped particles of granite jammed between the disc and the tube, resulting in a higher force to achieve any movement. Over a distance of less than 1500mm the disc completely jammed even though the sample started with a layer of less than 2mm ore under the ungraded ore. It was not possible for the test rig to pull past that point when testing for the ungraded ore, shown in Picture 35.

- Coal and gravel samples had some jamming effects, but the particles sheared, disintegrated, and became finer and rotated in a more uniform manner.

5.7.3.2 Ore Movement Visual Observations Discussion where the Tube to Disc Gap is 12.5mm

Discussion for this test relates to Picture 36-40. This test was done to demonstrate the effect of a larger disc to tube gap. In the example used granite of particle size as shown in Table 14. 4000grams of ore was placed on the disc as shown in Picture 37 . When this was pulled upwards the disc appeared to just pull through the ore pile on top of it and most of the ore had fallen off the disc by the distance of 250mm of lift. After the ore had been lifted 500mm and weighed there was 1206 grams of ore on the disc and 2794 grams of ore left in the tube, i.e. 69.9% of the ore fall off the disc. This lifting was done gently by hand, as any vibration from machine lifting, would expect greater ore spillage of the disc. In this test there was no visual observation of any ore at the tube surface movement. As a result of these observations the decision was made to use a small disc-tube gap of 2.5mm.

5.8 Test Rig 1 Operation

The test rig consists of three main parts which have interconnecting functions making it possible to measure the resistance of the ore sample to movement. Each section of the test rig shown in Figure 28, is described for the tube, the counterweight loading system and the computer recording system.

5.8.1 The Tube

The tube is supported on 3 ‘S’ shaped load cells each with a capacity of 45.45kg (100lb). (See Figures 26). When the loaded disc is pulled by the cable, ore has a binding effect on the sides of the tube connecting the disc and the ore together. Movement does not occur until the lifting force of the cable is sufficient to overcome all friction forces resisting the movement of the ore in the tube. Shear occurs at the tube surface resulting in the ore and disc starting to move. The tube load cells at this stage are unloading weight until shear occurs and the ore starts to move, at which stage the force needed for movement reduces. The recording station graphs show this action. (See graphs 1 - 3). The force being measured is the breakfree force BF_{ore} that is required to get the disc containing the ore to start sliding.

5.8.2 The Counterweight Loading System

To apply the force required to lift the ore loaded disc and overcome the resistance to movement, the cable is extended over a sheave and is attached to a bucket hanging on a 'S' shape load cell with a capacity of 45.45kg (100lb) which is connected to the cable. Water is added at a controlled rate. A constant head water tank made from poly pipe supplies a steady flow of water at 2 litres per minute. The water flow can be seen by the venturi flow gauge (Picture 19 on the left structural leg), as well as the steady increase on the graph showing the trace of the bucket weight. When the ore starts to move in the tube, the water flow stops, and the bucket lowers to a support. The maximum weight that the bucket received is measured in pounds then converted to Newton force, which mimics the same result of the tube load cells. Further pictures are in Appendix 5.

5.8.3 The Computer Recording System

The recording system is comprised of two Gedge System readout displays, each of which are independent of one another, one for the tube and a second one for the water bucket. There are independent tare button switches and a control switch for the water. There is no variability control for the water flow rate, which is fixed at 2 litres per minute. As the load changes on the tube take place, the results are graphed and recorded on a computer, (See graphs 1, 2, and 3). These results are in pounds and then separately converted to Newton force. The computer program was purpose written for this test rig.

5.8.4 Calibration

Calibration checking is applied using the method outlined in the Gedge System weighing manual. Three test weights of 5kg, 20kg, and 25kg certificated test weights are used for this. After the initial set up calibration, which took place each day prior to operation the test weights are suspended on the two weighing units to confirm accuracy. Recalibration takes place if required. All the load cells are supplied pre-calibrated.

5.9 Effect of Gravity Forces Acting on the Ore in the Test Rig

It is important to note that the above method discussed in Section 5.5 balances out the effect of the force of gravity acting down on the ore that is placed on the disc resulting from the counterweight.

Force of gravity $$F=m.g \qquad (5.4)$$

Where m is the mass weight of the ore and the g is the acceleration due to gravity of 9.81 m/s^2 . The weight of the ore, and hence the force of gravity, is balanced out by counterweighting by adding the same weight of water in the bucket on the opposite side of the cable. The effect of this method then ensures that the breakfree forces BF_{ore} is only the resultant force from friction forces acting in the system. The weight of the ore is m_{ore} and the weight of the water is m_w. The forces interacting in Test Rig 1 are shown in Figure 32, where the ore is at rest on the lifting disc.

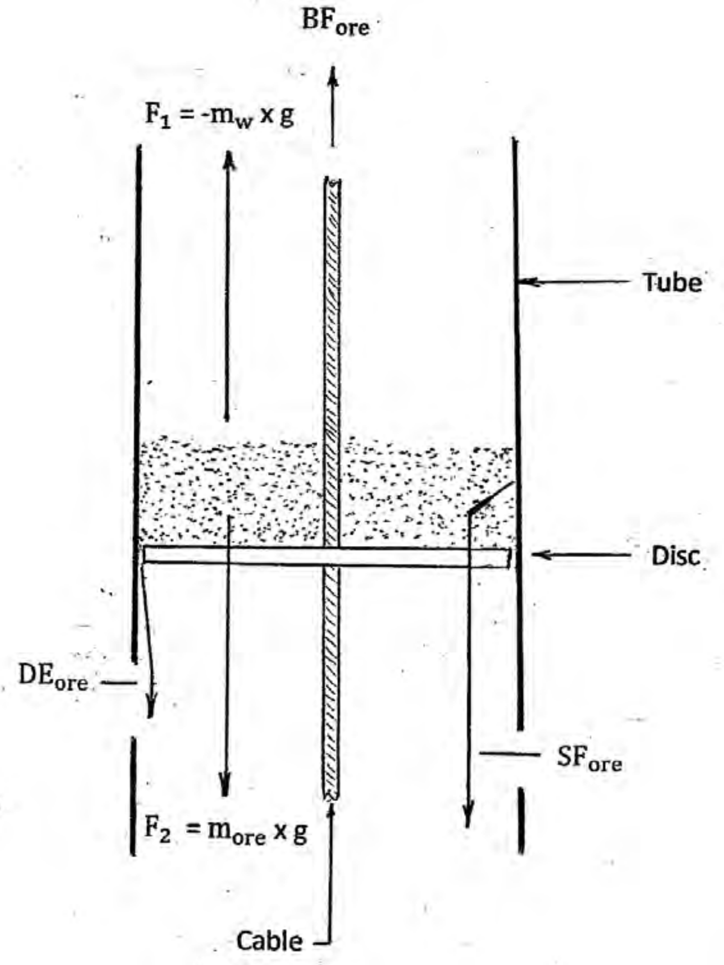


Figure 29, Ore laid on the disc. Diagram of forces acting at the disc.

F_1 and F_2 are opposing forces, each working in opposite directions when the mass of water in the counterweight bucket has the same mass as the ore on the disc (i.e. when the system is in equilibrium). These forces result from the gravitational pull on the water counterweight and the ore on the disc. There is no movement when they are equal in magnitude and opposite in direction.

The breakfree force BF_{ore} created by the additional weight of water added to the counter weight bucket, is counteracted by the reaction of friction forces of the static friction SF_{ore} and the disc effect DE_{ore}. The result is that:

Breakfree force $$BF_{ore} = SF_{ore} + DE_{ore} + J_{ore} \qquad (5.5)$$

Where SF_{ore} is the static friction force for the ore at the surface of the tube, DE_{ore} is the force required to overcome the effect of the ore between the disc and the tube, and J_{ore} is the effect between the disc and the tube resulting from any oversize particles that caused jamming.

As water is added to the counterweight bucket the lifting force increases in magnitude. The static friction force and the disc effect force increases and oppose disc movement. When the lifting force is of sufficient magnitude to equal the static and disc effect forces even the slightest increase in weight in the counterweight bucket increases the lifting force, which causes the disc to move. The lowest lifting force that causes the disc and ore to move is now called the breakfree force $\mathrm{BF_{ore}}$. The static friction force $\mathrm{SF_{ore}}$ and the disc effect force $\mathrm{DE_{ore}}$ are at that point defined by their maximum resistance to movement.

5.10 Samples Tested

Samples collected are tested ungraded and with different particle size after the ore is separated using the Endecott sieves.

5.10.1 Gravel

- Gravel ungraded with particle size distribution as determined in Table 15.
- Gravel sieved from the ungraded ore for particles retained on a 9.5mm sieve.
- Gravel sieved from the ungraded ore for particles retained on 5mm sieve but passed through a 9.5mm sieve.
- Gravel sieved from the ungraded ore for particles retained on 2mm sieve and passed through a 5mm sieve.
- Gravel sieved from the ungraded ore for particles passed through a 2mm sieve.
- Gravel sieved from the ungraded ore for particles passed through a 2mm sieve with added water.

5.10.2 Granite

- Granite ungraded with particle size distribution as determined in Table 14.
- Granite sieved from the ungraded ore for particles retained on a 9.5mm sieve.
- Granite sieved from the ungraded ore for particles retained on 5mm sieve but passed through a 9.5mm sieve.
- Granite sieved from the ungraded ore for particles retained on a 2mm sieve and passed through a 5mm sieve.
- Granite sieved from the ungraded ore for particles passed through a 2mm sieve.
- Granite sieved from the ungraded ore for particles passed through a 2mm sieve with added water.

5.10.3 Coal

- Coal ungraded with particle size distribution as determined in Table 12 and 13.
- Coal sieved from the ungraded ore for particles retained on a 9.5mm sieve.

- Coal sieved from the ungraded ore for particles retained on a 5mm sieve but passed through a 9.5mm sieve.
- Coal sieved from the ungraded ore for particles retained on a 2mm sieve but passed through a 5mm sieve.
- Coal sieved from the ungraded ore for particles passed through a 2mm sieve.
- Coal sieved from the ungraded ore for particles passed through a 2mm sieve with added water.

5.11 Calculations and Results for Test Rig 1

5.11.1 Introduction

This test rig:

- Measures the breakfree force for the three ores which is then used to calculate the static friction as $\mathrm{sf}_{\mathrm{ore}}^{\mathrm{size}}$ N/cm^2.
- Results are applied for calculations of the static friction at the disc and on the tube wall at various ore heights above the disc.
- Initial calculations refer to the static friction force $\mathrm{SF}_{\mathrm{ore}}^{\mathrm{size}}$ N, the force per square centimetre of ore contact surface area calculated as the static friction $\mathrm{sf}_{\mathrm{ore}}^{\mathrm{size}}$N/cm^2.
- There is also a strong reaction between the ore and the tube at the disc. This is taken into consideration as the disc effect $\mathrm{DE}_{\mathrm{ore}}^{\mathrm{size}}$.
- Larger ore particles greater than the disc to tube gap of 2.5mm caused jamming. This has not been considered as friction; however, results are considered in the breakfree force where applicable as this demonstrates some of the loading that can occur on the cable with tension T_1.
- Further calculations consider the measurements taken for the effect of added water on the breakfree force $\mathrm{BF}_{\mathrm{ore}}^{\mathrm{size}}$.
- Ungraded ore has large particles which jam between the disc and the tube. These ores are measured for friction and also measured for friction on top of fine coal. The coal is used to eliminate the effect of jamming then by difference a measurement of the jamming effect can be calculated.

This is represented by $\mathrm{BF}_{\mathrm{ore}}^{\frac{\mathrm{UG}}{\mathrm{coal}}}$.

5.11.2 Results and Observations for Ungraded Ore

Ores are tested using the method described in 5.5. The result recorded is the breakfree force $\mathrm{BF}_{\mathrm{ore}}$that was required for the ore to start moving. The breakfree force $\mathrm{BF}_{\mathrm{ore}}$ is made up of three interactions in the tube.

- Static friction force $\mathrm{SF}_{\mathrm{ore}}$ between the ore and the tube.
- Resistance between the disc ore and the tube at the sides of the disc named the disc effect force $\mathrm{DE}_{\mathrm{ore}}$.
- The effect of jamming $\mathrm{J}_{\mathrm{ore}}$ from ore wedged between the disc and the tube where the particles are larger than the gap between the disc and the

tube and are irregular in shape such that they get wedged between the disc and the tube.

Separation of these forces are calculated and are very significant to our understanding of the tension required when designing of the cables.

These calculations are presented in the Appendixes 1 and 2. Results of each test start as a graph which is similar to the sample graphs shown in graphs 1-3. The graph shows the steady force increase from water entering the counterweight water bucket at a rate of 2 litres per minute, until a weight is achieved that is sufficient to start the ore moving. This point is the breakfree force $\mathrm{BF}_{\mathrm{ore}}$ and is shown graphically at the graph peak and recorded in the data. The data for the graphs is logged in the test rig program. The break free $\mathrm{BF}_{\mathrm{ore}}$ is the numerical figure that is used in these analyses.

Ore samples have been mixed and drawn from this homogenous particle size mixture. For each sample, when tested in the rig there is a graph, and the largest force from each graph is recorded in the program in pounds and then entered into the relevant data table in Appendix 1 and 2, then converted to Newtons. (Refer to Graph 1). Results of the samples are shown in the relative appendix then summarised in these result tables.
The number in front of the ore is the tube size in inches, the upper number represents the particle size of the ore:

- $\mathrm{BF}_{8\,\mathrm{coal}}^{2}$ is the breakfree force for coal of less than 2mm in size tested in the 8-inch tube.
- $\mathrm{BF}_{5\,\mathrm{coal}}^{2}$ is the breakfree force for coal of less than 2mm in size tested in the 5-inch tube.

5.11.3 Ungraded Ore (UG)

Ungraded ore was collected from the mines and was not separated using sieves. The distribution of the particle sizes is shown in Tables12 to 15.

The ore samples are described in section 5.10.1 to 5.10.3. These are tested for the breakfree force $\mathrm{BF}_{8\mathrm{ore}}^{\mathrm{UG}}$,and the results using the 8-inch tube are shown in Table 17 and for the 5-inch tube in Table 18.

Table 17 the break free force $\mathrm{BF}_{8\mathrm{ore}}^{\mathrm{UG}}$, maximum, minimum and average for 10 samples in the 8 inch tube with disc diameter 198.2mm. Data from Appendix 1 Tables 157 Gravel, 158 Granite, and 159 Coal.

Table 17. Breakfree force for ungraded ore 1000g on one disc. 8-inch (203.2mm) tube

Ore Ungraded 1000g	Avg. Breakfree Force N. $\mathrm{BF}_{8\mathrm{ore}}^{\mathrm{UG}}$	Max. Breakfree Force N. $\mathrm{BF}_{8\mathrm{ore}}^{\mathrm{UG}}$	Min. Breakfree Force N. $\mathrm{BF}_{8\mathrm{ore}}^{\mathrm{UG}}$	Range for 10 samples N
Gravel	64.6	160.1	36.0	124.1
Granite	232.7	398.1	133.9	264.2
Coal	37.6	58.7	20.5	15.5

For Table 22 the maximum, minimum and average for 10 samples in the 5-inch tube with disc diameter 122mm. Data from Appendix 2 Tables 180 Gravel, 178 Granite and, 182 Coal.

Table 18. Breakfree force for ungraded ore 1000g on one disc. 5-inch(127mm) tube

Ore Ungraded 1000g	Avg. Breakfree Force N. BF_{5ore}^{UG}	Max. Breakfree Force N. BF_{5ore}^{UG}	Min. Breakfree Force N. BF_{5ore}^{UG}	Range for10 samples N
Gravel	46.8	105.9	16.5	89.4
Granite	91.6	225.1	28.0	197.1
Coal	57.6	88.1	47.1	41.0

Friction tension in the lifting cable of the elevator will be referred to as T_f, and is a component of the tension acting in the lifting cable T_1.

(Metlikovic, 2006) Fig. 24

$$T_1 = T_e^L + T_e^f + T_2 \tag{5.06}$$

- T_f is the tension required to overcome the breakfree force BF_{ore} which is the total of all the friction forces relating to the resistance to movement of the ore.
- T_e^L is the tension component of the cable required to carry the weight of the ore as a result of gravity.
- T_2 is the cable weight on the downside of the elevator. This is a fixed component of the tension and carries no ore, and for the lifting cable is the same on both sides of the elevator.

This method analyses the breakfree force BF_{ore} required to overcome the maximum friction force in Newtons for one disc in the cable disc elevator under various conditions. Results are then multiplied by the number of discs that may be required for an elevator of determined distance. For a cable lift of 1000 metres with discs at 250mm spacing, there are 4000 discs. Cable tension requirements are calculated which determines the lifting length that a cable of known tension capacity and specification may achieve. The objective for Test Rig 1 is to measure the static friction in order to determine the force required to overcome this friction, and then establish the cable design strength for a vertical 1000m continuous lift in a cable disc elevator. However, the data can be used for the cable disc elevator of the same design for greater lengths. Some consideration is given to larger diameter cables that could lift greater than 1000m.

Resistance to movement in the tube for static friction (T_f) is made up of the following:

- Jamming force J_{ore}. This is the force required to overcome jamming between the disc and the tube resulting from the effects of shards of ore that wedge themselves. Jamming is not considered here as friction but as a mechanical blocking issue that must be added to the break free force or eliminated from the process.
- Disc effect force DE_{ore} . This is part of the breakfree force that is required to overcome the effect of ore when it is compacted between the disc and the tube where the ore particle size is less than the gap between the disc and the tube, but does not relate to large particles that jam.

- Static friction force SF_{ore} This is the force required to overcome the resistance of the static friction reaction between the ore and the tube for the ore above the disc.

The breakfree force BF_{ore} is the sum of all these forces and can be represented in the equation below.

$$BF_{ore} = \sum J_{ore}, DE_{ore}, SF_{ore} \qquad (5.07)$$

Calculations were made to separate these measured friction forces and break these down into a unit of friction.

Measuring the circumference of the disc and applying that to the lowest amount of ore on the disc allows the disc effect force DE_{ore} to be calculated.

Measuring the surface area of the ore relative to the tube allows the calculation of the static friction sF_{ore}^{size} N/cm^2 from the static friction force SF_{ore}^{size} N.

The breakdown calculation method allows the following:

- Determination of the static friction sF_{ore} between the ore and the tube surface area in N/cm^2. This is determined by dividing the calculated static friction force SF_{ore} by the ore surface area contact with the tube. The surface area contact has been determined and shown in Tables 13, 14, and 16.

- Calculation of the resistance to movement between the disc $dE_{ore}$and the tube with ore present around the known circumference of the disc. This is determined as the resistance per unit of length of the circumference, measured in. N/cm, by dividing the calculated disc effect force DE_{ore} by the circumference of the disc.

Friction is represented using lower-case letters.

dE_{ore} disc effect friction N/cm.

sf_{ore} static friction N/cm^2.

Where there are no large particles that cause jamming the breakfree force is;

$$BF_{ore} = dE_{ore} \, x \, C + sF_{ore} \, x \, SA- \quad N \qquad (5.08)$$

The ores are represented by the following abbreviations:

Gravel	Gv
Granite	Gn
Coal	coal

These results, shown in Tables 17 and 18, are dominated by ore jamming. To get a perspective as to how large this force is, a calculation is made for 1000 grams per disc in section 5.11.4 for 4000 discs at 250mm apart which represents a lift of 1000metres and compared with the tension specifications of selected commercial available cables. No adjustment is made in the following table for any increase in the ore height in the tube which would result from the volume of the cable in the ore space.

5.11.4 Ungraded Ore Elevator Friction For 1000 Metres.

The ungraded ore was seen to cause considerable jamming. To get some perspective on the magnitude of this and to understand how this would influence the ability of the elevator to achieve a 1000m lift with these breakfree forces, the breakfree force for 1000m is calculated and compared to the cable tension specifications for the 3 selected cables. For an elevator at 1000m with disc separations of 250mm the cable tension contribution from the breakfree force or is calculated by multiplying the breakfree forces found in Tables 17 and 18 by 4000, the total number of discs. Ore loaded on the test disc was 1000 grams. These results are shown in the table below for the tube sizes 5 and 8-inches. Only the friction for T_e^f is calculated. The total tension T_1 would also need T_2 and T_w added.

Table 19. Breakfree force for ungraded ore in the 5-inch and 8-inch tubes projected for 1000m

Ore	Tube size inches	Average Breakfree Force for 4000 discs kN BF_{ore}^{UG} (T_e^f)	Maximum Breakfree Force for 4000 discs kN BF_{ore}^{UG} (T_e^f)	Minimum Breakfree Force for 4000 discs kN BF_{ore}^{UG} (T_e^f)
Gravel	8	258.4	640.4	144.0
Granite	8	930.8	1592.4	535.6
Coal	8	150.4	234.8	62.0
Gravel	5	187.2	423.6	66.0
Granite	5	366.4	900.4	112.0
Coal	5	230.4	352.4	188.4

The measurements for the breakfree force BF_{ore}^{UG} in the above Table 19 are for ungraded ore that has just landed on the disc. The data in Table 19 is only for the friction component T_e^f. Just the friction component alone demonstrates that any jamming will load existing cables to unsafe levels, without the addition of the cable weight and the effect of gravity on the ore.

For equation (5.06) where $T_1 = T_e^L + T_e^f + T_2$

Observation of the accumulation of large pieces of ore at the disc can be seen in Pictures 45-51. These contribute to jamming soon after movement has started.

The data in Table 19 above is taken from Tables 17 and 18. To enable comparison, safe cable lifting tensions for the selected cables are shown in Tables 7 to 9.

Dyform 34LR 40mm dia. 219.0 kN

Dyform 6AR 50mm dia.	308.9 kN
Goldstrand 75mm dia.	623.7 kN

5.12 Calculation for Static Friction of Ungraded Ore in the Stationary Tube

To measure the true static friction, of the ungraded ore in the tube, the influence on the disc resulting from jamming J_{ore}, and the ore disc tube DE_{ore} need to be eliminated. Ore above the disc will be affected only by the static friction force SF_{ore} between the ore and the tube. To eliminate the jamming effect at the disc for ungraded ore, it is underlain with 500 grams of 2mm particle size coal ore of known friction properties on the disc.

Placing this fine coal of less than 2mm particle size coal under the ungraded ore eliminates the forces of jamming J_{ore}, and the disc effect DE_{ore} of the ungraded ore. The fine coal is tested separately, and the results subtracted from the combined data.

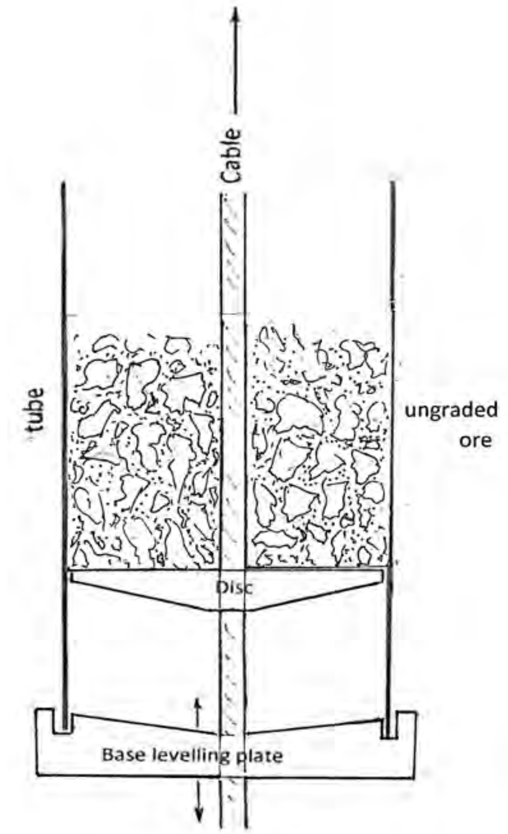


Figure 30. Drawing of ungraded ore on the test rig disc.

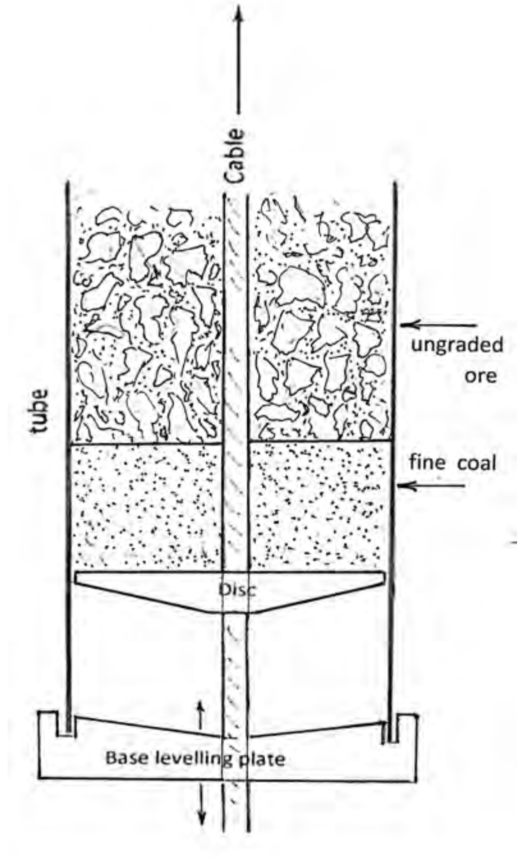


Figure 31. Drawing of ungraded ore clear of the test rig disc sitting on 2mm coal.

5.12.1 The Static Friction per Square Centimetre $\mathrm{sf}_{\mathrm{ore}}^{\mathrm{UG}}$ N/cm^2 for Ungraded Ore in the Selected Tubes

The breakfree force for 500 grams of 2mm coal tested in the 8-inch tube is taken from Table 20 where the average BF is 7.4 N, the maximum is 10.2 N, and minimum is 6.2N. This allows the static friction $\mathrm{sf}_{\mathrm{coal}}^{\mathrm{UG}}$ of the ore to be calculated without the ungraded ore disc effect. The data for 1000 grams of ungraded ore over 500 grams of coal for the 8-inch and 5-inch tube is taken from Table 21.

The breakfree force for 500 grams of 2mm coal tested in the 5-inch tube is taken from Table 20 where the Average $\mathrm{BF}_{5\mathrm{coal}}^{2}$ 4.8 N, the maximum is 5.8 N, and minimum is 4.0N. This allows the static friction between the ungraded ore and the tube to be calculated without the ungraded ore jamming at the disc.

The static friction force for the ungraded ore can be represented as;

.

Static friction force $$\mathrm{SF}_{\mathrm{ore}}^{\mathrm{UG}} = \mathrm{BF}_{\mathrm{ore/coal}}^{\mathrm{UG/2}} - \mathrm{BF}_{\mathrm{coal}}^{2} \text{ N} \qquad (5.09)$$

Where $\mathrm{BF}_{\mathrm{coal}}^{2}$ is the breakfree force in N for 500 grams of 2mm size coal resting on the cable disc in the tube, and $\mathrm{BF}_{\mathrm{ore/coal}}^{\mathrm{UG/2}}$ is the breakfree force for 500 grams of 2mm size coal on the disc plus

1000 grams of ungraded ore on top of the coal. In Table 24 the static friction force $\mathrm{SF}_{\mathrm{ore}}^{\mathrm{UG}}$ is calculated using equation (5.9) for the average, maximum, and minimum static friction force.

5.12.2 Testing With 1000grams Of Ungraded Ore Over 500grams Of Coal

The breakfree force with 1000 grams of ungraded ore on top 500 grams of coal smaller than 2mm in size. The particle size distribution of the ores is shown in Tables 8, to 11.

Table 20. Breakfree force for 1000 grams of ungraded ore over 500 grams of 2mm coal in the 5-inch and 8-inch tubes

Ore wt. 1000g.Tube size inches	2mm Coal 500g. under ore	Avg. Breakfree Force N $\mathrm{BF}_{\mathrm{ore/coal}}^{\mathrm{UG/2}}$	Max. Breakfree Force N $\mathrm{BF}_{\mathrm{ore/coal}}^{\mathrm{UG/2}}$	Min. Breakfree Force N $\mathrm{BF}_{\mathrm{ore/coal}}^{\mathrm{UG/2}}$	Range for 10 samples N
Gravel 8	Coal	18.6	24.0	15.1	8.9
Granite 8	Coal	20.2	23.6	16.9	6.7
Coal 8	Coal	17.8	20.7	14.9	4.2
Gravel 5	Coal	33.9	37.4	29.8	7.6
Granite 5	Coal	31.7	37.4	26.7	10.7
Coal 5	Coal	29.6	32.5	28.0	4.5

Breakfree force $\mathrm{BF}_{\mathrm{5ore/coal}}^{\mathrm{UG/2}}$ for the 5-inch tube in Table 24 is taken from Appendix 2, Tables, 181, 179, and 187.

The breakfree force $\mathrm{BF}_{\mathrm{8ore/coal}}^{\mathrm{UG/2}}$ for 1000 grams of ungraded ore over 500 grams of 2mm coal in the 8-inch tube is taken from Appendix 1 Tables, 135, to 137. Applying equation 5.9, the static friction force is calculated for ungraded ore and shown in Table 21. For this Table the data for fine coal is taken from Table 20 for both the 8-inch tube and Table 31 for the 5-inch tube.

Table 21. Static friction force for gravel, granite, and coal over coal for samples tested in the 5-inch and 8-inch tubes.

Ore 1000grams Tube size inches	2mm Coal 500grams Under the ore	Avg. Force N From Table 19 for 8 in. and for 5 in tubes. $\mathrm{BF}^{\mathrm{UG}/2}_{\mathrm{ore/coal}}$	Ave. Force N, Ave. less Coal 8 in. 7.4N, 5in. 4.8 N $\mathrm{SF}^{\mathrm{UG}}_{\mathrm{ore}}$	Max. Force N. from Table 19 for 8 in. and 5 in tubes. . $\mathrm{BF}^{\mathrm{UG}/2}_{\mathrm{ore/coal}}$	Max. Force N Max. less Coal max. 8 in. 10.2N 5 in. 5.8 $\mathrm{SF}^{\mathrm{UG}}_{\mathrm{ore}}$	Min. Force N from Table 19 for 8 in. and for 5 in tubes. . $\mathrm{BF}^{\mathrm{UG}/2}_{\mathrm{ore/coal}}$	Min. force N Less Coal 8 in. 6.2N 5in. 4.0 N $\mathrm{SF}^{\mathrm{UG}}_{\mathrm{ore}}$
Gravel 8	Coal	18.6	11.2	24.0	13.8	15.1	8.9
Granite 8	Coal	20.2	12.8	23.6	13.4	16.9	10.7
Coal 8	Coal	17.8	10.4	20.7	10.5	14.9	8.7
Gravel 5	Coal	33.9	29.1	37.4	31.6	29.8	25.8
Granite 5	Coal	31.7	26.9	37.4	31.6	26.7	22.7
Coal 5	Coal	29.6	24.8	32.5	26.7	28.0	24.0

From Table 25 the static friction force $\mathrm{SF}_{\mathrm{ore}}^{\mathrm{UG}}$ has been calculated for 1000 grams of ungraded ore after the coal breakfree force $\mathrm{BF}_{\mathrm{ore}}^{2}$ for 500 grams is subtracted. Using this static friction force $\mathrm{SF}_{\mathrm{ore}}^{\mathrm{UG}}$ and dividing it by the ore tube surface contact area for 1000 grams of ungraded ore, the static friction $\mathrm{sf}_{\mathrm{ore}}^{\mathrm{UG}}$ can be calculated as N/cm^2. The surface area SA data is taken from Table 17, and 18.

Static friction: $$\mathrm{sF}_{\mathrm{ore}}^{\mathrm{UG}} = \frac{\mathrm{SF}_{\mathrm{ore}}^{\mathrm{UG}}}{\mathrm{SA}_{\mathrm{ore}}} \qquad (5.10)$$

Table 22. Static friction determined in Newtons per square centimetres for ungraded Gravel, granite and coal.

Ore 1000g Tube dia. in.	Surface area cm^2 for 1000grams Table 16 & 17 ungraded ore	Average Static Friction N/cm^2 $\mathrm{sf}_{\mathrm{ore}}^{\mathrm{UG}}$	Maximum Static Friction N/cm^2 $\mathrm{sf}_{\mathrm{ore}}^{\mathrm{UG}}$	Minimum Static Friction N/cm^2 $\mathrm{sf}_{\mathrm{ore}}^{\mathrm{UG}}$
Gravel 8	178.7	0.063	0.077	0.050
Granite 8	159.5	0.080	0.084	0.067
Coal 8	701.8	0.095	0.095	0.079
Gravel 5	283.3	0.103	0.112	0.091
Granite 5	251.4	0.107	0.126	0.090
Coal 5	1093.3	0.023	0.030	0.022

Ore samples results in Table 26 were for tests in the 8-inch and 5-inch tubes. The static friction force, $\mathrm{SF}_{\mathrm{ore}}^{\mathrm{UG}}$, from Table 25 was divided by the relevant surface area to calculate the static friction, $\mathrm{sf}_{\mathrm{ore}}^{\mathrm{UG}}$.

These calculations have now established the static friction $\mathrm{sF}_{5\mathrm{ore}}^{\mathrm{UG}}$ for the ungraded ores tested with the effect of the disc and jamming of irregular particles eliminated. The results are shown in bold in Table 28 for ore placed above the 2mm fine coal.

Comparing the breakfree force for the ores in Tables 21 and 22 where the ungraded ore rests on the disc, to the static friction force calculated with the fine coal sitting under the ore, we can see that there is a significant difference. This difference has come about by eliminating the disc effect for the ungraded ore and replacing the layer covering the disc with fine 2mm particle sized coal. This implies that the disc effect and ore jamming are an important part of the force that makes up the total breakfree force for the ungraded ores. The breakfree force divided by the surface area of the ungraded ore that has no coal underlying the ore is shown in the Table 27.

The results of applying equation 5.10 to the breakfree force in Tables 17 and 18 are shown in Table 23.

Table 23. Ungraded ore breakfree friction

Ore	Tube size inches	Tube ore Surface Area for 1000g ungraded ore cm^2	Ave. Breakfree Force/surface area kN/cm^2 bF_{ore}^{UG}	Max. Breakfree Force/surface area kN/cm^2 bF_{ore}^{UG}	Min. Breakfree Force/surface area kN/cm^2 bF_{ore}^{UG}
Gravel	8	178.7	0.359	0.896	0.201
Granite	8	159.9	1.460	2.496	0.839
Coal	8	702.2	0.054	0.084	0.029
Gravel	5	283.3	0.165	0.374	0.058
Granite	5	251.4	0.364	0.894	0.111
Coal	5	1093.3	0.053	0.081	0.043

The difference between the breakfree friction and the ungraded ore static friction is calculated using the formula.

$$bF_{ore}^{UG} - sf_{ore}^{UG} = J_{ore} + DE_{ore} \tag{5.11}$$

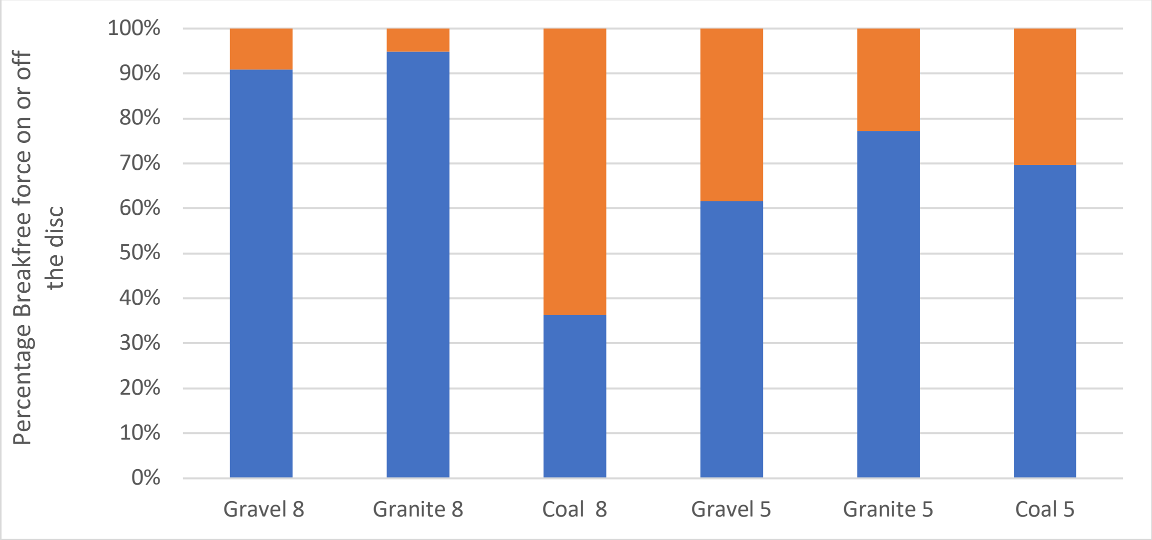
Where bF_{ore}^{UG} is the result of the total breakfree force divided by the ore tube contact area SA.

$$bF_{ore}^{UG} = BF_{ore}^{UG}/SA_{ore} \tag{5.12}$$

These results allow for the calculation of the percentage of the breakfree force for ungraded ore that relates to jamming. These are shown in red in the Table 24.

Table 24. Percentage of the breakfree friction resulting from forces acting at the disc caused by large pieces of irregular shaped ore ungraded ore.

Ore & tube size inches	Ave. Breakfree Force/surface area kN/cm^2 On the disc bF^{UG}_{ore} Table 27	Avg. Static Friction N/cm^2 sf^{UG}_{ore} Clear of the disc. On coal. Table 26	Jamming J_{ore} and disc effect DE_{ore} Eqn. (5.11)		Max. Breakfree Force/surface area kN/cm^2 On the disc bF^{UG}_{ore} Table 27	Max. Static Friction N/cm^2 sf^{UG}_{ore} Clear of the disc. On coal Table 26	Jamming J_{ore} and disc effect DE_{ore} Eqn. (5.11)		Min. Breakfree Force/surface area kN/cm^2 On the disc bF^{UG}_{ore} Table 27	Min. Static Friction N/cm^2 sf^{UG}_{ore} Clear of the disc. On coal Table 26	Jamming J_{ore} and disc effect DE_{ore} Eqn. (5.11)	
			N	%			N	%			N	%
Gravel 8	0.361	**0.063**	0.505	71.5	0.896	**0.077**	0.819	91.4	0.201	**0.050**	0.151	75.1
Granite 8	1.460	**0.080**	1.38	94.5	2.496	**0.084**	2.412	96.6	0.839	**0.067**	0.772	92.0
Coal 8	0.054	**0.095**	-0.041		0.084	**0.095**	-0.011		0.029	**0.079**	-0.050	
Gravel 5	0.165	**0.103**	0.062	37.5	0.374	**0.112**	0.262	70.1	0.058	**0.091**	-0.033	
Granite 5	0.364	**0.107**	0.257	70.6	0.894	**0.126**	0.658	73.6	0.111	**0.090**	0.021	18.9
Coal 5	0.053	**0.023**	0.030	56.6	0.081	**0.030**	0.051	63.0	0.043	**0.022**	0.021	48.8



Graph 4. Comparing the breakfree friction of ungraded ore on the elevator disc in blue and the static fiction of ungraded ore on top of 2mm coal.

For Graph 4 are tests where the ore sits above the coal off of the disc as shown in Figure 31. Data is drawn from Table 24.

These calculations demonstrate that for the effect of the jamming of ungraded ore can account for as much as 96.6 % of the resistance to the movement starting.

Results in Table 19 show that even for a small diameter cable disc elevator a very large cable would be required just to overcome the resistance of jamming because further effort is required to lift the ore.

This resistance is high enough to have a magnitude greater than the selected cables. However lower lift heights could be achieved successfully. Other cable tension components resulting from the cable weight and ore weight will add further to the load on the cable.

An interpretation of the above results is that jamming at the disc is the reason behind the high resistance to movement. This is observed by the samples of ore that were put on top of the low resistant fine 2mm granite in Pictures 29-35.

The next round of tests uses ore of separate particle size to understand the influence of these large particles on jamming.

5.13 Different Particle Sized Ore in the 8-inch Tube

The high resistance to movement for ungraded ore requires some investigation in order to determine what part of the ore is responsible for jamming. This is done by grading the ore various into different particle size groups.

In the following tests, ore is tested for the breakfree force BF_{ore} of various particle sizes. The separation of the ore is done by sieving the ore into a range of sizes.
These are ores: -

- Larger than 9.5mm.
- Between 5mm and 9.5mm.
- Between 5mm and 2mm.
- That pass through the 2mm screen.

This testing is done with an 8-inch (203.2mm). tube. For the selected ore particle sizes, the ore is separated by sieving the ungraded ore through the Endecott sieves and collecting the samples required.

Distribution of the particle sizes are shown in Tables 8, 9, 10 and 11. Ore samples are described in 5.10.1 gravel, 5.10.2 granite, and 5.10.3 for coal. All samples tested in the Table 25 below weigh 1000g. This allows for an equal comparison between the ores.

Table 25. Breakfree force for ore sizes 9.5+mm, 5.0-9.5mm, 2.0-5.0mm, less than 2.0mm. Sample size 1000g

Ore 1000g Tube dia. inches	Surface contact area of ore on the tube. cm^2 Table 17	Particle size mm	Avg. Breakfree Force N.BF_{ore}	Max. Breakfree -Force N. BF_{ore}	Min. Breakfree - Force N. BF_{ore}	Range for 10 samples N
gravel 8	166.0	9.5+	79.2	159.2	36.9	122.3
granite 8	191.5	9.5+	>205.5	>444.8	34.7	>410.1
coal 8	510.7	9.5+	28.2	44.9	10.7	34.2
gravel 8	172.4	5.0-9.5	55.2	155.7	34.7	121.0
granite 8	178.7	5.0-9.5	Jam			
coal 8	600.1	5.0-9.5	30.4	58.3	16.5	41.8
gravel 8	191.5	2.0-5.0	125.9	250.8	32.9	217.9
granite 8	166.0	2.0-5.0	Jam			
coal 8	555.4	2.0-5.0	27.6	36.9	23.1	13.8
gravel 8	166.0	≤2.0	14.7	20.9	3.6	17.3
granite 8	153.2	≤2.0	16.4	20.9	13.7	7.2
coal 8	574.6	≤2.0	9.3	11.7	8.0	3.7

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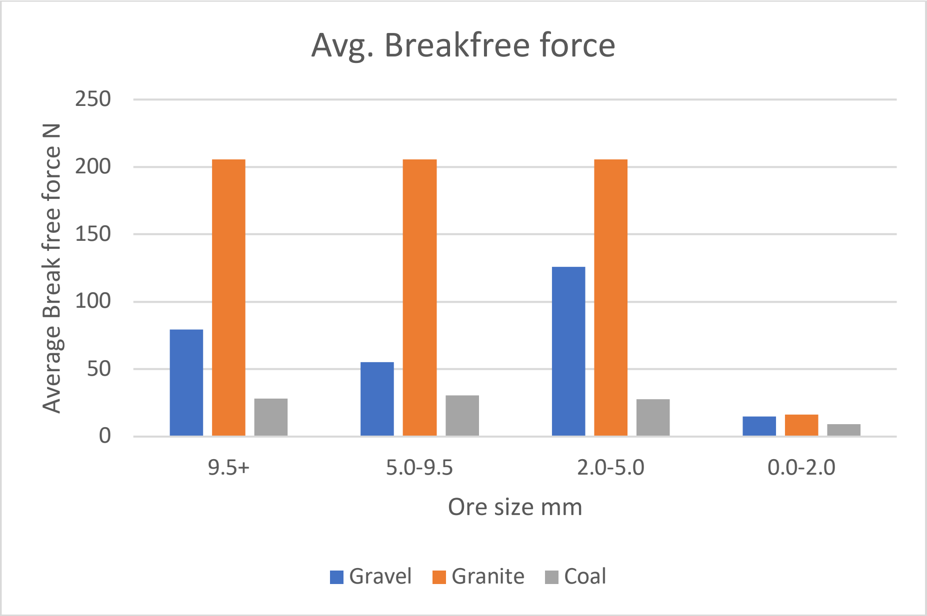
Sources for the data in Table 25 are listed below:

- Breakfree force $BF_{8ore}^{9.5+}$ for ore retained on a 9.5mm screen 1000g. 8-inch (203.2ID) tube. Maximum, minimum and average for 10 samples. Data from gravel Table 108, granite Table 140, and coal Table 141.
- Breakfree force $BF_{8ore}^{5-9.5}$ for ore through a 9.5 mm screen and retained on a 5mm screen 1000g. 8-inch (203.2ID) tube. Maximum, minimum and average for 10 samples. Data from gravel Table 107, and coal Table 139.
- Breakfree force BF_{8ORE}^{2-5} for ore through a 5 mm screen and retained on a 2mm screen 1000g. 8-inch (203.2ID) tube. Maximum, minimum and average for 10 samples. Data from gravel Table 106, and coal Table 138.
- Breakfree force BF_{8ORE}^{2} for ore through a 2mm screen and collected in the pan, 1000g. 8-inch (203.2ID) tube. Maximum, minimum and average for 10 samples. Data from gravel Table 101, granite Table 121, and coal Table 127



Graph 5. Average breakfree force for 1000 grams of ore for different particle sizes of gravel, granite, and coal. Data plotted from Table 29

Graph 5 displays the effect of jamming that has taken place with the larger size particles.

Coal had the least amount of jamming for the 9.5, 5.0-9.5, and 2.0-5.0 sizes. The larger coal particles tended to disintegrate, which aided sliding.

Gravel particles jamming, and some disintegrated, therefore in this case jamming was a significant part of the breakfree force.

Granite particles showed no tendency to shear or disintegrate. Where the particles were larger than the 2.5 mm gap between the disc and the tube these large wedge shape particles jammed and stopped the disc from moving. For Graph 7 the testing for granite was stopped and the maximum force that Test Rig 1 can safely apply is used, albeit the result would have been higher.

Particles smaller than the gap (i.e. 2.0 to 0.0 mm in size) all slide and the resistance to movement is then taken for the static friction force between the ore and the tube.

These results show that the effect of jamming is very important to be aware of as the consequence of jamming could cause the elevator to fail to breakfree when being restarted under a load of ore.

Our focus now turns to ore that has been sieved though a 2mm Endecott screen.

5.14 Testing 2mm Ore with Different amounts of Ore on the Disc for the 8-inch Tube

Testing then took place with ore that has passed through a 2mm sieve and which was retained on the sieve pan. Using ore with a particle size of below 2mm removes the effect of jamming $\mathrm{J_{ore}}$ as the particle size is less than the 2.5mm gap between the disc and the tube. It is important to develop testing and data that will allow this elevator to operate successfully. Large particle sizes that cause jamming now need to be discarded.

Hence, the breakfree force $\mathrm{BF^2_{8ore}}$ is the same as the static friction force $\mathrm{SF^2_{8ore}}$ between the ore and the tube.

$$\mathrm{BF^2_{8ore}} = \mathrm{SF^2_{8ore}} \tag{5.13}$$

$$\mathrm{bf^2_{8ore}} = \mathrm{sf^2_{8ore}} \tag{5.14}$$

when divided by the same surface area.

For the Dynamic Test Rig (Test Rig No.2), the distance between the discs has been selected at 250mm. This equates to 4000 discs for a 1000 metre lift. In this design, there is a volumetric maximum amount of ore that can be loaded onto each disc. This section examines the breakfree force effect for various ore loadings on the disc, which will further determine the cable tension strength requirement. Increasing the amount of ore on the disc increases the surface area contact between the ore and the tube. The increased weight of ore may also increase the side pressure between the ore and the tube on lower layers of ore resulting in an increase in static force between the lower levels of ore and the tube. This may also increase the amount of ore compaction between the disc and the tube resulting from added ore weight above the disc.

$$\mathrm{sf^2_{8Gv}} = \frac{\mathrm{BF^2_{8Gv}}}{\mathrm{SA}} \tag{5.15}$$

5.14.1 Gravel Less Than 2.0mm

Gravel less than 2mm in size is tested in the 8-inch tube and the breakfree force measured. The static friction is then calculated by dividing the breakfree force by the surface area contact between the ore and the tube, see equation 5.15. These results are in Table 26 and the breakfree force for gravel is taken from Appendix 1, data for 500g Table100, 1000g Table 101, 1500g Table 102, 2000g Table 103, 2500g Table 104, 3000g Table105. The ore surface area at the tube is taken from Table 13.

Table 26. Breakfree force for gravel less than 2mm in the 8-inch tube. Average, maximum, and minimum force

Ore wt. g.	Ore tube contact Surface area cm^2 Table 13	Avg. Breakfree Force N BF^2_{8Gv}	Avg. Static friction N/cm^2 sf^2_{8Gv}	Max. Breakfree Force N BF^2_{8Gv}	Max. Static friction N/cm^2 sf^2_{8Gv}	Min. Breakfree Force N BF^2_{8Gv}	Min. Static friction N/cm^2 sf^2_{8Gv}
500	83.0	15.1	0.18	31.6	0.38	3.1	0.04
1000	166.0	14.7	0.09	20.9	0.13	3.6	0.02
1500	249.0	23.5	0.09	31.1	0.12	13.3	0.05
2000	332.0	25.3	0.08	32.0	0.10	19.6	0.06
2500	414.0	28.5	0.07	35.1	0.08	21.7	0.05
3000	478.0	40.5	0.08	56.9	0.12	26.7	0.06

5.14.2 Granite Less Than 2.0mm

Gravel less than 2mm in size is tested in the 8-inch tube and the breakfree force measured. The static friction is then calculated by dividing the breakfree force by the surface area between the ore and the tube, see equation. 5.15. These results are in Table 27, the breakfree force BF^2_{8Gn} for granite results are taken from Appendix 1. Data for 500g Table120, 1000g Table 121, 1500g Table 122, 2000g Table 123, 2500g Table 124, 3000g Table 125. Ore surface area is from Table 13.

Table 27. Breakfree force for granite less than 2mm in the 8-inch tube. Average maximum and minimum force

Ore wt. g.	Ore tube contact Surface area cm^2 Table 13	Avg. Breakfree Force N BF^2_{8Gn}	Avg. Static friction N/cm^2 sf^2_{8Gn}	Max. Breakfree Force N BF^2_{8Gn}	Max. Static friction N/cm^2 sf^2_{8Gn}	Min. Breakfree Force N BF^2_{8Gn}	Min. Static friction N/cm^2 sf^2_{8Gn}
500	76.6	8.0	0.10	13.5	0.2	3.1	0.04
1000	153.2	16.0	0.10	20.8	0.14	8.0	0.05
1500	236.2	16.4	0.07	20.9	0.09	13.7	0.06
2000	312.8	18.7	0.06	23.6	0.08	12.9	0.04
2500	389.4	20.9	0.05	32.0	0.08	17.3	0.04
3000	466.0	21.8	0.05	28.5	0.06	22.7	0.05

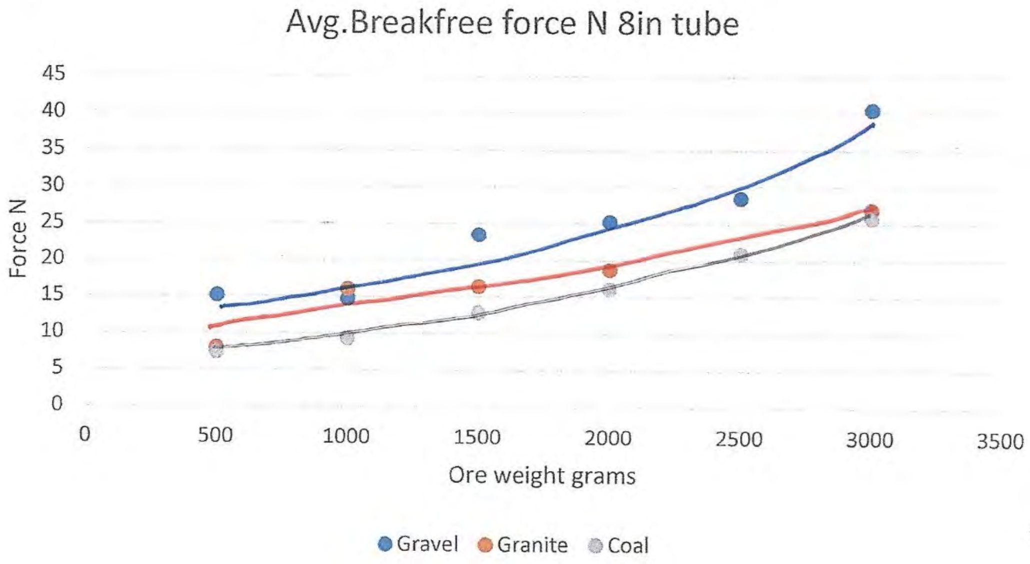
5.14.3 Coal Less than 2.0mm in Size

Coal breakfree force is measured up to 3000 grams, as per the other ores. Additional testing included the effect of increasing the weight of ore on the disc to 7000grams. This would require the discs in a cable tube elevator (as in Test Rig 2) to be further apart. The height of the ore for greater weight was measured and is shown in Table 13. Any distance greater than 250mm would require a greater separation between the discs. Here, coal less than 2mm in size is tested in the 8-inch tube and the breakfree force measured. The static friction is then calculated by dividing the breakfree force by the surface area between the ore and the tube, (as in equation. 5.15.

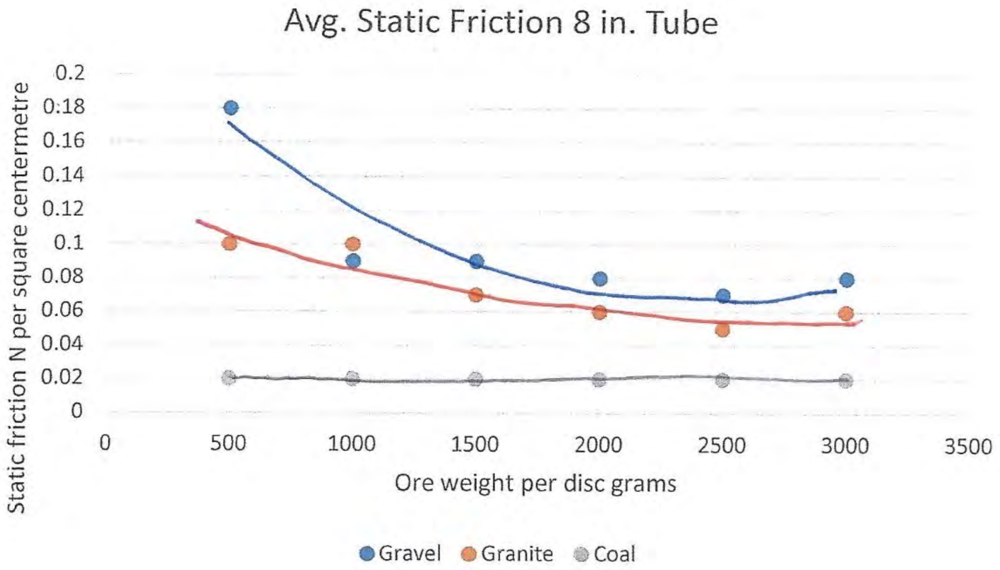
Table 28 is for coal 2mm size, Data for the various ore weights on the disc, data was taken from the tables in the Appendix 1 as listed here. For 500g Table126, 1000g Table 127, 1500g Table 128, 2000g Table 129, 3000g Table 130, 4000g Table 131, 5000g Table 132, 6000g Table 133, 7000g Table 134. The ore surface area is taken from Table 13.

Table 28. Breakfree force for coal less than 2mm in the 8-inch tube

Ore wt. g.	Ore tube contact Surface area cm^2 Table 13	Avg. Breakfree Force N $\mathrm{BF}^2_{8\mathrm{coal}}$	Avg. Static friction $\mathrm{N/cm}^2$ $\mathrm{sf}^2_{8\mathrm{coal}}$	Max. Breakfree Force N $\mathrm{BF}^2_{8\mathrm{coal}}$	Max. Static friction $\mathrm{N/cm}^2$ $\mathrm{sf}^2_{8\mathrm{coal}}$	Min. Breakfree Force N $\mathrm{BF}^2_{8\mathrm{coal}}$	Min. Static friction $\mathrm{N/cm}^2$ $\mathrm{sf}^2_{8\mathrm{coal}}$
500	383.0	7.4	0.02	10.2	0.03	6.2	0.02
1000	574.6	9.3	0.02	11.7	0.02	8.0	0.01
1500	766.1	12.8	0.02	13.8	0.02	9.8	0.01
2000	957.6	16.0	0.02	20.8	0.02	8.0	0.01
3000	1340.6	25.8	0.02	28.5	0.02	22.7	0.02
4000	1723.7	40.9	0.02	45.8	0.03	30.2	0.02
5000	2106.7	67.8	0.03	77.4	0.04	56.0	0.03
6000	2498.8	110.6	0.04	120.1	0.05	101.2	0.04
7000	2872.8	148.4	0.05	153.0	0.05	135.2	0.05



Graph 6. Breakfree force in the 8-inch tube. Data from Tables 26,27, and 28. Breakfree force increasing with weight on the disc.



Graph 7. Static friction as tested in the 8-inch tube. N/cm^2 Data from Tables 26,27, and 28.

5.15 Testing in a Small Diameter 5-inch Tube

This testing is done with ore that has passed through a 2mm sieve. Using ore below 2mm particle size removes the effect of jamming $\mathrm{JE_{ore}}$. Ore is tested using a 5inch(127mm) internal diameter tube. The disc diameter is 122mm leaving a gap between the disc and the tube of 2.5mm. This is the same gap for the 8-inch tube. The breakfree force is divided by the contact surface area between the ore and the tube as measured in Table 14.

Adapted from equation (5.15)

$$\mathrm{sf^2_{5Gv}} = \frac{\mathrm{BF^2_{5Gv}}}{\mathrm{SA}} \tag{5.16}$$

5.15.1 Gravel less than 2mm, Breakfree Force in the 5 Inch (127mm) Tube.

Data used in Table 29 for the gravel 2mm breakfree force $\mathrm{BF^2_{5Gv}}$ is from Appendix 2, Tables 160 - 165.

Table 29. Breakfree force for gravel less than 2mm in the 5-inch tube

Ore wt. g. Gravel	Ore tube contact Surface area cm^2 Table 14	Avg. Breakfree force N $\mathrm{BF^2_{Gv}}$	Avg. Static friction N/cm^2 $\mathrm{sf^2_{5Gv}}$	Max. Breakfree Force N $\mathrm{BF^2_{Gv}}$	Max. Static friction N/cm^2 $\mathrm{sf^2_{5Gv}}$	Min. Breakfree Force N $\mathrm{BF^2_{Gv}}$	Min. Static friction N/cm^2 $\mathrm{sf^2_{5Gv}}$
500	119.7	18.0	0.15	41.8	0.35	12.0	0.10
1000	231.4	43.1	0.19	52.9	0.23	31.1	0.13
1500	359.1	51.4	0.14	62.7	0.17	30.2	0.08
2000	438.9	89.6	0.20	104.0	0.24	66.3	0.15
2500	558.6	94.0	0.17	117.9	0.21	79.6	0.14
3000	637.3	136.8	0.21	170.4	0.27	109.9	0.17

5.15.2 Granite Less Than 2mm, Breakfree Force in the 5 Inch (127mm) Tube

Data for the breakfree force $\mathrm{BF^2_{5Gn}}$ in Table 30 is from Appendix 2 Tables 166-171

Table 30. Breakfree force for granite less than 2mm ore in the 5-inch tube

Ore wt. g. Granite	Ore tube contact Surface area cm^2 Table 14	Avg. Breakfree Force N. $\mathrm{BF^2_{5Gn}}$	Avg. Static friction N/cm^2 $\mathrm{sf^2_{5Gn}}$	Max. Breakfree Force N $\mathrm{BF^2_{5Gn}}$	Max..Static friction N/cm^2 $\mathrm{sf^2_{5Gn}}$	Min. Breakfree Force N $\mathrm{BF^2_{5Gn}}$	Min..Static friction N/cm^2 $\mathrm{sf^2_{5Gn}}$
500	99.8	16.9	0.17	25.8	0.26	9.3	0.09
1000	159.6	28.3	0.18	58.3	0.37	14.2	0.09
1500	259.4	44.0	0.17	111.6	0.43	20.0	0.08
2000	359.1	50.4	0.14	68.9	0.19	32.0	0.09
2500	438.9	54.9	0.13	81.1	0.18	42.3	0.10
3000	518.7	71.0	0.14	87.2	0.17	51.6	0.10

5.15.3 Coal Less Than 2mm, Breakfree Force in the 5-Inch (127mm) Tube.

In Table 31 breakfree force BF^2_{5coal} for coal, the data is from Appendix 2 Tables. 172 - 177

Table 31 Breakfree force for coal less than 2mm ore in the 5-inch tube

Ore wt. g. Coal	Ore tube contact Surface area cm^2 Table 14	Avg. Breakfree Force N BF^2_{5coal}	Avg. Static friction N/cm^2 sf^2_{5coal}	Max. Breakfree Force N BF^2_{5coal}	Max. Static friction N/cm^2 sf^2_{5coal}	Min. Breakfree Force N BF^2_{5coal}	Min. Static friction N/cm^2 sf^2_{5coal}
500	251.4	4.8	0.02	5.8	0.02	4.0	0.02
1000	498.8	10.8	0.02	13.3	0.03	8.5	0.02
1500	837.9	27.1	0.03	40.0	0.05	24.0	0.03
2000	1037.4	72.3	0.07	146.8	0.14	46.7	0.05
2500	1296.8	113.0	0.09	143.2	0.11	89.4	0.07
3000	1600.0	245.3	0.15	311.4	0.19	214.4	0.13

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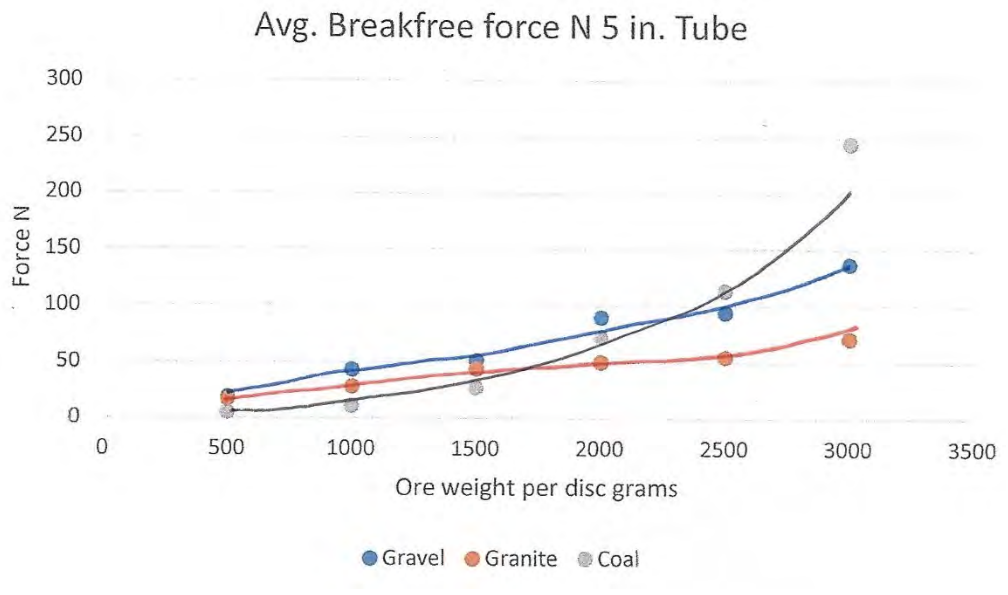
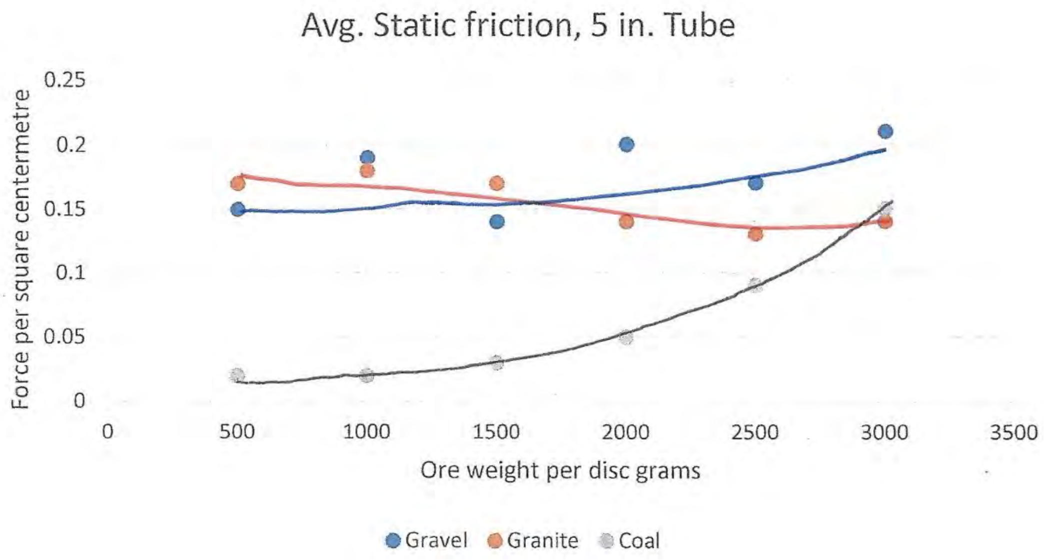


Graph 8. Breakfree force in the 5-inch tube. Data from Tables 29, 30 and 31.

Breakfree force increasing with weight on the disc.



Graph 9 Average static friction N/cm^2. for the ores in the 5-inch tube, data taken from Tables 29, 30, and 31.

5.16 Measuring the Static Friction for Coal when the Weight on the Discs is Increased to 7000 grams

When ore is loaded onto the disc there is downward pressure from the ore above. In this trial coal less than 2mm size is loaded in intervals to a maximum of 7000grams on the disc. This would not fit in the ore cell volume between the discs where the discs are only 250mm apart. This is to calculate what breakfree force increase occurs, and the effect of spreading the discs further apart. This trial also demonstrates the influence of the higher breakfree force at the disc. For each weight the results are a summary of 10 tests.

Data for Table 32 is taken from Appendix 1 Tables 126-134.

Table 32. Average static friction for coal in the 8-inch tube for 500 to 7000grams on the disc

Ore Coal wt. per disc grams	Ore tube contact Surface area cm^2 Table 13	Avg. breakfree force N BF^2_{8coal}	Increase in the Breakfree force N per each weight increase	Avg. Static friction N/cm^2 sf^2_{8coal}	%Increase in Static friction N/cm^2 for each weight increase	Height of ore on the disc. mm	Selected Disc separation mm	Number of discs for 1000 m tube	Avg. breakfree force kN BF^2_{8coal} 1000m.
500	383.0	7.4	7.4	0.02	0.0	60	250	4000	29.6
1000	574.6	9.3	1.9	0.02	0.0	90	250	4000	37.2
1500	766.1	12.8	3.5	0.02	0.0	120	250	4000	51.2
2000	957.6	16.0	3.2	0.02	0.0	150	250	4000	64.0
3000	1340.6	25.8	9.8	0.02	0.0	210	250	4000	103.2
4000	1723.7	40.9	15.1	0.02	0.0	270	500	2000	81.8
5000	2106.7	67.8	26.9	0.03	33.0	330	500	2000	135.6
6000	2498.8	110.6	42.8	0.04	25.0	390	500	2000	221.2
7000	2872.8	148.4	37.8	0.05	20.0	450	500	2000	296.8

5.17 Static Friction Force Calculated for 1000m Elevator and, Total Ore to Tube Contact Surface Area

The table below uses the static friction in the 8-inch tube for the three ores to project the total static friction force (breakfree force) for ore with a particle size of 2mm or less, on a 1000 metre lift with variable weights of ore on each disc. These results are not adjusted for the cable volume in the tube. This simple calculation below multiplies the existing data by 4000. Ore height used in Table 33 above is taken from Table 13. Breakfree force data is from Tables 26 for gravel, Table 27 for granite and Table 28 for coal.

Table 33. Comparison of static friction force for a 1000m elevator with 4000 discs for 3 different ores in the 8-inch tube

Ore wt. per disc g.	Ore type	Ore tube contact Surface area cm^2 per disc Table 17	Total ore tube contact Surface area for 4000 discs m^2	Height of ore on the disc. mm	Avg. Breakfree Force per disc N BF^2_{8ore}	Avg. Static friction per disc N/cm^2 sf^2_{8ore}	No. of disc's at 250mm centres	Avg. breakfree force kN BF^2_{8ore}= SF^2_{8ore} for 1000m
500	Gravel	83.0	33.2	13	15.1	0.18	4000	60.4
1000	Gravel	166.0	66.4	26	14.7	0.09	4000	58.8
1500	Gravel	249.0	99.6	39	23.5	0.09	4000	94.0
2000	Gravel	332.0	132.8	52	25.3	0.08	4000	101.2
2500	Gravel	414.0	165.6	65	28.5	0.07	4000	114.0
3000	Gravel	478.0	191.2	78	40.5	0.08	4000	162.0
500	Granite	99.8	39.2	12	8.0	0.08	4000	32.0
1000	Granite	153.2	61.3	24	16.0	0.10	4000	64.0
1500	Granite	236.2	94.5	37	16.4	0.07	4000	65.6
2000	Granite	312.8	125.1	49	18.7	0.06	4000	74.8
2500	Granite	389.4	155.8	61	20.9	0.05	4000	83.6
3000	Granite	466.0	186.4	73	21.8	0.05	4000	87.2
500	Coal	383.0	153.2	60	7.4	0.02	4000	29.6
1000	Coal	574.6	229.8	90	9.3	0.02	4000	37.2
1500	Coal	766.1	306.4	120	12.8	0.02	4000	51.2
2000	Coal	957.6	383.0	150	16.0	0.02	4000	64.0
3000	Coal	1340.6	536.2	210	25.8	0.02	4000	103.2

5.18 Static Friction Force Calculated for a full 8-inch Tube

When the cable is carrying the maximum amount of ore that can theoretically fit between the discs, the tube is fully loaded and the maximum ore to tube contact is reached. Using the results for static friction in N per $\mathrm{cm}^2$of the ores at 3000grams per disc, the total friction force is calculated using the maximum surface area contact between the ore and the tube to calculate the load on the cable. This maximum friction load is shown in the right-hand side column. The surface contact area between the discs is 1596 cm^2 or a total contact surface area of 638.4 m^2 for a 1000metre tube.

The surface area for an 8-inch (203.2mm) diameter tube, 1000 metres long elevator is calculated using the following equation.

$$SA = h \,.\, \pi \quad D \tag{5.17}$$

$$SA = 1000m \text{ x } \boldsymbol{\pi} \text{ x } 0.2032(\text{Diameter m})$$
$$SA=638.4m^2$$

An example calculation in Table 34 below is for coal.

The static friction for coal is 0.02 $\mathrm{N/cm}^2$, from Table 37.

Then the static friction force is;

$$SF^2_{8coal}= 638.4 \text{ m}^2 \, x \, 0.2 \text{ N}$$

$$= 127.7 \text{ N},$$

Where the static friction is 0.05 $\mathrm{N/cm}^2$ or 0.5 $\mathrm{kN/m}^2$ for a full elevator with 500mm disc spacings the total Static Friction Force is the static friction force can be calculated from equation 5.15.

$$SF^2_{8coal} = SA \, x \, sf^2_{8coal} \tag{5.18}$$

$$SF^2_{8coal}= 638.4 \text{ m}^2 \, x \, 0.5 \text{ kN}$$

$$SF^2_{8coal}= 319 \text{ kN}$$

In Table 34 the surface area and height of the ore in the tube is taken from Table 13, and the breakfree force from Table 33. The maximum weight that can be placed between the discs is based on the maximum height being 250mm and the ore density.

Table 34. Theoretical maximum static friction force when the lifting tube is fully loaded. * Maximum theoretical ore weight that can be placed between the discs

Ore wt. per disc g.	Ore type	Ore tube contact Surface area per disc cm^2	Total ore tube contact Surface area for 4000 discs m^2	Height of ore on the disc. mm	Avg. Breakfree Force per disc N $\text{BF}^2_{8\text{ore}}$	Avg. Static friction N/cm^2 $\text{sf}^2_{8\text{ore}}$	No. of disc's at 250mm centres	Avg. breakfree force kN $\text{BF}^2_{8\text{ore}}$= $\text{SF}^2_{8\text{ore}}$ 1000m
3000	Gravel	478.0	191.2	78	40.5	0.08	4000	162.0
*9615		1596.0	638.4	250	129.8	0.08	4000	519.2
3000	Granite	466.0	186.4	73	21.8	0.05	4000	187.1
*10296		1596.0	638.4	250	74.8	0.05	4000	299.3
3000	Coal	1340.6	536.2	210	25.8	0.02	4000	103.2
*3571		1596.0	638.4	250	30.7	0.02	4000	122.8

5.19 Testing Ores in the 8-Inch Tube with Different Amounts of Water Added

This testing for the breakfree force in the 8-inch tube is to simulate a situation in the mine where free water may dampen or flood the ore. The water may be from hosing a face, scraped off the bottom of an ore pile where there is free water. Free water is not part of the chemically valance bonded water that makes up part of the normal ore moisture. The results and knowledge of the impact of free water may help to determine how the ore and water are handled in the mine. All testing for is for wetted ores using the 8-Inch (203.2mm) tube.

In Table 35, the results are for wet gravel breakfree force $\text{WBF}^2_{8\text{GV}}$ where a 100g of water is added per 1000g of ore. This data is taken from Appendix 1 Tables**.** 109 to 112. Data for the addition of 200g of water per 1000g of ore is taken from Appendix 1 Tables.114, to 118. Data the addition of 300g of water per 1000g of ore is taken from Appendix 1 Table119.Table 113 for 5000g of gravel with 500g of water was for 3 samples.

The sample of 1000g of ore with 300g of water was flooded with water pooling on the top of the ore and draining from the base. It was not practical to test samples with greater amounts of water.

5.19.1 Gravel Particle Less Than 2mm In Size. Breakfree Force with Added Water

Table 35. Wet gravel breakfree force for particle size less than 2mm

Ore wt. g.	Water added wt. g.	%	Avg. Breakfree force N WBF^2_{8GV}	Max. Breakfree force N WBF^2_{8GV}	%Above Avg.	Min. Breakfree force N. WBF^2_{8GV}	% Below Avg.	Range for 10 Samples
1000	100	10	22.1	33.4	51.1	15.6	29.4	17.8
2000	200	10	34.5	48.9	41.7	21.4	38.0	27.5
3000	300	10	40.9	52.5	30.6	34.3	16.1	18.2
4000	400	10	52.9	70.3	17.4	49.8	5.9	20.5
5000	500	10	67.6	76.5	13.2	60.1	9.9	n/a
1000	200	20	26.1	35.6	36.4	15.1	42.1	20.5
2000	400	20	39.2	58.7	49.7	32.0	18.4	26.7
3000	600	20	66.3	83.2	25.5	56.0	15.5	27.2
4000	800	20	81.6	104.1	27.6	59.6	27.1	44.5
5000	1000	20	100.5	135.6	34.9	72.1	28.3	63.5
1000	300	30	24.2	47.6	96.7	17.2	28.9	30.4

5.19.2 Granite Particle Size less than 2mm. Breakfree Force with Added Water

Table 36 shows the results for the wet granite breakfree force WBF^2_{8Gn}, data for the addition of 100g of water per 1000g of ore is taken from the Appendix 1, Tables.152, to 155. Data for water addition of 200g per 1000g of ore is taken from Appendix 1 Table 156.

Table 36. Wet granite breakfree force for particle size less than 2mm

Ore wt. g.	Water added g.	%	Avg. wet Breakfree force N WBF^2_{8Gn}	Max. wet Breakfree Force N. WBF^2_{8Gn}	% Above Avg	Min. wet Breakfree Force N. WBF^2_{8Gn}	% below Avg	Range for 10 Samples
1000	100	10	29.7	50.1	68.7	14.2	48.8	35.9
2000	200	10	38.7	72.1	86.3	21.4	44.7	50.7
3000	300	10	47.9	59.6	24.4	43.1	10.0	16.5
4000	400	10	60.0	68.5	14.2	48.9	18.5	19.6
1000	200	20	33.9	55.6	64.0	17.8	47.5	37.8

5.19.3 Coal Particle Size Less than 2mm. Breakfree Force with Added Water

Table 37 are the results for the wet breakfree force $\mathrm{WBF}^2_{8\mathrm{coal}}$ for coal. Data for water addition of 100 grams per 1000g of ore is taken from Appendix 1 Tables. 142, to 146. Data for water addition of 200g per 1000g of ore is taken from Appendix 1 Tables 147, to 150. It can be seen from this data that the added water increased the static friction force $\mathrm{SF}_{\mathrm{ore}}$ and the disc effect $\mathrm{DE}_{\mathrm{ore}}$.

Table 37. Wet coal breakfree force for particle size less than 2mm

Ore wt. g	Water added g.	%	Avg wet. Breakfree force N. $\mathrm{WBF}^2_{8\mathrm{coal}}$	Max. wet Breakfree Force N $\mathrm{WBF}^2_{8\mathrm{coal}}$	% Above Avg.	Min. wet breakfree Force N $\mathrm{WBF}^2_{8\mathrm{coal}}$	% Below Avg	Range for 10 Samples
500	50	10	6.8	9.3	36.8	3.6	47.1	5.7
1000	100	10	14.6	16.0	9.6	11.6	20.5	4.4
2000	200	10	34.4	45.8	33.1	24.9	27.6	20.9
3000	300	10	38.3	47.2	18.9	23.6	38.4	23.6
4000	400	10	74.4	98.8	32.8	61.4	17.5	37.4
1000	200	20	24.7	68.5	177.3	13.3	46.2	55.2
2000	400	20	39.2	43.1	9.9	26.7	31.9	16.4
3000	600	20	54.7	80.5	47.2	36.0	34.2	44.5
4000	800	20	45.4	101.0	122.5	15.6	65.6	85.4

5.19.4 Ore Static Friction Comparison of Dry Ore versus Wet Ore for Gravel, Granite and Coal in the 8-Inch Tube

In Table 38 Data for wet ore is taken from Tables 34, to 36. Data for the dry ore is from Tables 29, to 31. For the three ores in the Table 38-40, below data is compared and the percentage influence on the static friction is calculated and shown in the right-hand column.

Table 38. Static friction comparison for dry and wet gravel in the 8-inch tube

Ore weight g	Water added g	Ave. Breakfree force $\mathrm{WBF}^2_{8\mathrm{Gv}}$ N	Surface area SA cm^2 Table 17	Static Friction $\mathrm{wsf}^2_{8\mathrm{Gv}}$ $\mathrm{N/cm}^2$	Dry ore Static Friction $\mathrm{sf}^2_{8\mathrm{Gv}}$ $\mathrm{N/cm}^2$	Percent increase in Static friction from added water $\mathrm{sf}^2_{8\mathrm{Gv}}$
1000	100	22.1	197.8	0.11	0.09	22
2000	200	34.5	338.1	0.10	0.08	25
3000	300	40.9	504.0	0.08	0.08	0
1000	200	26.1	121.2	0.22	0.09	144
2000	400	39.2	268.0	0.15	0.08	88
3000	600	66.3	376.4	0.18	0.08	125

Further observations for the Tables 38, 39 and 40 where water was added are as follows:

- There was a limit at which the amount of water in each ore resulted in the ore being too sloppy to handle, or when it was dropped onto the disc the water separated and floated to the top and pooled on the sample. Results in the above tables are of tests where this did not happen; the addition of further water would have led to water pooling on top of the sample.
- Coal was viscus. This may have resulted from the coal being young (15-25 million years old), there is still some visible tree bark fibre to further react to the water alongside with other forms of carbon.
- Most results showed an increase in static friction with an increase in water content.
- Static friction results were more variable for the wet ore.

Table 39. Static friction comparison for dry and wet granite in the 8-inch tube

Ore weight g	Water added g	Ave. Breakfree force WBF^2_{8Gn} N	Surface area SA cm^2 Table 17	Static Friction wsf^2_{8Gn} N/cm^2	Dry ore Static Friction sf^2_{8Gn}	Percent increase in Static friction from added water sf^2_{8Gn}
1000	100	29.7	159.5	0.19	0.10	90
2000	200	38.7	287.1	0.13	0.06	117
3000	300	47.9	453.0	0.11	0.06	83

Table 40. Static friction comparison for dry and wet coal in the 8-inch tube

Ore weight g	Water added g	Ave. Breakfree force WBF^2_{8coal} N	Surface area SA cm^2 Table 17	Static Friction wsf^2_{8coal} N/cm^2	Dry ore Static Friction sf^2_{8coal}	Percent increase in Static friction from added water sf^2_{8coal}
1000	100	14.6	383.2	0.04	0.02	100
2000	200	34.4	733.7	0.05	0.02	150
3000	300	38.3	1078.2	0.04	0.02	100
4000	400	74.4	1582.2	0.05	0.03	67
1000	200	24.7	306.2	0.08	0.02	300
2000	400	39.2	510.4	0.08	0.02	300
3000	600	54.7	803.9	0.07	0.02	250
4000	800	45.4	1059.1	0.04	0.03	33

5.20 Calculation of the Vertical Lifting Distance

This section what lifting distance that could be achieved using the three selected cables, Dyform 34, 6AR and Goldstrand as specified in Tables 4, 5 and 6. There is an adjustment made for the ore/tube contact surface area for different cable diameters as these cables occupy different volumes and ore is displaced.

Ore height adjustment in the tube is required for the larger cables which can be theoretically used to achieve large lifting heights. The cables selected occupy some of the volume in the ore cell between the discs.

Analysis for ore packing density took place with no cable present. The cable in Test Rig 1 is 3mm in diameter, and the volume of the cable in the ore lifting cell is 1.77 cm^3,compared to the cell itself, which is 250mm long with a 203.2mm diameter, and a volume of 8107.3 cm^3. Hence, the reduction effect on the volume of the cell by the testing cable is 0.022%.

When measuring the ore height, a change in volume of 0.022% represents a variation in height variation of 0.07mm. The height of the ore in the tube was measured at 1 mm intervals. As 0.07mm is not measurable in these tests, the volume effect of the lifting cable in Test Rig 1 is considered irrelevant. This is not the case for the 40, 50, and 75mm cables.

The influence of the 3 selected cable volumes on ore tube contact surface area is calculated as per the equations below. The following symbols shown in Table 41 are used in this section for the calculation of ore surface area adjusted after taking into consideration of the cable volume.

Table 41. List of symbols for calculations in Section 5.2

Symbol	item	Unit of measurement
R	Radius	cm
R_1	Radius of the tube	cm
R_2	Radius of the cable	cm
h	Height of ore on the disc	cm
ρ	Ore density	grams/cm^3
v	Volume of ore on the disc	cm^3
SA	Contact surface area between the ore and the tube	cm^2
m	Weight of ore on the disc	grams
SF	Static Friction force	N
sf	Static Friction	N/cm^2
C	Circumference	cm
D	Tube diameter	cm

When there is a cable in the tube holding the lifting disc, that cable occupies volume and displaces some of the ore. For a given weight and bulk density of the ore the volume of the ore is constant hence the variable is the height of the ore in the tube. Increasing the height in the tube increases the ore tube surface area.

The volume of ore in the tube with the cable occupying some of that volume results in the ore fill being higher in the tube, creating a larger surface area contact with the tube and a lower available cell volume for ore.

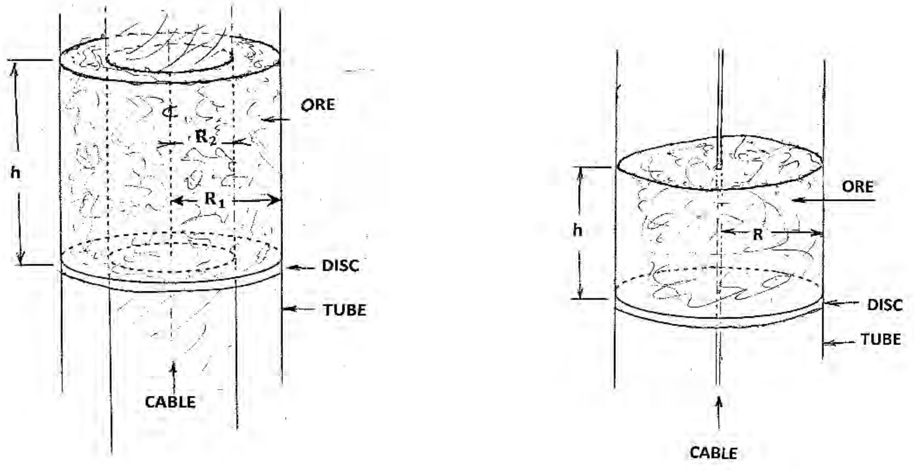


Figure 32. Change of ore height in the tube for a fixed ore volume when the cable volume is added.

5.20.1 Volume of Ore in the Tube.

Volume of ore $\quad v = \pi \ (R_1^2 - R_2^2) \ . \ h \quad \text{cm}^3 \quad (5.18)$

Example calculation for the 8-inch tube (203.7mm diameter) using the 40mm diameter cable. The volume of ore is calculated using equation 5.18

Volume of ore $\quad v = \pi \ (10.16_1^2 - 2.0_2^2) \ x \ 25 \quad \text{cm}^3$

$= 7796.3 \text{ cm}^3$

Or at 80% full $\quad = 6327.0 \text{ cm}^3$

Volume of ore in the 5 inch tube,40mm cable $\quad v = \pi \ (6.35_1^2 - 2.0_2^2) \ x \ 25 \quad \text{cm}^3$

$= 2853.9 \text{ cm}^3$

At 80% full $\quad = 2283.1 \text{ cm}^3$

5.20.2 Surface Area Displacements for the 3 Selected Cables Calculated on Ore Weight. and Ore Density.

From equation 4.04 the density of the ore $\rho = \frac{m}{v}$ g/cm^3

Substituting for volume v, from equation 5.18 the, density can be shown as:

density $$\rho = \frac{m}{\pi\ (R_1^2 - R_2^2)\ h} \text{g/cm}^3 \quad (5.19)$$

Re arranging the equation for height, then;

Ore height in the tube $$h = \frac{m}{\pi\ (R_1^2 - R_2^2)\ \rho} \quad (5.20)$$

Surface area SA of ore on the tube is from equation (4.01) SA = h x π x D cm^2

Substituting the ore height h into equation 4.1 the increased ore tube surface contact area SA resulting from the displacement of volume by the cable is;

$$SA = \frac{m}{\pi\ (R_1^2 - R_2^2)\ \rho}\ \pi\ D \quad (5.21)$$

Simplifying the equation 5.21 $$SA = \frac{m\ x\ D}{(R_1^2 - R_2^2)\rho}\ \text{cm}^2 \quad (5.22)$$

5.20.3 Ore/Tube Contact Surface Area Adjusted for Cable Displacement in the 8-Inch Tube.

Example calculation.

Using the endurance Dyform 34LR cable.

D is 20.32 cm
R_1 is 10.16 cm
R_2 is 2.0 cm

Calculating the contact surface area for the ore using equation 5.22:

$$SA = \frac{m\ x\ 20.32}{\rho\ (10.16^2 - 2^2)}$$

Dyform 34. 40mm cable $$SA = 0.204\ \frac{m}{\rho}\ \text{cm}^2 \quad (5.23)$$

Endurance Dyform 6AR using the same calculation the surface area is.

Dyform 6AR 50 mm cable $SA = 0.210 \frac{m}{\rho}\ cm^2$ (5.24)

Gold Strand 75mm cable $SA = 0.228 \frac{m}{\rho}\ cm^2$ (5.25)

5.20.4 Ore/Tube Contact Surface Area Adjusted for Cable Displacement in the 5-Inch Tube.

Only the Endurance Dyform 34LR. cable is considered at 40mm diameter. The other two selected cables would occupy a large percentage of the available cell volume between the discs and hence, are not considered.
Using formula 5.22;

Dyform 34LR. 40mm cable $SA = 0.35 \frac{m}{\rho}\ cm^2$ (5.26)

Surface contact area between the ore and the tube is now calculated using formula 5.2.1 for ore of weights of 1000, 2000 and 3000g per lifting disc. These are shown in Table 42 below.
The maximum surface area between discs when on the cable at 250mm centres is calculated below using equation 4.1.

5.20.5 Maximum Tube Surface Area Available in the Cell Between the Discs

From equation 4.01 $SA = \pi\ D\ h\ cm^2$

For the 8-inch tube (203.2mm Diameter) the maximum ore height available is 250mm (25.0 cm), meaning that the ore tube contact surface area is:

$$SA = \pi\ 20.32 \times 25\ \ cm^2$$
$$SA = 1595.93\ cm^2$$

At 80% loading efficiency $SA = 1276.74\ cm^2$

For the 5-inch tube (127.0mm Diameter), the maximum ore height available is 250mm (25.0 cm), and the ore tube's maximum available contact surface area.

$$SA = \pi\ 12.7 \times 25\ \ cm^2$$
$$SA = 997.46\ cm^2$$

At 80% loading efficiency: $SA = 797.96\ cm^2$

Tension resulting from the static friction sf between the ore and the tube is calculated by multiplying the static friction by the surface area. From equation 5.18, the tension force is the static friction N/cm^2:

$$SF = sf \times SA \quad N \tag{5.27}$$

5.20.6 Adjusted Tensions T_{SF} for the Increase in Surface Area (SA).

The values for the average static friction for gravel, granite and coal in the 8-inch tube are taken from Table 33.

For the 5-inch tube the static friction values are taken from Table 29 for gravel, Table 30 for granite and Table 31 for coal.

Test Rig 1 is a single disc test rig that allows the disc to have an amount of ore greater than the amount of ore that would fit into a 250mm long cell. This has been useful for establishing the effect that having the discs further apart would have.

In Table 42 the 1000, 2000, and 3000-g samples of ore can fit into a 250mm long ore cell except for the 5-inch tube where the ore volume for the weight is greater than the cell volume between the discs. Granite at 3000 grams would occupy 826.77 cm^2 surface area, however the limit set at 80% of available space then the maximum surface area available is 797.96 cm^2. Static friction for that was determined for the ore at 3000g is used.

Table 42. Calculations of the static friction force SF, N per disc

.	Gravel ρ =1.19ρ			Granite ρ= 1.27			Coal ρ=0.44		
Static Friction sf N/cm^2	0.09	0.08	0.08	0.10	0.06	0.04	0.02	0.02	0.02
8-inch tube	1000 g	2000 g	3000 g	1000 g	2000 g	3000 g	1000 g	2000 g	3000 g
40mm cable									
SA= 0.204 w/ ρ per disc	171.42	342.86	514.28	160.63	321.26	481.89	463.64	927.27	1390.90
Max.SA @ 80% cm^2	1276.74	1276.74	1276.74	1276.74	1276.74	1276.74	1276.74	1276.74	1276.74
Static Friction Force SF N per disc	15.43	27.43	41.14	16.06	19.28	19.28	9.27	18.55	27.82
50mm cable									
SA= 0.210 w/ ρ per disc	176.47	352.94	529.41	165.35	330.71	496.06	477.27	954.55	1431.82
Max. SA@ 80% cm^2	1276.74	1276.74	1276.74	1276.74	1276.74	1276.74	1276.74	1276.74	1276.74
Static Friction Force SF N per disc	15.88	28.24	42.35	16.54	19.84	19.84	9.55	19.09	28.64
75mm cable									
SA= 0.228 w/ ρ per disc	191.60	383.19	574.79	179.53	359.06	538.58	518.18	1036.36	1554.55
Max. SA @ 80% cm^2	1276.74	1276.74	1276.74	1276.74	1276.74	1276.74	1276.74	1276.74	1276.74
Static Friction Force SF N per disc	17.24	30.66	45.98	17.95	21.54	21.54	10.36	20.72	31.09
5-inch tube 40mm cable	ρ =1.37			ρ =1.79			ρ =0.60		
Static Friction sf N/cm^2	0.19	0.20	0.21	0.18	0.14	0.14	0.02	0.07	0.15
SA= 0.350 w/ ρ per disc	255.47	510.95	766.42	195.59	391.06	586.59	583.33	1166.67	1750.00
Max.SA @ 80% cm^2	797.96	797.96	797.96	797.96	797.96	797.96	797.96	797.96	797.96
Static Friction Force SF N per disc eqn. (5.27)	48.54	102.19	160.94	35.10	54.75	82..09	11.67	55.86 *81.67	119.69 *262.50

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Table 42 shows the ore /tube contact surface area cm^2 for adjusted volume of the lifting cable. Ore densities averages are used from Tables 13 and 14.

A similar adjustment for coal in the 5-inch tube for the 2 and 3 kg example. The amount of coal has to be reduced to fit in the 80% volume of the ore cell between the discs. The numbers in red represent what the friction would be if that for 2000, and 3000g was applied.

5.21 Lifting Distance Based on Static Friction

The lifting distance that a cable disc elevator can lift is a balance between the safe lifting tension available from a cable and the total of the forces that oppose lift. There are two themes in this section. One is to evaluate the tension required for various lifting distances, and the other is to establish the safe lifting distance for the cables that were selected as examples in Tables 4 to 6.

5.21.1 Cable Tensions T_{max}, T_1, T_2, T_e^L

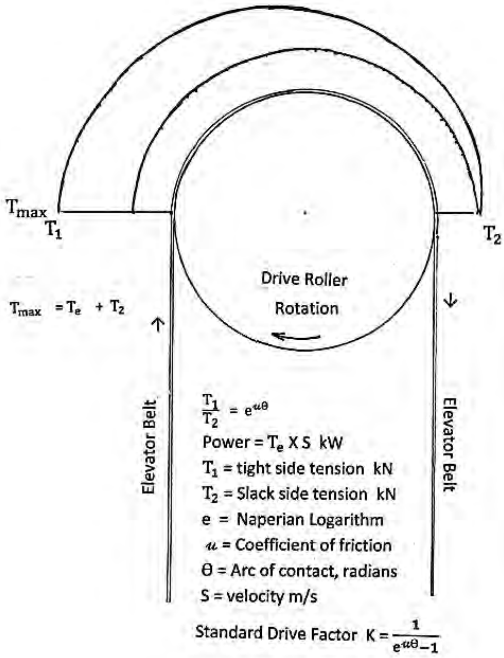

Figure 33. Tensions for the drive sheave resulting from the static friction force (Metlikovic 2006).

T_{max} is the maximum tension that is exerted on the cable at any one time.

For Test Rig 1, $T_{max} = T_1$

T_2 is the tension of the cable at the downward side of the elevator. There is no lifting effort and no ore on the cable. Hence T_2 is a result only from the weight of the cable.

T_e^f is the tension required to overcome the static friction force. This equals the static friction force (breakfree force).

T_e^L is the tension required to overcome gravity. That is the weight of ore on the discs resulting from the force of gravity at $9.81 m/s^2$.

The equation for the total cable tension on the lifting side of the elevator is given in equation 5.06.

Total cable lifting tension $$T_1 = T_e^f + T_e^L + T_2 \quad (5.06)$$

5.21.2 Calculation the Tension Contribution from the Cable Weight

Cables are selected from Tables 4-6.

The disc weight has been selected at 250 grams with the swage. There are 4 discs per metre at 250mm centres on the cable.

$$T_2 = m.g \quad (5.07)$$

Table 43. Assembled cable weight and cable tension T_2 for the three selected hoisting cables

	Endurance Dyform 34LR	Endurance Dyform 6AR	Gold Strand
Cable weight m per meter kg	8.00	11.00	24.70
Disc weight per metre. kg	1.00	1.00	1.00
Total assembled Cable weight per metre.kg	9.00	12.00	25.70
Tension load per metre. N	88.29	117.72	252.12
T_2 kN per metre	0.088	0.118	0.252

5.21.3 Calculation of the Tension from Ore Weight T_e^L on the Cable.

These tension loadings are based on 1, 2, and 3 kg of ore on the disc. The number of discs is selected at 4 per metre or 4000 discs for 1000m of cable.

Applying equation 2.07 where the acceleration is that of gravity, then:

$$T_g^L = m.g \quad (5.08)$$

The ore loading is calculated and shown in Table 44.

Table 44. Ore weight loading for one metre of cable

Ore weight m per disc kg	1.00	2.00	3.00
Ore weight m per metre kg	4.00	8.00	12.00
T_e^LTension load for ore at 1m N	39.24	78.48	117.72
T_e^LkN ` x 10^{-2}per metre	3.9	7.9	11.8

5.21.4 Calculation for Cable Tension T_e^f Resulting from Static Friction in the 8-Inch Tube

The static friction force is shown below in Table 45 for ore loaded on the disc at 1000g, 2000g, and 3000g. at 100m intervals to 1000m. The breakfree force is taken from Table 33 where there is no jamming of the ore, then the break free force equals the static friction force and the tension T_e^f required for the cable results from static friction. There are 4 discs per metre as the disc spacing is 250mm. Calculation for cable tension T_e^f resulting from static friction in the 8-inch tube
T_e^f the cable tension, for one metre, is the cable tension required for one-disc times 4 when each is 250mm apart and is taken from Table 33, where 1 N = 0.001kN.

Table 45. 40mm cable. Tension to overcome static friction for gravel, granite and coal in the 8-inch tube at 1000, 2000 and 3000g per disc for one metre

Ore	Gravel			Granite			Coal		
Ore weight per disc g	1000	2000	3000	1000	2000	3000	1000	2000	3000
BF_{8ore}^2=SF_{8ore}^2=T_e^f per disc N	15.4	27.4	41.4	16.1	19.3	19.3	9.3	18.6	27.8
T_e^f for 1m. N	61.7	109.7	165.6	64.2	77.1	77.1	37.2	74.4	111.3
T_e^f kN x 10^{-2} per metre	6.2	11.0	16.6	6.4	7.7	7.7	3.7	7.4	11.1

5.21.5 Calculation for the Total Cable Tension T_1 kN at various Depths

Tables 46, to 49 shown the distance which the selected cables can lift ore at the nominated weights. (1000, 2000, and 3000 g per disc).

Although, these nominated weights are based on the weights that were loaded on the single disc in Test Rig 1, they do not imply that there is sufficient volume in the cell between the to discs to fit the volume of ore these weight would occupy.

The lifting distances are projected in 100m intervals in black for the selected cable. Distances beyond the capability of these cables are shown in green. There are many cables that could be selected that may have the tension strengths required to lift from these greater distances. The lifting distance is calculated from the cable capability in Newtons divided by the maximum tension T_1.

From equation (5.06) $T_1 = T_e^L + T_2 + T_e^f$ N

The data is taken from Table 49 for T_e^f the working tension resulting from friction,

Table 48 for the working tension from the ore weight T_e^L. i.e. the effect of gravity,
and Table 47 for the working tension from the weight of the lifting cable T_2.

The sum of these tensions gives the maximum tension for T_1 load on the cable in Newtons for one metre.
The maximum distance the cable can then lift is calculated by:

Lifting distance $\frac{\text{Cable safe tension N}}{\mathrm{T_1 \;\; N/m}}$; (5.28)

An example calculation can be made for a 40mm cable at 219kN capacity with the FoS 6.67 and 1 kg of gravel per disc.

From Table 48 T_e^L = 39.24 N/m.

From Table 47 T_2. = 88.29 N/m

And from Table 49 T_e^f = 61.70 N/m

Then using eqn. 5.06 T_1 = 39.24 +88.29 + 61.70
T_1 = 189.23 N/m

Lifting distance using eqn. 5.28 $\mathrm{LD} = \frac{219{,}000\ \mathrm{N}}{189.23\ \mathrm{N/m}}$

LD = 1156m

In Table 46 the lifting side of the cable tension T_1 is calculated using equation (5.06) and the data is shown in Tables 47-49. This includes the tension required for the cable and discs, ore weight on the cable and the tension required for friction. The calculated tensions shown in green are out of the selected cable safe tension load range.

Table 46. Gravel T_1 calculation of cable tension for lifting depths for the 8-inch tube. The green tensions are beyond the cable scope

	GRAVEL								
Lifting cable Safe working load.	Dyform 34LR 219.0kN			Dyform 6AR 308.9 kN			Gold Strand 623.7kN		
Cable Tension	T_1 kN			T_1 kN			T_1 kN		
Ore weight per disc g	1000	2000	3000	1000	2000	3000	1000	2000	3000
Cable diameter mm	40	40	40	50	50	50	75	75	75
Lifting Distance LD m (eqn. 5.7)	**1156**	**794**	**558**	**1512**	**1490**	**769**	**1768**	**1465**	**1260**
100	18.9	27.7	37.2	21.9	30.7	40.2	35.3	44.1	56.3
200	37.8	55.4	74.4	46.3	61.2	80.2	70.5	88.1	107.1
300	56.8	83.0	115.5	65.6	91.8	120.3	105.9	132.1	160.6
400	75.5	110.5	148.6	87.4	122.4	160.5	141.1	176.1	214.2
500	94.4	138.2	209.2	109.3	153.1	200.6	176.4	220.2	248.1
600	113.2	165.7	222.8	131.0	183.5	240.6	211.6	264.1	297.7
700	132.4	193.4	260.0	153.2	214.2	280.7	247.2	308.2	347.3
800	151.0	221.0	297.2	174.8	244.8	320.9	282.2	352.2	396.9
900	170.3	248.7	334.4	197.0	275.5	361.1	317.9	395.5	446.5
Cable tension 1000	**189.2**	**276.4**	**371.6**	**218.6**	**306.2**	**401.3**	**352.9**	**440.2**	**496.1**
1100	208.1	304.1	408.8	240.5	336.9	441.5	388.2	484.3	549.7
1200	227.0	331.8	446.0	247.1	367.6	481.7	423.4	528.3	603.2
1300	245.9	359.5	483.2	264.9	398.3	521.9	458.8	572.3	656.7
1400	264.8	387.2	520.4	284.2	429.0	562.1	494.0	616.3	713.0
1500	283.7	414.9	557.6	306.0	459.7	602.3	529.3	660.4	769.3
1600	302.6	442.6	594.8	327.9	490.4	642.5	564.5	704.5	825.6
1700	321.5	470.3	632.0	349.8	521.1	682.7	599.8	748.6	881.9
1800	340.4	498.0	669.2	371.7	551.8	722.9	635.1	792.7	938.2

Table 47. Granite T_1 calculation of cable tension for lifting depths for the 8-inch tube. The green tensions are beyond the cable scope

	Granite								
Lifting cable Safe working load.	Dyform 34LR 219.0kN			Dyform 6AR 308.9 kN			Gold Strand 623.7kN		
Cable Tension	T_1 kN			T_1 kN			T_1 kN		
Ore weight per disc g	1000	2000	3000	1000	2000	3000	1000	2000	3000
Cable diameter mm	40	40	40	50	50	50	75	75	75
Lifting Distance LD m. (eqn. 5.7)	**1144**	**899**	**670**	**1398**	**1133**	**974**	**1695**	**1542**	**1295**
100m	19.1	24.4	56.7	22.1	27.4	31.3	32.8	40.5	48.1
200	39.3	48.9	84.9	44.1	54.7	65.6	60.1	81.1	96.2
300	57.3	73.2	113.1	66.4	82.0	93.7	98.6	121.5	144.2
400	76.6	97.4	141.5	88.5	109.3	125.0	131.4	162.0	192.3
500	95.7	121.9	169.7	110.6	136.8	156.4	164.2	202.5	240.6
600	114.8	146.2	198.0	132.6	164.0	187.5	197.0	242.9	288.6
700	133.9	170.6	226.3	154.7	191.4	218.8	229.8	283.5	336.7
800	153.2	194.9	283.0	177.0	218.7	250.1	262.8	323.9	384.8
900	172.3	219.3	339.7	199.0	246.0	281.2	295.6	364.5	432.9
Cable tension at 1000m	**191.7**	**243.7**	**396.4**	**221.1**	**273.3**	**321.5**	**328.5**	**404.9**	**481.1**
1100	210.8	268.1	453.1	243.2	300.7	352.8	366.3	445.4	529.1
1200	230.0	292.5	509.8	265.2	328.0	384.1	388.6	486.0	577.3
1300	249.1	316.9	566.5	287.5	355.4	415.4	427.1	526.4	625.3
1400	268.2	341.3	623.2	309.6	328.8	446.7	459.9	566.9	673.4
1500	287.3	365.7	679.9	331.7	410.2	478.0	558.3	607.4	721.5
1600	306.4	390.1	736.6	353.8	437.6	509.3	591.3	647.8	769.6
1700	325.5	414.5	793.3	375.9	465.0	540.6	624.1	687.9	817.7

Table 48. Coal T_1 calculation of cable tension for lifting depths for the 8-inch tube. The green tensions are beyond the cable scope

	Coal								
Lifting cable Safe working load.	Dyform 34LR 219.0kN			Dyform 6AR 308.9 kN			Gold Strand 623.7kN		
Cable Tension	T_1 kN			T_1 kN			T_1 kN		
Ore weight per disc g	1000	2000	3000	1000	2000	3000	1000	2000	3000
Cable diameter mm	40	40	40	50	50	50	75	75	75
Lifting Distance LD m (eqn. 5.7)	**1348**	**909**	**691**	**1590**	**1139**	**890**	**1895**	**1487**	**1244**
100	16.4	24.1	31.7	19.4	27.1	34.7	32.8	40.5	48.1
200	27.4	48.4	63.5	33.2	54.2	69.3	60.1	81.1	96.2
300	49.5	72.4	95.1	58.3	81.2	103.9	98.6	121.5	144.2
400	65.8	96.7	126.7	77.7	108.3	138.6	131.4	162.0	194.3
500	82.2	120.5	158.6	97.1	135.4	173.5	164.2	202.5	240.6
600	98.6	144.5	190.2	116.4	162.3	208.0	197.0	242.9	288.6
700	115.0	168.7	221.9	135.8	189.5	242.7	229.8	283.5	336.7
800	131.6	192.7	253.6	155.4	213.5	277.4	266.5	323.9	384.8
900	148.0	216.9	285.3	174.7	243.6	312.0	295.6	364.5	432.9
Cable tension at 1000m	**164.7**	**241.2**	**317.0**	**194.1**	**270.6**	**346.7**	**328.4**	**404.9**	**481.0**
1100	181.1	265.3	348.7	213.5	297.7	381.4	361.2	445.4	529.1
1200	192.1	289.4	380.4	227.3	324.8	416.1	388.5	486.0	577.2
1300	214.2	313.5	412.1	252.4	351.9	450.8	427.0	526.4	675.3
1400	230.6	337.6	443.8	271.8	379.0	485.5	459.8	566.0	723.4
1500	247.0	361.7	475.5	291.2	406.1	520.2	492.6	647.8	771.5
1600	263.4	385.8	507.2	310.5	433.1	554.9	525.4	688.3	819.6
1700	279.8	409.9	538.9	329.9	460.3	589.6	558.2	728.8	867.7
1800	296.2	434.0	570.6	349.3	487.4	624.3	594.9	769.3	915.8
1900	312.6	458.1	602.3	368.7	514.5	659.0	624.0	809.8	963.9

Table 49. Coal T_1 calculation of cable tension for lifting depths for the 5-inch tube. The green tensions are beyond the cable scope

.	Lifting cable Safe working load Dyform 34LR, 219.0kN						
	Gravel			Granite			Coal
Cable Tension	T_1 kN			T_1 kN			T_1 kN
Ore weight per disc g	1000	2000	3000	1000	2000	3000	1000
Static Friction T_e^f N/cm²	0.15	0.2	0.21	0.18	0.14	0.14	0.02
Static Friction Force per disc T_{SF} N	48.54	102.19	160.94	35.10	54.75	82.09	11.67
Static Friction Force per metre T_{SF} kN	0.19	0.41	0.63	0.14	0.22	0.33	0.05
$T_1 = T_e^L + T_2 + T_e^{sf}$	T_1 kN	T_1 kN	T_1 kN	T_1 kN	T_1 kN	T_1 kN	T_1 kN
Lifting Distance LD m. for the 34LR cable (eqn. 5.7)	**690**	**379**	**262**	**817**	**631**	**408**	**1257**
100	31.7	57.7	83.6	26.8	34.7	53.7	17.4
200	63.5	115.5	167.3	53.6	69.4	107.4	34.8
300	95.3	173.1	250.8	80.4	104.1	161.1	52.2
400	126.9	230.6	334.4	107.2	138.8	214.8	69.6
500	168.6	288.3	418.0	134.0	173.5	268.5	87.0
600	190.3	346.0	501.6	160.8	208.2	322.2	104.4
700	222.0	403.7	585.2	187.6	242.9	375.9	121.8
800	253.7	461.4	668.8	214.4	277.6	429.6	139.2
900	285.4	519.1	752.4	241.2	312.3	483.3	156.6
Cable tension for 1000m	**317.1**	**576.8**	**836.0**	**268.0**	**347.0**	**537.0**	**174.0**
1100	348.8	634.5	919.6	294.8	381.7	590.7	191.4
1200	380.5	692.2	1003.2	321.6	416.4	644.4	208.8

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5.22 Summary of Results for Static Friction Testing

Understanding the static friction for a cable disc elevator is important if we are to have the knowledge for the tension strengths required to restart a fully loaded elevator. The tensions relating to cable weight and the force of gravity are well known, adding the tension resulting from the static friction completes these tension requirements.

It is inevitable that at some time an elevator will stop mid production loaded with ore. The elevator cable must have the strength to allow a restart.

The static friction of the selected ores has been tested for two tube diameters 8-inch (203.2mm) and 5-inch (127mm). The three ores tested gravel, granite, and coal) were collected locally.

Natural extracted ore that was ungraded for particle size was tested. There were three parts that resisted movement.

- The static friction between the ore and the tube.
- Jamming of large irregular shards and pieces of ore that wedge between the disc and the tube.
- Plus, the effect between the disc and the tube was tested even for fine ore smaller than the disc to tube gap but packed as tight at the disc.

The static friction force was measured for the ungraded ore by placing this ore on top of fine coal. This avoided the potential for jamming. This allowed the actual static friction between the ore and the tube of the ungraded ore and the effect of jamming and compaction to be measured. However, for an operational elevator it is not possible to load all the discs with coal dust.

The movement of ore on the disc was examined in a clear tube, showing that ore rotated in a vertical motion as summarised in Figure 28. Larger sized ore tended to accumulate at the side of the tube and led to jams between the disc and the tube.

Ungraded ore was separated into particle sizes ranging from 9.5+mm, 5-9.5mm, 2.0-5.0 mm. These larger sized ore contributed to jams. Table 24 shows that jamming can make up to 96.6% of the total breakfree force. Larger particles would jam the elevator.

Based of these results and observations, testing concentrated on ore whose particle size was less than the gap between the disc and the tube. Ore was selected if it had been sieved through a 2mm Endecotts sieve.

Ore sieved through the 2mm screen was also tested with 100 and 200g of water added per 1000 grams of ore. Water caused doubling of static friction, as we can see in Tables 35-37. This demonstrated the increased fiction that may occur when the ore has had free water added in the mine.

Table 50 is a summary of results for static friction testing for ore less than 2mm size in the 8-inch and 5-inch tubes. There is no water added to the ore for Table 50.

Table 50. A summary of static friction for the 5-inch and 8-inch tubes for gravel, granite and coal.

Tube Diameter	Ore tested	Static Friction determined for the selected ores N/cm^2		
		1000g per disc	2000g per disc	3000g per disc
8-inches 203.2mm	Gravel	0.09	0.08	0.08
	Granite	0.10	0.06	0.04
	Coal	0.02	0.02	0.02
5-inches 127mm	Gravel	0.19	0.20	0.21
	Granite	0.18	0.14	0.14
	Coal	0.02	0.07	0.15

The following table is a summary of results for the maximum lifting depth calculated from the test results. All ore tested for this was less than 2mm in size.

Table 51. Lifting Depth for ore weights and selected cables for gravel, granite and coal.

Tube Diameter	Cable size	Ore Tested	Maximum Lifting Depth for the ore weight and cable size as determined in Tables 50-52, in metres.		
			1000g	2000g	3000g
8-inch 203.3mm	40mm	Gravel	1156	794	558
		Granite	1144	899	670
		Coal	1348	909	691
	50mm	Gravel	1512	1490	769
		Granite	1398	1133	974
		Coal	1590	1139	890
	75mm	Gravel	1768	1465	1260
		Granite	1695	1542	1295
		Coal	1895	1487	1244
5-inch 127.0mm	40mm	Gravel	690	379	262
		Granite	817	631	408
		Coal	1257		

6.0 Test Rig 2

Test Rig 2 is a fully operational cable disc elevator designed to measure the dynamic friction of the selected ore being dragged up a 5-inch (127mm) steel tube. Dynamic friction, also known as sliding friction, moving friction or kinetic friction which is the amount of retarding force between two objects that are moving relative to each other. The section of the elevator where friction is measured is shown in Figures 34 and 35, where the ore is dragged up the lifting side tube of the elevator. The tube is held in place by load cells and is only connected to the elevator with flexible tape.

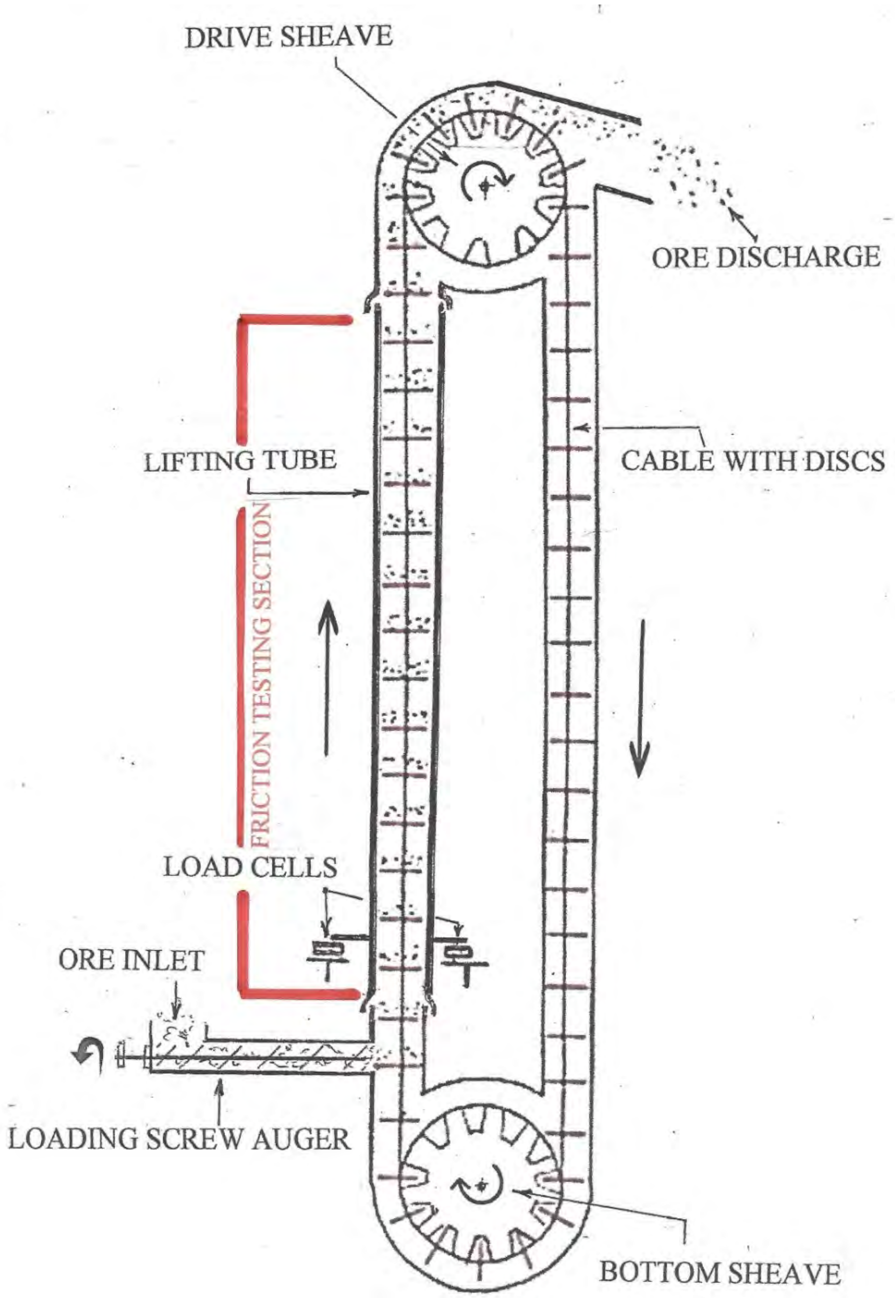


Figure 34: Internal Parts of the Test Rig 2.

Test Rig 2 measures the dynamic friction when:

- the elevator is travelling at different velocities
- various amounts of ore are loaded on the elevator discs
- when the elevator is stop then started when loaded with ore
- the production capacity of the test rig is calculated

Further calculations are made for the lifting force by reducing the friction force to that of one disc and then multiplying by the number of discs needed over the proposed lifting distance. Projections are applied for an elevator with a 1000m lifting distance. The tension requirements for lifting against friction are added to the tension requirements for the weight of the ore and acceleration of the ore and that for the cable weight to obtain the sum of the tensions for the maximum tension T_1. Plus allow for the factor of safety (FoS) of 15% (6.67) is used.

6.1 Ore Samples Tested

The ore samples tested in Test Rig 1 that had the lowest static friction were those of particle size 2mm. These ores had the most favourable topography at the ore tube. Hence to select the ore that can give the cable disc elevator of Test Rig 2 the best chance of success the 2mm ore is used in all tests for dynamic friction experiments in this chapter.

6.2 Test Rig Description

A cable disc elevator consists of a top powered drive sheave and a bottom free running sheave around which a continuous cable with evenly located discs travels. Ore is added in the side of the lifting tube from an ore feed bin by a screw auger which forces the ore into the tube, as shown in Figure 35. Ore is then centrifugally thrown out of the top of the elevator and despatched down a chute.to the ore feed bin.

There are 19 discs carrying ore in the elevator at any one time, but only 16 discs in the test rig of the friction testing tube section held by the weigh load cells.

The elevator is 8 metres high with the isolated static lifting tube of the friction testing section, 4 metres long mounted on four weigh load cells. The load cells holding the lifting tube allow for measurement of the force that holds the tube in place when the friction force between the ore and the tube tries to drag the tube upward during operation. The objective is to obtain knowledge of the dynamic friction for this elevator in the tube.

The main components for measuring the elevator performance and the dynamic friction in the friction testing section are:

- An RPM meter which measures the shaft rotations over time from which the cable speed can be calculated.
- Digital weigh displays show the weight measured by the load cells on the lifting side tube of the elevator. There are four load cells that holds the tube in place, and which resists the friction forces that stem from lifting the tube as the cable lifts. These are measured as a combined weight. To calculate the resistance of the ore and discs in the tube per disc, the lifting force is divided by 16 (the number of discs in the tube at any one time).

- Ore feeds into the elevator from the bin which is also mounted on four weigh load cells. This allows for the measurement of the ore in that bin. The test rig is a closed circuit with ore returning to the bin. When running the elevator, the weight of the ore in the elevator can be calculated on the basis of the amount of ore that is not in the bin. There is a digital weigh display that measures the weight of ore in the ore bin.
- A computer with the relevant program records all the data in real time.

The amount of ore on each disc can be varied by using two methods.

- Increasing the speed of the ore bin auger discharge screw conveyor, with the elevator cable at constant speed. The amount of ore entering the elevator is then greater. Hence, the quantity of ore on each disc increases, provided the elevator cable speed remains constant.
- Increasing the elevator speed returns the ore to the ore bin quicker. meaning there is less ore on each disc. (Provided the ore discharge speed remains constant).

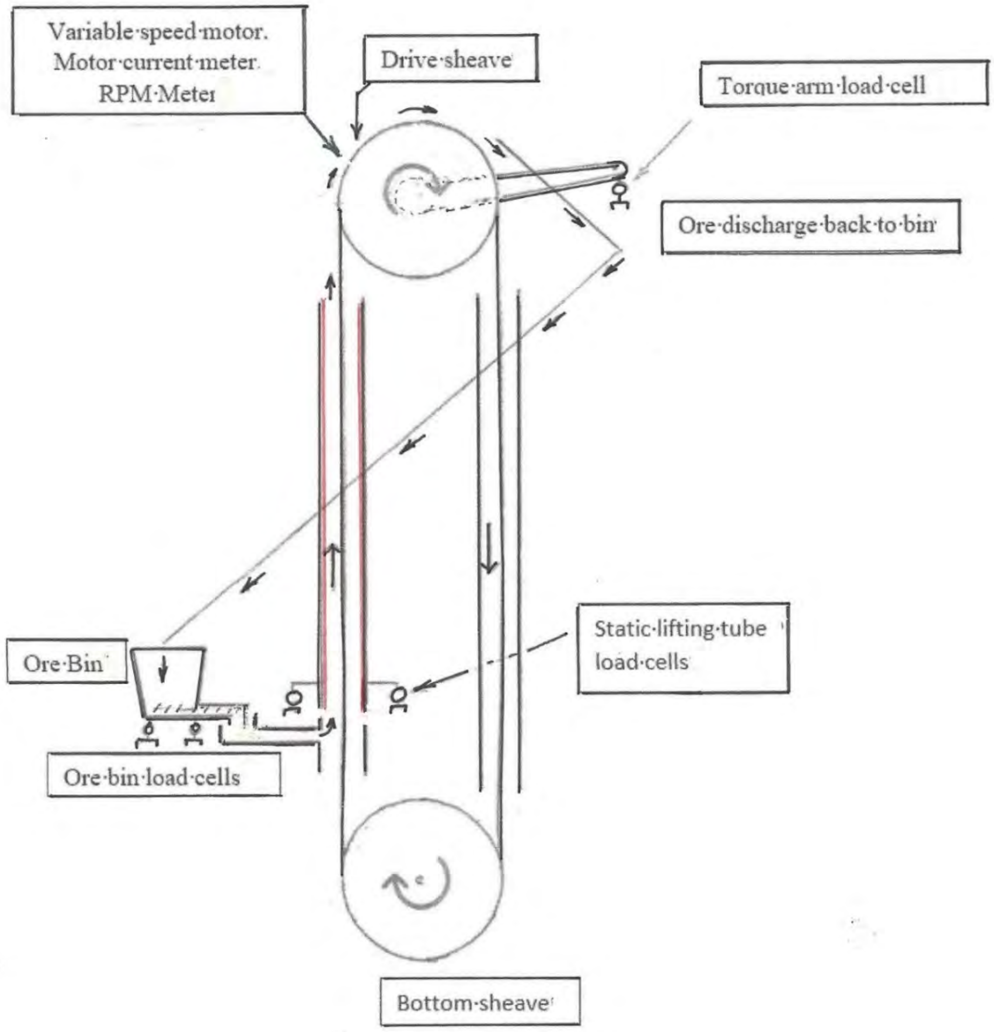


Figure 35. Test Rig 2 showing the layout of the load cells.

Contact area between the static tube and the ore in the test rig is shown in Figure 36.

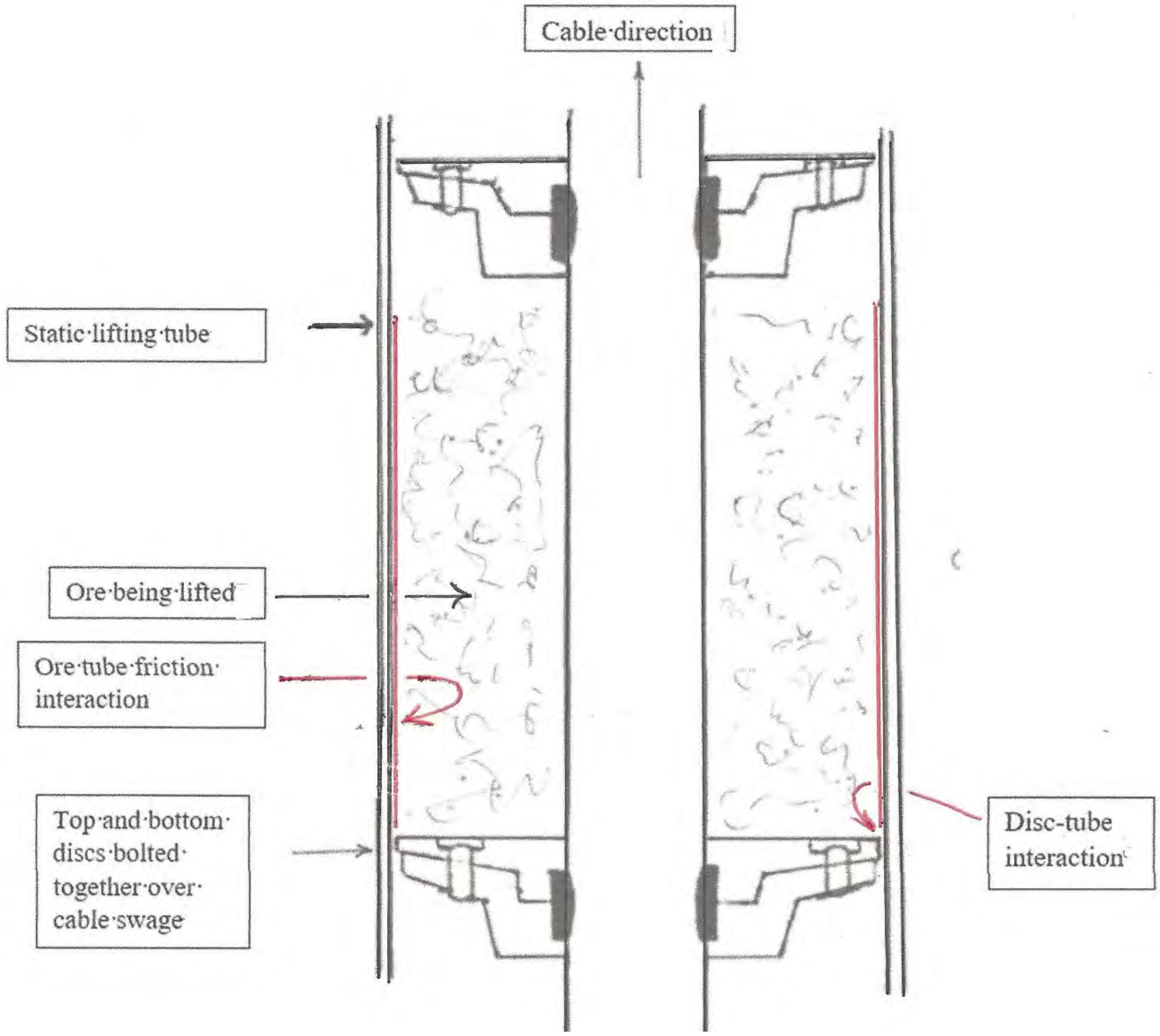


Figure 36. Sketch of the ore on the disc and in contact with the tube.

The gap between the discs and the tube is 2.5mm. Discs are bolted together and clamped over the compressed swage on the cable. The side wall of the tube that is in contact with the ore via friction is shown in red. This is the area of friction that is being measured.

6.2.1 Test Rig 2 Picture

Picture 40 of the test rig shows the cable disc elevator with the ore bin, ore feed screw auger, and the control panel containing the weigh cell readout displays and the recording computer. The ore lifting side fixed tube is mounted on load cells. Ore is returned via the white tube which is supported off the ore bin.

Picture 40. Complete Test Rig 2.

Further pictures of this test rig are in Appendix 6

Picture 41. Ore bin mounted on 4 load cells.

6.2.2 Test Rig 2 Equipment

- The elevator consists of a 5-inch, 127 mm diameter tubed cable disc drag elevator. It is 8m high and the sheaves have a diameter of 470mm with the lifting side tube mounted on load cells.
- The elevator motor drive was a Techtop 5.5kW 3 phase model, with a reduction drive ratio of 10:1. The model number was TRI7100101325 and used with variable speed controller VSD IP66. Motor cooling was achieved using a fan forced electric blower which allowed for cooling when the motor was running slowly. The motor has a torque arm on a load cell to measure the tension applied to the lifting cable for cable overload protection. The speed of the motor is set manually by the operator reading the RPM meter output.
- The elevator torque arm load cell is a Gedge GK2107GIP67/IP68 Shear beam load cell.
- The cable used was a Bridon 100 34 LR EN Dyform RHL 1960B. The diameter was 9.6mm.
- Discs are made of cast nylon and had a diameter of 2.5mm less than the internal diameter of the lifting tube.
- The ore bin hopper that supplies ore to the elevator had a capacity of 0.3 cubic metres, with a 150mm screw auger discharge.

- The hopper motor drive is Techtop 1.1kW 3 phase 2.58A, reduction drive ratio 8.2:1, model TRD0220820905 with variable speed controller VSD IP66. Motor cooling is by a fan forced electric blower to allow cooling when the motor is running slow.
- The hopper was mounted on 4 x Gedge GK2101K250, calibrated shear beam 250kg capacity weigh load cells.
- The elevator lifting tube was mounted on 4 x Gedge GK 2107 G1 capacity shear beam weigh load cells, which were pre calibrated to 0-100kg capacity. These directly measure the friction between the tube and the ore.
- The load cell indicators used were 3 x GS100P-HV4 panel mount RS485 indicators.
- The RPM of the elevator sheave shaft speed was measured with a strobe light recorder.
- Electrical current meter with a 0.1 amp to 200amp range.
- Computer software operating system.

Mechanical components have been manufactured in house including swaging for the disc attachments and machining of the discs.

6.3 Time Taken for Ore to be Loaded on the Elevator Discs

Time to load ore on the discs is limited to the time that the gap between the discs is exposed to the ore feed tube.

The amount of ore that can be loaded into the elevator is dependent on:

- The rate at which ore the auger can push ore into the tube (Picture 42).
- The time available to load each disc which will affect the production capacity of the cable disc elevator.
- The volume capacity of the cell between the discs which will limit how much ore can be loaded.

The time taken for the discs to pass the inlet side chute is the ore loading time for one disc. For Test Rig 2 the ore is force augured into the elevator. Loading time is calculated below.

$$\text{Time to load} = \frac{1}{(\text{Elevator speed in m/s}) \text{ x } (\text{number of discs per metre})} \text{ seconds}$$

Loading time for one-disc. seconds

$$\text{Loading time} = \frac{1}{V_2 \text{ x } D^n} \text{ s} \qquad (6.01)$$

Where V_2 is the cable velocity.

D^n is the number of discs per metre on the cable.

The discs in Test Rig 3 were at 250mm apart. i.e.4 discs per metre. The test rig was operated in the range shown in blue in Table 52.

Table 52. Elevator theoretical ore loading times in seconds. Test Rig 2 numbers are in blueprint

Number of discs per metre D^n	Distance between disc centres mm	Cable speed 1.75m/s	Cable speed 2.0m/s	Cable speed 2.5m/s	Cable speed 3.0m/s	Cable speed 3.5m/s	Cable speed 4.0m/s
		Loading time s	Loading time s	Loading time s	Loading time s	Loading time s	Loading time s
5.00	200	**0.13**	**0.10**	**0.08**	**0.07**	**0.06**	**0.05**
4.00	**250**	**0.14**	**0.13**	**0.10**	**0.08**	**0.07**	**0.06**
3.33	300	**0.17**	**0.15**	**0.12**	**0.10**	**0.09**	**0.08**
2.86	350	**0.20**	**0.17**	**0.14**	**0.12**	**0.10**	**0.09**

6.4 Elevator Cable Speed Calculation.

The motor speed is used to control the cable velocity and is set by using a VSD frequency controller by manually turning the knob of the VSD potentiometer. The speed of the elevator is read from the RPM meter.

The diameter of the sheave is taken to be the diameter at the centre of the lifting cable. This is measured at diameter of 477.0 mm, (i.e. a radius of 238.5 mm). The cable diameter is 9.6mm and is recessed into the sheave groove. The elevator cable speed is set from the measurement of the shaft rotation speed.

Circumference $$C = \pi\, 2r \qquad (6.02)$$

Then the effective circumference of the sheave is $C = \pi \text{ x } 0.477 \text{ m}$
$C = 1.50$ metres.

The cable speed is then calculated from the RPM of the sheave shaft.

Cable speed V_2 is then $$V_2 = \frac{\text{RPM x C}}{60 \text{ seconds}} \text{ m/s} \qquad (6.03)$$

Table 53 Elevator cable speed m/s relative to the drive shaft rotation speed, RPM.

Sheave RPM	60	70	80	100	120	140
Cable speed V_2 m/s	1.5	1.75	2.0	2.5	3.0	3.5

6.5 Forces Acting in the Friction Testing Section Tube

There are several forces observed to be acting in the cable disc elevator. Results from the static friction testing in test rig 1, show that when the breakfree force was large enough the disc with the ore on top broke free from the tube and travelled up the tube until the water bucket came to a stop. This is demonstrated in section 5.3 Test Rig 1 graph example. In Graphs 1, 2, and 3, when the sample broke free the resistance decreased to below 0.23kg (0.5 lb). This proved that for every static friction test, the static friction was much higher than the dynamic friction. The speed that the disc moved at was subject to acceleration from gravity of the weight of water in the bucket.

As a further part of testing for static friction, tests were done to isolate the reaction of friction for ores at the disc interface with the tube. This was done by underlaying fine coal of known friction on the disc with placing ore on top of the coal and then determining the breakfree force as in Section 5.12. By subtracting the known breakfree force for the coal, the true static friction between the ore on top of the coal and the tube could be calculated. This would not be possible to replicate in an operating cable disc elevator. However, the experience from Test Rig 1 would imply that there will be a higher resistance to movement at the disc than for ore of the same contact surface area above the disc.

For dynamic testing results the total lifting force combines of the following:

- The friction between the ore and the tube above the disc.
- The friction or physical wedging/jamming of the ore between the disc and the tube. To avoid jamming only ore below 2mm particle size is used.

Measurements that are fixed during each test run:

- The elevator cable speed. This is monitored by the shaft rotation speed with an RPM meter. Speeds are changed but set to be constant for each measurement.
- Ore bin auger discharge speed. This speed is also monitored using an RPM meter.

For the above points, the elevator cable speed and the auger speed are set at the required speed, and do not vary during testing. Measurements are recorded on the computer for the bin weights and the force acting in the static lifting tube in the friction testing section. For each set chosen, the test rig is allowed to settle and be in a steady state to allow for reasonable data collection.

There are two weight measurements both of which are variable which are the results of the elevator operation. Results are a consequence of the ore properties, the speed of the elevator cable and the ore feed rate.

- The ore bin weight is a function of how fast the auger is taking the ore away and how fast the elevator is returning it. The amount of ore that has been discharged from the bin and not returned is in the elevator.

- The drag of ore in the friction testing section of the lifting tube is strictly the friction between the ore, and the tube to form the lifting friction force.

These two variable measurements are used to calculate the lifting force and the dynamic friction.

6.6 Dynamic Force-Testing the Operating Elevator with No Ore

The dynamic friction between the ore and the tube without any disc effect is difficult to isolate and measure in Test Rig 2.

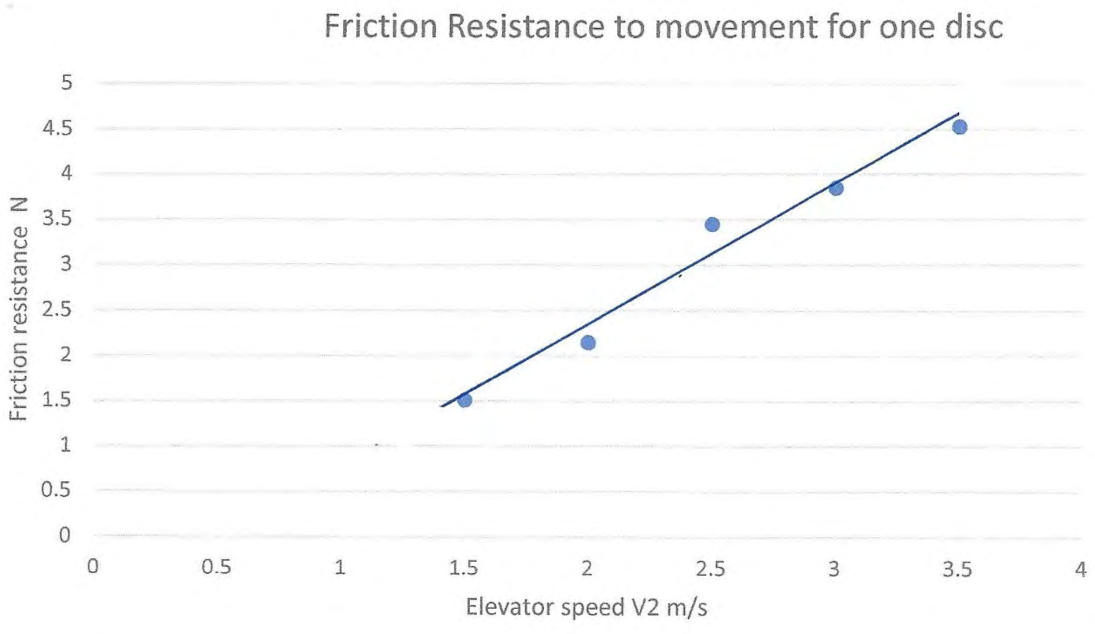
A blank test with no ore in Test Rig 1, was not possible as the one disc had no contact with the tube as the space around the disc to the tube is 2.5mm that contained only air. Ideally it would be expected to be the same in this test rig, however, the 16 discs on the cable are leaning in slight various orientations against the tube, and hence there is a degree of horizontal pendulum movement as the cable and discs travel up the tube. Operating the elevator with no ore produced a drag resistance between the discs and the tube. This resistance from the discs rubbing on the tube is recorded by the load cells holding the tube.

To establish what the true dynamic friction is between the ore and the tube without some disc effect may not be possible, however operating the elevator with no ore at the selected test speeds gives a resultant force that could be used to subtract from the lifting force, which will for an approximation of the dynamic friction of the ore to be calculated. There is an observed quietening of the discs rattling up the tube when the ore enters the operating elevator.

Table 54. Resistance to disc movement in the elevator running with no ore present. Data from run number 1009

Elevator speed RPM	60	70	80	100	120	140
Time of sample reading 24hr time	13:12:33- 13:12:20	13:13:59- 13:14:35	13:14:52- 13:15:50	13:16:22- 13:17:20	13:17:50- 13:18:58	13:19:34- 13:20:35
Cable speed m/s	1.5	1.75	2.0	2.5	3.0	3.5
Resistance for 16 discs. kg	2.46	3.51	4.57	5.64	6.28	7.39
Resistance per disc. g	153.75	219.38	285.63	352.50	392.50	461.88
Resistance per disc. N	1.51	2.15	2.89	3.45	3.85	4.53
Friction resistance x 10^{-2} for one disc per cm of circumference	3.78	5.39	6.99	8.60	9.62	11.22

Graph 10. Blank, no ore friction trace at selected speeds of 1.5,1.75, 2.0, 2.5, 3.0 and 3.5 m/s.



Graph 11. No ore present. Resistance to movement graph for empty discs. Line of best fit.

6.7 Calculations

Results for all measurements are taken when the elevator is operating in a steady state.

- There are several sections to these results and calculations. The lifting force required to operate the elevator includes the force to overcome gravity, the force to overcome the resistance from friction in the elevator tube between the ore and the tube, plus the discs contacting the tube sides, with or without ore.
- For this test rig, or a commercial elevator, the required knowledge is the dynamic lifting force.
- The force required to select a cable that has sufficient design tension strength capability to overcome the dynamic friction force for the elevator depth required. Knowing the makeup of the dynamic friction force is important in understanding the friction forces acting in the elevator and to answer one of the research questions of dynamic friction of the ore.

6.7.1 Calculation of the Weight of Ore on the Discs

The amount of ore in the elevator is the amount of ore that has been discharged from the ore bin. With the elevator operating the ore is returned to the ore bin and a steady state is established with a constant weight of ore in the bin. The weight of the ore left in the bin is measured by the bin weigh load cells.

Using the recorded ore bin weights, the amount of ore on each disc can be measured. There are 16 discs in the elevator, with the friction measuring tube held in position by the load cells, plus, 3 discs on the drive sheave. The ore after the elevator is in free fall in the return tube. The return pipe is mounted on the bin and is included in the bin weight. This allows the ore weight per disc to be calculated and the fiction force per disc in the lifting tube to be calculated.

$$\text{Weight of ore on one disc} = \frac{\text{The amount of ore discharged}}{\text{The number of discs in the elevator}}\ \text{kg} \qquad (6.04)$$

$$\text{Ore weight} = \frac{\mathrm{m}_2-\mathrm{m}_1}{16+3}\ \ \text{g} \qquad (6.05)$$

Where m_1 is the weight in the bin before starting the test rig. Before starting the test rig the ore bin weighing display is tared to zero, hence m_1 equals 0.00 kg.

$$\text{Ore weight per disc} = \frac{m_2}{19}.\ \text{kg} \qquad (6.06)$$

6.7.2 Dynamic Friction Calculation

Table 55 Symbols used for cable tensions in this Section

Symbol	Description.	Unit of measure
T_1	Maximum lifting side cable tension.	kilo Newton’s
t	Time for the ore to reach the lifting height.	seconds
m	Mass of ore on the disc.	kilograms
l, or LD	Lifting length.	metres
V_2	Cable speed.	m/s
D	Tube diameter	cm, or mm
df	Dynamic friction	$\mathrm{N/cm}^2$
DF_1	Dynamic friction force for the ore on one disc.	Newton’s
D^{n}	Number of discs per metre on the cable.	number
T_2	Return side cable tension	kilo Newton’s
h	Height of ore in the tube.	cm
SA	Surface area	cm^2

Measurement for the dynamic friction force is taken from the load cells holding the static lifting tube in the friction testing section.

The lifting dynamic force DF in the tube results from the resistance to movement in the lifting tube and is measured from the weigh load cells holding the tube. This is made up from any mechanical contact between the discs and the tube plus the dynamic friction between the ore and the tube that resist sliding. Therefore, the lifting dynamic force $\mathrm{DF_1}$ per disc is that force divided by the number of discs in the tube. The lifting dynamic force includes all the forces to drag the ore up the static lifting tube. As there are 16 discs in the tube, the lifting dynamic force for one disc is calculated below.

Dynamic lifting force (DF) per disc $\mathrm{DF_1} = \frac{\mathrm{DF_{16}}}{16}$ N (6.07)

As for Test Rig 1 the amount of ore on the disc occupies a known volume. For the 5-inch tube (127mm), the ore heights are shown in Table 14. Knowing the ore height for a given ore weight the surface area (SA) ore tube contact can be calculated.

From equation (4.01)

Ore surface area contact with the tube is $\mathrm{SA} = \mathrm{D}\,\boldsymbol{\pi}\,\mathrm{h}$ $\mathrm{cm^2}$ (4.01)

For the 5-inch (127mm) tube. the contact surface area between the ore and the tube can be calculated using the ore heights as shown in Table 14.

5-inch tube (127mm) dia. $\mathrm{SA} = 39.90\ \mathrm{h}$ $\mathrm{cm^2}$ (6.08)

Dynamic friction (df) is the dynamic friction force ($\mathrm{DF_1}$) per unit of surface area of ore contact with the tube.

Dynamic friction (df) $\mathrm{N/cm^2}$ $\mathrm{df} = \frac{\mathrm{DF_1}}{\mathrm{SA}}$ $\mathrm{N/cm^2}$ (6.09)

Substituting for surface area SA using equation (6.08).

Then the dynamic friction (df) for the 5-inch tube is $\mathrm{df} = \frac{\mathrm{DF_1}}{39.90\ \mathrm{h}}$ $\mathrm{N/cm^2}$ (6.09)

The results from Test Rig 2 will produce the data required to calculate the lifting force that contributes to the cable tension $\mathrm{T_1}$ design. This does not separate the disc effect but combines the friction per square centimetre with the disc effect.

6.7.3 Cable Tensions for Lifting Ore.

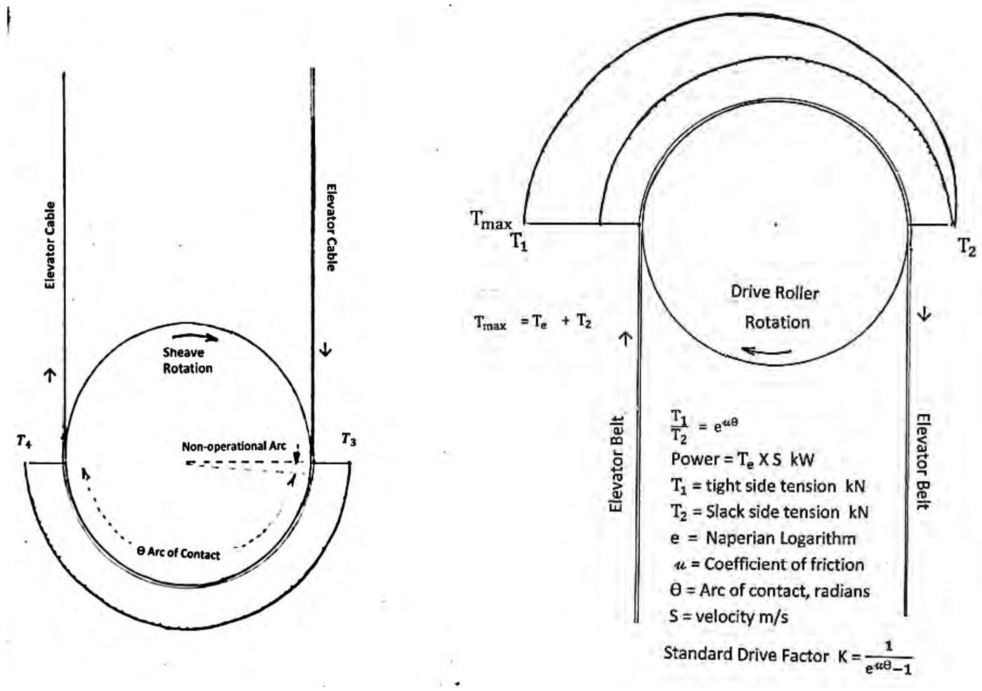


Figure 37. Top sheave and bottom sheave with tension members. T_{max}, T_1, T_2,and T_e. T_3, and T_4 .(Metlikovic, 2006).

Cable tensions requirement are the principle knowledge required to determine the success of the cable disc elevator.

- T_1 is the cable tension to overcome all forces in the elevator. This includes the forces required to overcome friction resistance, carry the weight of the ore to the surface and, carry the cable/disc weight.
- T_2 is the tension of the return side at the top of the elevator cable. This has no ore and carries only the weight of the cable. This is calculated from the weight of the cable, plus the swages and discs.
- T_3 is the tension of the return side of the cable at the bottom sheave. At this position, there is virtually no load on the cable which should be fully relaxed and only carrying any pretension that may have been added to the cable between the drive and bottom sheave. There is no relationship for this tension component to the ore friction in the tube.
- T_4 is virtually equal to T_3. If the elevator has ore added at the bottom sheave the tension component of T_4 will include any digging of ore in the sheave which will then increase the tension on T_1 but will not contribute to the ore friction with the tube in the elevator.
- T_e is the working load tension resulting from lifting the ore. This includes the effect of gravity for lifting and acceleration, plus the effect of the dynamic friction when in operation. This would include the force due to digging of the ore if ore was added at the bottom sheave. In Test Rig 2 the ore is conveyed into the lifting tube by a horizontal auger and no digging takes place.

(From Metlikovic, 2006) $T_1 = T_e + T_2$ (6.10)

Working tension T_e for lifting with this elevator is made up of 3 parts.

- Tension T_e^L to lift ore against overcome gravity when the ore is travelling at a constant velocity.
- Tension T_e^a created when the ore is loaded into the elevator and accelerated up to the cable speed.
- Tension T_e^f required to overcome friction.

Working tension (Harrison, 2009) $T_e = T_e^L + T_e^a + T_e^f$ 6.11

Equation 6.10 can be expressed as;

Maximum tension $T_1 = T_e^L + T_e^a + T_e^f + T_2$ (6.12)

6.7.3.1 Calculation of Working Tensions for Lift. T_e^L

Calculating the makeup of tension T_e^L due to gravity to lift the ore

Force to lift against gravity is $F = m\ a$ from equation (2.7)

The mass in the elevator is $= m \text{ x } D^n \text{ x } l$ N (6.13)

At constant velocity then the tension for lift is also constant

Lifting tension component per disc. $T_e^L = m\ g$ (6.14)

6.7.3.2 Calculation of Working Tension for Acceleration

Acceleration of the ore is calculated based on the elevator operating conditions. This is not measured in the rig, nether the less, to calculate the maximum lifting distance that the elevator could achieve, the tension required for the acceleration, needs to be calculated and added into T_e.

The force or acceleration is expressed by equation 2.07 $F = m\ a$
Where a is the acceleration of the ore from stationary ($V_1 = 0$) to the velocity V_2 of the cable.

The equation for constant acceleration is from Woan equation 2.11, where l is the distance travelled metres, V_1.is the starting velocity m/s, t is the acceleration time in seconds and a is the acceleration m/s^2.

Distance travelled during acceleration is

$$l = V_1 .\, t + \frac{1}{2}\, a\, t^2 \qquad (6.15)$$

The ore is stationary when loaded into the elevator hence V_1 is zero and resolving for acceleration

Acceleration m/s^2

$$a = \frac{2\ l}{t^2} \qquad (6.16)$$

Where t in seconds is the time taken to accelerate the ore to the cable speed V_2, over a distance l metres.

The cable disc elevator is in constant motion at a selected cable speed of V_2. When the ore enters the elevator, the ore is immediately picked up by the disc then travels at the cable speed (V_2). Test Rig 2 has discs at 250mm separation between discs. Ore enters the cell between the two discs and is stationary until the disc below the ore makes contact and pushes the ore forward. The distance the ore travels to reach the operating speed V_2 is 250mm.

The time taken for the ore to accelerate to the cable speed, is the distance in metres, divided by the cable speed in m/s. For this test rig with discs 250mm apart.

Time to accelerate from zero to V_2.

$$t = \frac{0.250}{Cable\ speed} \text{ seconds} \qquad (6.17)$$

Example calculation Cable speed 2.0m/s.

Equation 6.17 $t = 0.125$ second

Equation 6.16 $a = \frac{2\ x\ 0.250}{0.125\ x\ 0.125}$

$a = 32.00$ m/s^2

Equation 6.14 $T_e^a = m\ a$ N

$T_e^a = m\ 32.00$ N

Table 56. Cable tension resulting from ore acceleration T_e^a. m is the mass of ore.

Cable speed m/s	1.00	1.50	2.00	2.50	3.00	3.50
Time to accelerate (6.17) seconds	0.250	0.167	0.125	0.100	0.083	0.071
(6.16) m/s^2	8.00	17.93	32.00	50.00	72.58	99.19
Tension T_e^a to accelerate N (6.13)	8 x m	17.93 x m	32.00 x m	50.00 x m	72.58 x m	99.19x m

6.7.4 Cable Tension T_2 Calculation for the Endurance Dyform 34 LR Cable

To calculate the potential lifting distance for a cable disc elevator the weight of the cable needs to be selected in order to calculate the tension in the cable due to the cable weight. T_2 is the cable tension for the downside (non-lifting side) of the elevator. This carries no ore as the cable is returning to the bottom sheave. At the top of the elevator the cable has only to support its own weight. As this test rig has a 5-inch tube, calculations for T_2 are for the 40mm cable the same as one example selected in the Test Rig 1 calculations. The selected cable is the Endurance Dyform 34LR. It is acknowledged there may be stronger cables that could be used.

Table 57. Endurance Dyform 34LR cable specification from Table 7, (Bridon,2011

Cable diameter mm	40
Nominal length mass kg/m	8.00
Minimum kN	1468
Axial stiffness at 20% load (MN)	92
Torque generated at 20% load ordinary, Nm	94
Lang's Nm	211
Metallic cross section, mm^2	930
Polymer filled rope	

The gross lifting capacity of this rope is 149 t. Applying the factor of safety of 6.67 the effective working potential is to carry weight of 22.33 tonnes. Then the total cable tension force T_1 would need to be 219.0 kN or less.

For equation (6.10) $T_1 = T_e + T_2$

The mass of the cable is the cable weight plus the weight of the discs and the swages. Cable weight is given by Bridon at 8kg per metre.
The disc and swage weight is 250 grams, which equates to 1.00 kg per metre of cable.

T_2 = Cable total weight per metre x g

T_2 = 9.0 x 9.81 N

Where l is the lifting height metres.

Tension for the cable per metre length. T_2 = 88.29 x l N (6.18)

Table 58. Tension T_2 calculated for Endurance Dyform 34LR cable

	Endurance Dyform 34LR
Cable weight per meter kg	8.0
Disc weight per metre. kg	1.0
Total assembled Cable weight per metre.kg	9.0
Tension load per metre.	88.29 N
Lifting Distance LD. metres	T_2 kN
100	8.8
200	17.7
300	26.5
400	35.2
500	44.0
600	52.8
700	61.6
800	70.4
900	79.2
1000	88.3
1100	97.1
1200	106.0
1300	114.8
1400	123.6

6.8 Dynamic Friction Calculations df. N/cm^2

Dynamic friction T_e^f for the elevator is calculated from the dynamic friction force DF used to lift the ore and the surface area of the ore in contact with the tube.
For these calculations the following symbols are used.

Table 59. Symbols used for the dynamic friction calculation

Symbol	Item	Unit of measurement
R	Radius	cm
h	Height of ore on the disc	cm
ρ	Ore density	$grams/cm^3$
v	Volume of ore on the disc	cm^3
SA	Contact surface area between the ore and the tube	cm^2
m	Weight of ore on the disc	grams
DF	Dynamic Friction force	grams
df	Dynamic Friction	N/cm^2
C	Circumference	cm

Calculation of the dynamic friction (df) from the dynamic friction force (DF) and the weight of the ore on one disc is determined in this test rig. Density is selected from the average density as determined and shown in Table 14. The 5-inch tube has a diameter of 12.7cm or a radius of 6.35cm.

Applying equation 4.05

Volume of the ore on the disc $v = \pi R^2 \ h$

Equation 4.04

Density $\rho = \frac{m}{v}$

Substituting for volume using equation 4.05 is then the same as equation 4.06

Density $$\rho = \frac{m}{\pi R^2 \ h} \ g/cm^3 \qquad (6.19)$$

Resolving for ore height h by multiplying both sides of the equation by height h, and dividing by the density ρ of the ore on the disc, the height of the ore can be expressed as;

$$h = \frac{m}{\pi R^2 \ \rho} \ cm \qquad (6.20)$$

Calculating the surface area (SA) contact between the ore and the tube.

The circumference of the tube is.

$$C = \pi\, 2\, R \quad \text{cm} \qquad (6.21)$$

and the surface area of the ore contact with the tube is adapted from equation 4.1

$$SA = C \text{ x } h \quad \text{cm}^2 \qquad (6.22)$$

Dynamic friction dF $df = \frac{DF}{SA}$ g/ cm^2 (6.23)

Substituting for surface area $df = \frac{DF}{C \text{ x } h}$ g/cm^2 (6.24)

Substituting for circumference C (6.21) $df = \frac{DF}{\pi \text{ x } 2\, R \text{ x } h}$ g/cm^2 (6.25)

Substituting for h equation (6.20) $df = \frac{DF \text{ x } \pi \text{ x } R^2 \text{ x } \rho}{\pi \text{ x } 2\, R \text{ x } m}$ g/cm^2 (6.26)

Rationalizing equation (6.26) $df = \frac{DF \text{ x } R \text{ x } \rho}{2 \text{ x } m}$ g/cm^2 (6.27)

Radius R is the same for these calculations and density ρ is selected for each ore.

Re arranging equation (6.27) $df = \frac{DF}{m}\left(\frac{R \text{ x } \rho}{2}\right)$ g/cm^2 6.28)

Simplifying for each ore use $K_{ore}=\left(\frac{R \text{ x } \rho}{2}\right)$ g/cm^2 (6.29)

Then $df = \frac{DF}{m} \text{ x } K_{ore}$ g/cm^2 (6.30)

or $df = \frac{DF}{m} \text{ x } K_{ore} \text{ x } 0.00981$ N/cm^2 (6.31)

Calculating K_{ore} for each ore in the 5-inch (127mm) tube using equation (6.29).

Table 60. Calculations of K_{ore}. Average ore density is selected from Table 14

Ore	Tube radius cm	Average Ore Density ρ g/cm^3	K_{ore} g/cm^2 x 10^{-2}
Gravel	6.35	1.37	4.35
Granite	6.35	1.79	5.68
Coal	6.35	0.60	1.91

Equation 6.23 is used to calculate the dynamic friction df. K_{ore} is selected from Table 60.

6.8.1 Adjusted Contact Surface Between the Ore and the Tube in the Cable Disc Elevator

This test rig has a 9.6 mm diameter cable. A larger elevator requires a cable of significantly diameter to achieve the tension strength required. Ore volume displacement by the larger cable causes the ore to occupy a larger surface area with the lifting tube. In section 5.3 the influence of the larger diameter cable on the increase in ore surface area with the tube is explained and a formula is developed. Figure 32 pictorially demonstrates that effect.

The equation developed for calculating the surface area of the ore is the tube with the larger cable is equation 5.22.

Effective surface area

$$SA = \frac{m\ x\ D}{(R_1^2 - R_2^2) x\ \rho}\ \text{cm}^2 \qquad (6.32)$$

Where D is the tube diameter of 12.70cm, R_1 is the tube radius of 6.35cm and m is the mass of ore on the disc.

Applying these values equation 6.32 can now be simplified for the 5-inch tube.

Simplified equation for surface area

$$SA = 0.73\ \frac{m}{\rho}\ \text{cm}^2 \qquad (6.33)$$

Or for one kilo of ore on the disc the surface area is:

Surface area when m is 1kg

$$SA = \frac{0.73}{\rho}\ \text{cm}^2 \qquad (6.34)$$

Maximum Surface area per cell

$$SA_{max} = \pi\ D\ \ h\ \text{cm}^2 \qquad (6.35)$$

When h is 250mm, the distance between the discs, and D is 12.7 cm then:

$$SA_{max}^{100\%} = 997.45\ \text{cm}^2$$

For practical operation the ore is takes up 80% of available space,

Surface area at 80% fill

$$SA_{max}^{80\%} = 797.96\ \text{cm}^2 \qquad 6.36$$

For practical production purposes when calculating the effective dynamic friction T_e^f the surface ore to tube contact area will not exceed the 80% fill level of $SA_{max}^{80\%}$.

Applying equation (6.35) the height of the ore for $SA_{max}^{80\%}$ is then 200mm.

From equation (5.18) the volume of the ore cell can be calculated.

Volume of ore $v = \pi \ (R_1^2 - R_2^2) \ h$ cm^3 (6.37)

For the 5-inch tube where the height of the ore in the cell is 200mm. the volume of ore is:

$$v = \pi \ (6.35_1^2 - 2_2^2) \times 20 \text{ cm}^3$$

$$v = 2283.1 \text{ cm}^3$$

Using equation 4.4 the mass of ore (m) that can occupy 2283.1 cm^3 can be calculated.

Arranging for ore mass m $m = v \rho$ grams (6.38)

The average density for each ore tested is taken from Table 18.

Resolving equations 6.37 and 6.35 for ore contact surface area simplifies the equation.

Ore contact with the tube surface area $SA = \frac{D \ x \ v}{(R_1^2 - R_2^2)}$ cm^2 (6.39)

Ore contact with the tube surface area $SA = 0.35 \ v$ cm^2 (6.40)

Table 61. Contact surface area for dynamic friction for 1kg of ore per disc when a 40mm diameter cable is used

	Gravel	Granite	Coal
Ore density for 1 kg (Table 18) grams/cm^3	1.37	1.79	0.60
Mass of ore (m) for volume 2283.1cm^3. grams (eqn. 6.28) max. vol.	3,127.85	4086.75	1369.86
Volume (v) for ore mass (m) =1 kg of ore. cm^3 *eqn. (6.28)	729.93	558.66	1666.67
Surface area of ore contact for 1 kg of ore weight. cm^{2}eqn. (6.29)	255.48	195.53	583.33

The dynamic friction is determined by experimenting with Test Rig 2. The resistance of moving ore up the tube is referred to as the dynamic friction force DF and the dynamic friction force for one disc is DF_1. This is used to calculate the dynamic friction in the test rig tube, as df in N/cm^2. When the dynamic friction df is multiplied by the surface area in Table 64 then the friction can be calculated for a larger diameter cable. This is T_e^f , the tension relating to friction.

6.9 Production Ore Movement Rate

Table 62 shows the ore movement capacity for ore at 100-gram intervals per disc at various speed from 1.5 to 3.5 m/s. Based on these speeds and disc ore loading the ore production movement can be calculated. The figures in blue represent the through-put range that was achieved in the 5-inch test rig. These results are taken from the average results in all the tables presented in this chapter. Observations show that the limitation for these tests was the ability of the ore bin and the feed screw to get enough ore into the elevator. For ores being transferred at low speeds between 1.5 and 1.75 m/s, the elevator did not clear the ore by throwing cleanly, and an alternative exit spout below the drive sheave and between the two pipes may have allowed for better ore discharge. This is recommended in the discussion for slow speed operation. This extra discharge spout is employed in the third test rig. In Table 62, production rates achieved in the test rig are shown in blue.

Table 62. Average elevator ore production rate for the 5 inch elevator during testing

Sheave RPM	60	70	80	100	120	140
Cable speed m/s	1.5	1.75	2.0	2.5	3.0	3.5
Number of discs per metre on the cable	4	4	4	4	4	4
Number of discs per second	6	7	8	10	12	14
Number of discs per hour	21,600	25,200	28,800	36,000	43,200	50,400
Ore tonnes per hour for various ore weight on the disc	T/h	T/h	T/h	T/h	T/h	T/h
Average ore weight /disc grams 100	**2.16**	**2.52**	**2.88**	**3.60**	**4.32**	**5.04**
200	**4.32**	**5.04**	**5.76**	**7.20**	**8.64**	**10.08**
300	**6.48**	**7.56**	**8.64**	**10.8**	**12.96**	**15.12**
400	**8.64**	**10.08**	**11.56**	**14.4**	**17.28**	**20.16**
500	**10.80**	**12.60**	**14.40**	**18.00**	**21.60**	**25.40**
600	**12.96**	**15.12**	**17.28**	**21.60**	**25.92**	**30.24**
700	15.12	**17.64**	**20.16**	**25.20**	**30.28**	**35.28**
800	17.28	**20.16**	**23.04**	**28.80**	**34.56**	**40.32**
900	19.44	**22.68**	**25.92**	**32.40**	**38.88**	**45.36**
1000	21.60	**25.20**	**28.80**	**36.00**	**43.20**	**50.40**
1100	23.76	**27.72**	**31.68**	**39.60**	**47.52**	**55.44**
1200	25.92	30.24	**57.60**	**43.20**	**51.84**	**60.48**
1300	28.08	32.76	**37.44**	**46.80**	**56.16**	**65.52**
1400	30.24	35.28	**40.32**	**50.40**	**60.48**	70.56
1500	32.40	37.80	**43.20**	**54.00**	**64.96**	75.60
1600	34.56	40.32	**46.08**	**57.60**	**69.12**	80.64
1700	36.72	42.84	**48.96**	**61.20**	**73.44**	85.68
1800	38.52	45.36	**51.88**	**64.80**	**77.76**	90.72
1900	41.04	47.88	**54.72**	**68.40**	82.08	95.76
2000	43.20	50.40	**57.60**	72.00	86.40	100.80
2100	45.36	52.92	60.48	75.60	90.72	105.84
2200	47.52	55.44	63.36	79.20	95.04	110.88

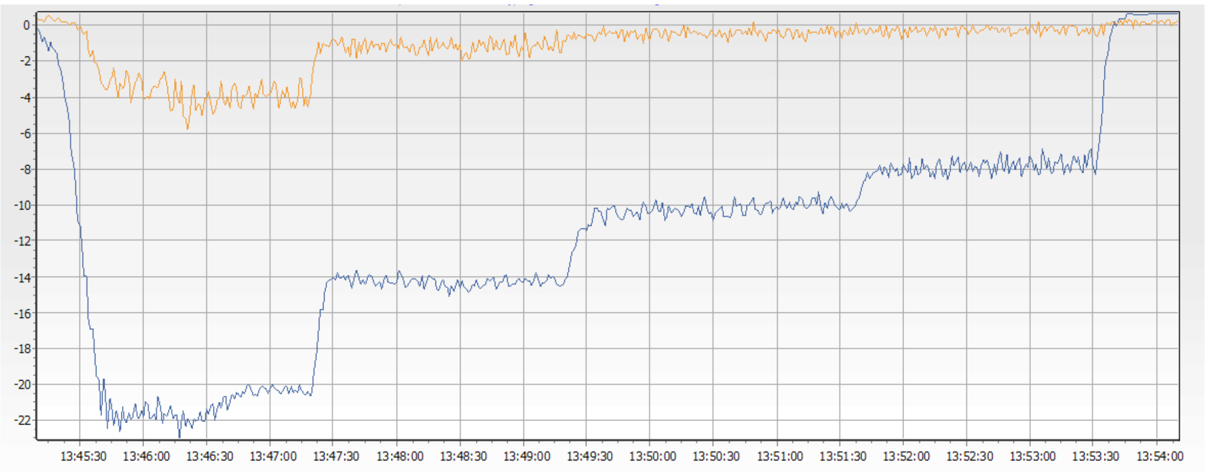
6.10 Test Examples for Gravel, Granite and Coal

The examples shown in Section 6.10 are the graph traces for the ores where there is a constant ore feed rate with variable elevator speed, and alternatively, graph traces for the ores where the elevator speed is constant, and the ore feed rate is variable. Graph traces are also shown where there is a stop start with ore loaded on the elevator discs. The times are recorded where the test rig is stable and the data for the force is selected and averaged. Data is recorded every 1 second in the computer data table. Summaries of the data are recorded in Appendix 3. These average results are used for the calculations. Examples below are for each ore, where the cable speed V_2 is changed and the ore flow is constant, and where the ore flow changes and cable speed V_2 is constant.

6.10.1 Gravel

Gravel is tested for constant ore flow and variable elevator cable speed.

For the Graphs 12, 13 and 15, the ore bin weight is shown by the blue line. The amount of ore that has been removed from the bin is the amount of ore that is in the elevator. Resistance to movement of the ore at the tube is shown by the orange line.



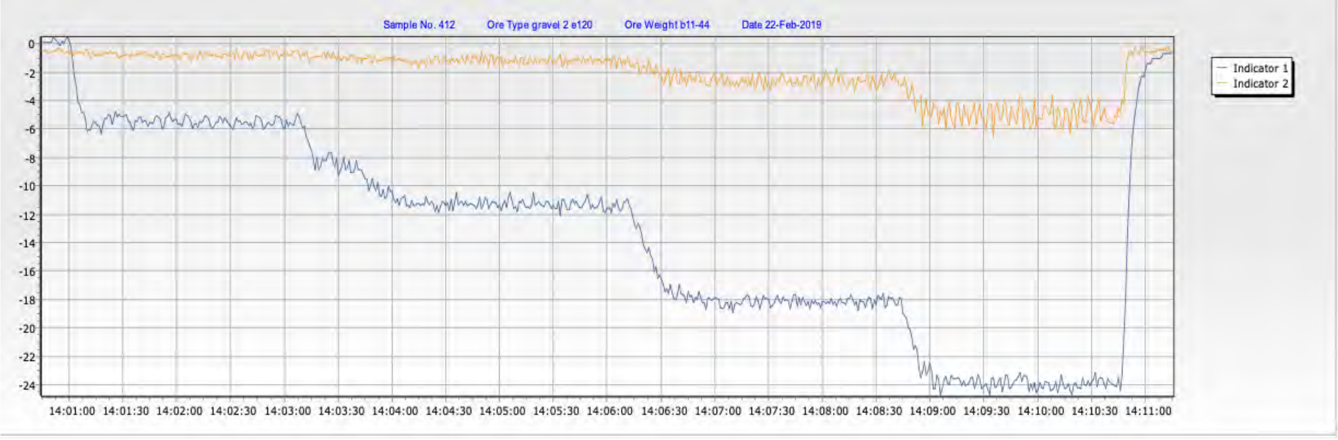
Graph 12. Gravel 2mm ore size. Ore feed constant Bin auger speed at 22 rpm. Elevator speed increased in steps, of 2.0, 2.5, 3.0 and 3.5 metres per second. Appendix 3 Table 207.

In Graph 12, the ore feed is at a constant output from the ore bin. At the slowest elevator cable speed ore is returned more slowly to the ore bin, hence, there is more ore on each disc and a larger surface area of ore in contact with the tube surface. When the elevator speed is increased, the ore is returned more rapidly to the ore feed bin, which results in less ore on each disc, resulting in each disc carrying less ore and less surface area contact between the ore and the tube. Then there is a lower dynamic friction force between the ore and the tube. This is repeated in steps of increased elevator cable speed.

Table 63. Gravel data from Appendix 3 Table 207. K_{Grav} = 4.35 g/cm^2. Results from Graph 12

Time of sample reading 24hr time			Speed RPM		Elevator cable speed	Dynamic Lifting Force in the tube. LDF		Weight of Ore on the disc		Dynamic Friction dF df = $\frac{LDF_1}{m}$ x K_{ore} x 0.00981
hr.	Min.	Sec.	Ore bin auger	Elevator	m/s	Tube 16 discs kg	Per disc. g	Wt. on 19 discs kg	m, Wt. on one disc g	df N/cm^2 x 10^{-3}
13	47	00	22	80	2.0	4.10	256.25	20.36	1071.58	10.20
13	48	30	22	100	2.5	1.04	65.00	14.56	766.32	3.62
13	50	30	22	120	3.0	0.40	25.00	10.84	571.05	1.14
13	53	00	22	140	3.5	0.18	11.25	8.01	421.58	1.14

Gravel is tested for constant elevator cable speed of 3.0 metres per second and variable ore flow rate.

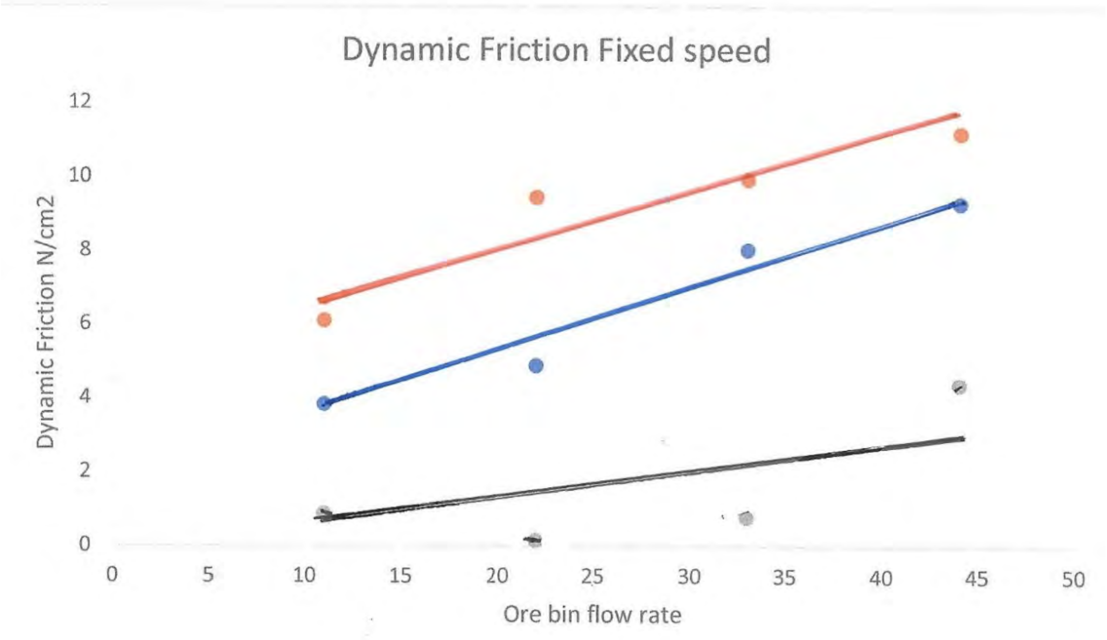


Graph 13 Gravel 2mm ore size. Constant elevator speed at 3.0 metres per second. Ore bin speed increased in steps. 11,22,33 and 44 RPM. Data from Appendix 3 Table 209.

The blue line in Graph 13 shows the amount of ore that has been removed from the ore bin, which is then in the elevator on the discs. The orange line is the force being applied on the lifting tube against gravity. As the elevator cable speed is constant at 3.0 metres per second, when the ore supply increases, the amount of ore on each disc also increases. This results in a higher surface area contact between the ore and the tube, resulting in a higher dynamic friction force (DF).

Table 64. Gravel data from Appendix 3 Table 209,. K_{Grav} = 4.35 g/cm^2.Results from Graph 13. Constant elevator speed, variable ore feed rate

Time of sample reading 24hr time			Speed RPM		Elevator cable speed	Dynamic Force in the tube. DF		Weight of Ore on the disc		Dynamic Friction dF $dF = \frac{DF}{m}$ x K_{ore} x 9.81
hr.	Min.	Sec.	Ore bin auger	Elevator	m/s	Tube 16 discs kg	Per disc. Grams	Wt. on 19 discs kg	m, Wt. on one-disc g	dF N/cm^2 x 10^{-3}
14	02	00	11	120	3.0	0.43	27.03	5.72	301.05	3.83
14	05	00	22	120	3.0	1.09	68.13	11.30	594.74	4.89
14	07	45	33	120	3.0	2.80	175.00	17.69	931.05	8.02
14	09	45	44	120	3.0	4.45	278.13	24.25	1276.32	9.30



Graph 14 Dynamic friction. Variable ore flow rate at speed 11 22,33, and 44. Fixed cable speed of 3.0 metres per second. Line of best fit. The line colours are Gravel-orange, granite -blue, and coal grey.

Gravel is tested for static friction effects at two ore flow rates with a fixed elevator cable speed of 2.5 metres per second.

Static friction is tested by stopping the elevator when operating at load and, then restarting it. The static and dynamic frictions can then be compared. Ore bin speed settings are at 22 and 33RPM.

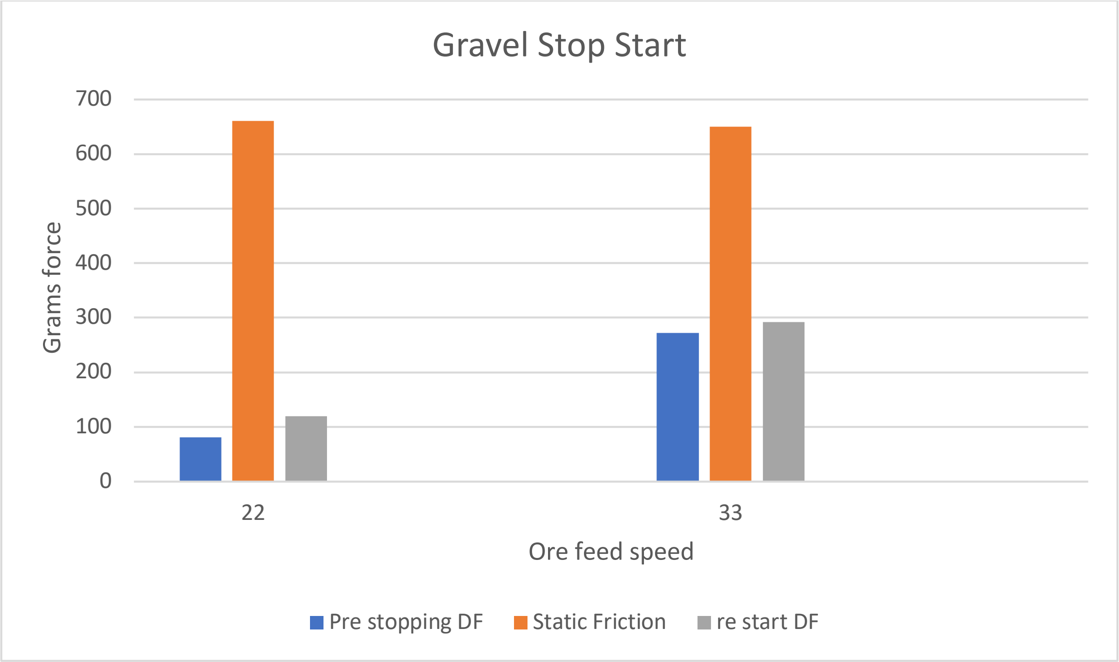
Graph 15. Gravel. Stop start static friction test. Appendix 3 Table 211. Sample 413, run 918.

For Graph 15 and Table 65, the elevator is turned off and restarted. The elevator cable speed is 2.5 metres per second throughout this test. The first stop has the bin ore feed at 22 RPM (14:19:30). At 14:21:30 the ore feed bin was increased to 33 RPM.

For both stops and restarts the system was stopped for approximately 1 minute before it was restarted. Note that during the stopped time the ore bin weight is constant, however the load at the tube reduces slightly as the tube settles back down from being lifted.

Table 65. Gravel stop start static friction test. Data from Graph 15. Ore rate at speeds 22 and 33. Elevator cable speed 2.5 m/s

Time of sample reading 24hr time			Activity	Dynamic Friction force in the tube DF		Weight of Ore on the disc		df	sf	Ore Bin Speed
hr	min	sec		16 discs kg	Per disc grams DF_1	19 discs kg	Per disc grams	N/cm^2	N/cm^2	RPM
14	18	00	Operating stable 22	1.29	80.63	16.33	859.47	4.00		22
14	18	30	Stop							
14	19	00	Stopped and stable	0.17	10.63	14.73	775.26			
14	19	30	Restart	10.58	661.25	19.12	1006.32		28.04	22
14	20	15	Operating stable	1.91	119.38	15.76	829.47	6.14		
14	22	00	Increase ore rate 33	4.36	272.50	24.19	1273.16	9.13		33
14	23	45	Stop							
14	24	10	Restart	10.40	650.00	20.45	1076.80		25.76	33
14	25	31	Operating stable	4.68	292.50	24.83	1306.84	9.55		

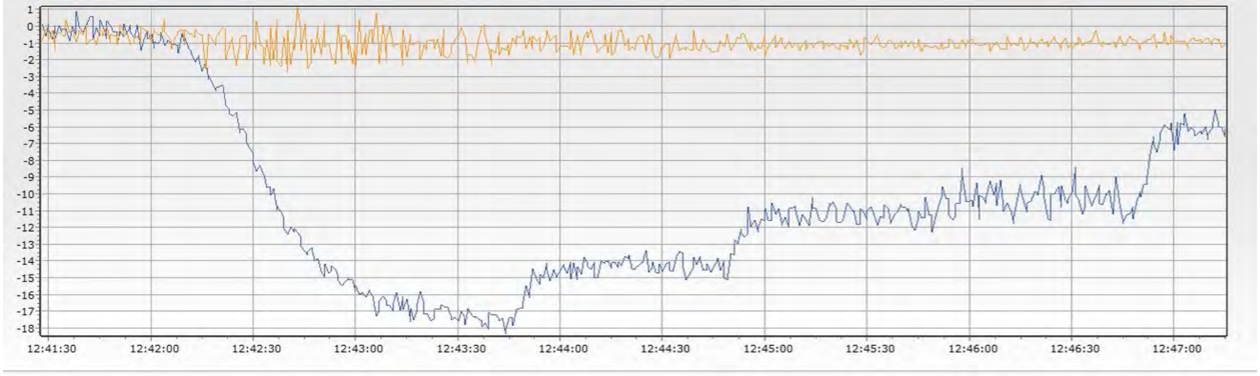


Graph 16. Gravel. Comparison of the static and dynamic frictions DF_1 in grams.

Data from Table 69.

6.10.2 Granite.

Granite of 2mm particle size is tested with a constant ore flow rate at bin discharge setting B22 and variable elevator speed of 2.0, 2.5, 3.0 and 3.5m/s
These results are shown in Graph 17 and Table 66.



Graph 17. 2mm Granite, ore bin speed B22, Elevator cable speed of 2.0, 2.5, 3.0, and 3.5 m/s. Appendix 3 Table 203.

Table 66. Granite, run number 33, sample 23. $K_{Granite} = 5.68$ g/cm^2. Results from Graph 17

Time of sample reading 24hr time			Speed RPM		Elevator cable speed	Dynamic Friction Force in the tube. DF		Weight of Ore on the disc		Dynamic Friction dF $dF = \frac{DF}{m} \times K_{ore} \times 9.81$
hr.	Min.	Sec.	Ore bin auger	Elevator	m/s	Tube 16 discs kg	Per disc. g	Wt. on 19 discs kg	m. Wt. on one-disc g	dF N/cm^2 x 10^{-3}
12	43	35	22	80	2.0	1.05	65.63	17.82	937.89	3.90
12	44	15	22	100	2.5	1.01	63.13	14.22	748.42	4.70
12	45	20	22	120	3.0	1.00	62.50	11.37	598.42	5.82
12	46	30	22	140	3.5	0.98	61.25	10.26	540.00	6.32

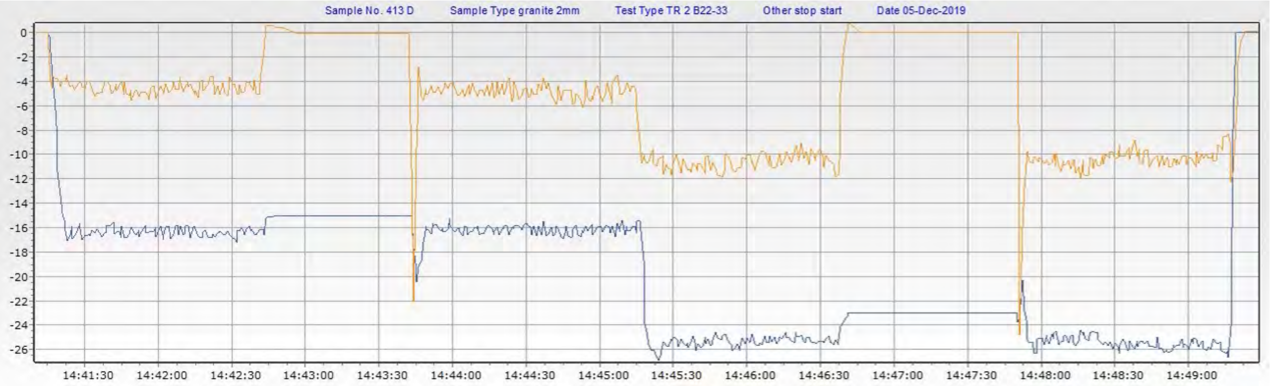
6.10.3 Granite is tested with a constant elevator cable speed and variable ore flow

Graph 18. 2mm Granite. Elevator speed 3.0 metres per second. Ore bin speed 11, 22, 33, and 44. Data from Appendix 3, Table 204.

Table 67. Granite $K_{Granite}$ = 5.68 g/cm^2. Results from Graph 18. Constant elevator speed, and variable ore feed rate

Time of sample reading 24hr time			Speed RPM		Elevator cable speed	Dynamic Friction Force in the tube. DF		Weight of Ore on the disc		Dynamic Friction dF $dF = \frac{DF}{m} \times K_{ore} \times 9.81$
h	M	S	Ore bin auger	Elevator	m/s	Tube 16 discs kg	Per disc. g	Wt. on 19 discs kg	m. Wt. on one-disc g	dF N/cm^2 x 10^{-3}
12	59	15	11	120	3.0	0.08	5.00	9.31	490.00	0.57
13	00	15	22	120	3.0	1.48	92.50	17.89	941.58	5.47
13	01	30	33	120	3.0	3.95	246.88	27.31	1437.37	9.57
13	02	30	44	120	3.0	6.01	375.63	38.33	2017.37	10.38

Graph 19 is a test run where granite is tested for static friction effects at two ore flow rates with a fixed elevator cable speed of 2.5 metres per second. Static friction is tested by stopping the elevator when operating at load and, then restarting it. The static and dynamic frictions can then be compared. Ore bin speed settings are at 22 and 33RPM.



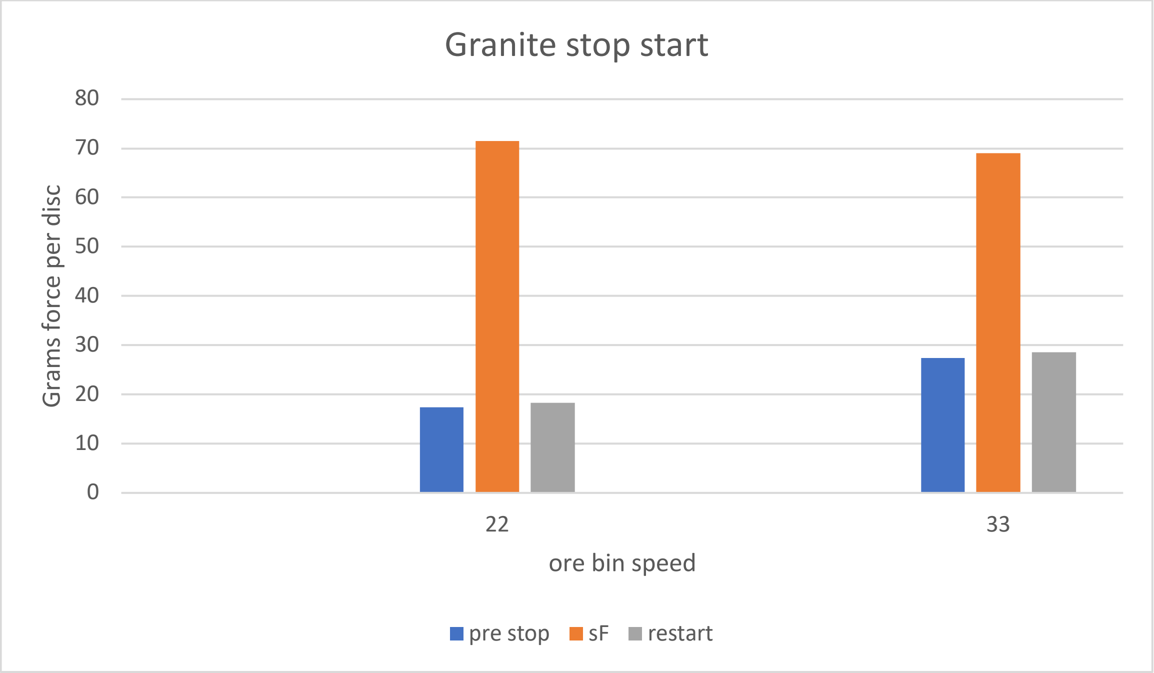
Graph 19. Granite. Stop start static friction test. Sample 413 D, run 918.

In Graph 19 the elevator is turned off and restarted. The elevator cable speed is 2.5 metres per second throughout this test. The first stop has the bin ore feed at 22 RPM (14:42:00). At 14:45:5 0 the ore feed bin was increased to 33 RPM.

For both stops and restarts, the system was stopped for approximately 1 minute before it was restarted. Note that during the stopped time the ore bin weight is constant, however the load at the tube reduces slightly as the tube settles back down from being lifted. The graph data is shown in Table 68

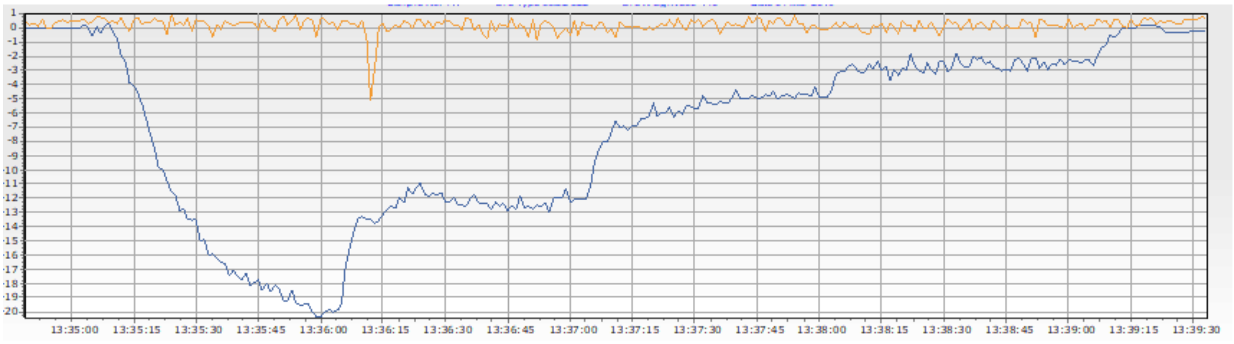
Table 68. Granite, stop start static friction test. Data from Graph 19. Ore rate at speeds 22 and 33. Elevator cable speed at 2.5m/s

Time of sample reading 24hr time			Activity	Dynamic Friction force in the tube DF		Weight of Ore on the disc		df	sf	Ore Bin Speed
h	m.	s		16 discs kg	Per disc grams DF_1	19 discs kg	Per disc grams	N/cm^2	N/cm^2	RPM
14	42	00	Operating stable 22	4.45	278.13	16.93	891.05	17.39		22
14	42	43	Stop							
14	43	00	Stopped and stable	0.36	22.50	15.05	792.11			
14	43	43	Restart	22.04	1377.50	20.39	1073.16		71.52	22
14	44	20	Operating stable	4.58	286.25	16.54	870.53	18.32		
14	45	50	Increase ore rate 33	10.68	667.50	25.82	1358.95	27.37		33
14	47	22	Stop							
14	47	51	Restart	24.80	1550.00	23.75	1250.00		69.09	33
14	48	43	Operating stable	10.88	680.00	25.18	1325.26	28.59		



Graph 20. Granite. Comparison of the static and dynamic frictions DF_1 in grams.
Data from Table 72. Ore bin feed rates at 22 and 33 rpm.

6.10.4 Coal. -Coal Tested at Constant Ore Flow and Variable Elevator Speed, Constant Elevator Speed, and Variable Ore Flow



Graph 21. Coal. 2mm ore size. Data from Appendix 3 Table 211. Ore feed constant bin auger speed at 22 rpm.
Elevator speed increased in steps. 2.0, 2.5, 3.0, and 3.5 m/s.

Results from the test shown in Graph 21 are shown in Table 69.

Table 69. Coal results from Graph 19, K_{Grav} = 1.91 g/cm^2

Time of sample reading 24hr time			Speed RPM		Elevator cable speed	Dynamic Force in the tube. DF		Weight of Ore on the disc		Dynamic Friction dF dF = $\frac{DF}{w}$ x K_{ore} x 9.81
h	m	s.	Ore bin auger	Elevator	m/s	Tube 16 discs kg	Per disc. g	Wt. on 19 discs kg	m, Wt. on one-disc. g	N/cm^2 x 10^{-3}
13	36	00	22	80	2.0	0.76	47.50	20.35	1071.05	0.83
13	36	45	22	100	2.5	0.08	5.00	12.89	677.89	0.14
13	37	45	22	120	3.0	0.64	10.24	4.97	261.57	0.73
13	38	45	22	140	3.5	0.40	25.00	2.16	113.68	4.12

Coal is then tested with the elevator speed constant and the ore bin feed variable. These results are in Graph 22 and Table 70.

Graph 22 Coal 2mm ore size. Ore feed constant elevator speed at 3.0 m/s. Ore bin speed increased in steps. 11,22,33 and 44 RPM. Appendix 3 Table 210.

Results from tests shown in Graph 22 are shown in Table 70.

Table 70. Coal, results from Graph 22. K_{coal} = 1.91 g/cm^2. Results from Graph 27. Constant elevator speed 3m/s and variable ore feed rate.

Time of sample reading 24hr time			Speed RPM		Elevator cable speed	Dynamic Force in the tube. DF		Weight of Ore on the disc		Dynamic Friction dF dF = $\frac{DF}{w}$ x K_{ore} x 9.81
hr.	Min.	Sec.	Ore bin auger	Elevator	m/s	Tube 16 discs kg	Per disc. g	Wt. on 19 discs kg	m Wt. on one disc g	N/cm^2 x 10^{-3}
13	47	15	11	120	3.0	0.04	2.50	2.82	148.40	0.32
13	48	30	22	120	3.0	0.08	3.08	4.88	256.84	0.22
13	50	15	33	120	3.0	0.90	56.25	12.24	644.21	1.63
13	51	30	44	120	3.0	1.09	68.13	17.16	903.16	1.41

In the next test Coal is tested for static friction at two ore flow rates with a fixed elevator cable speed of 2.5 metres per second.

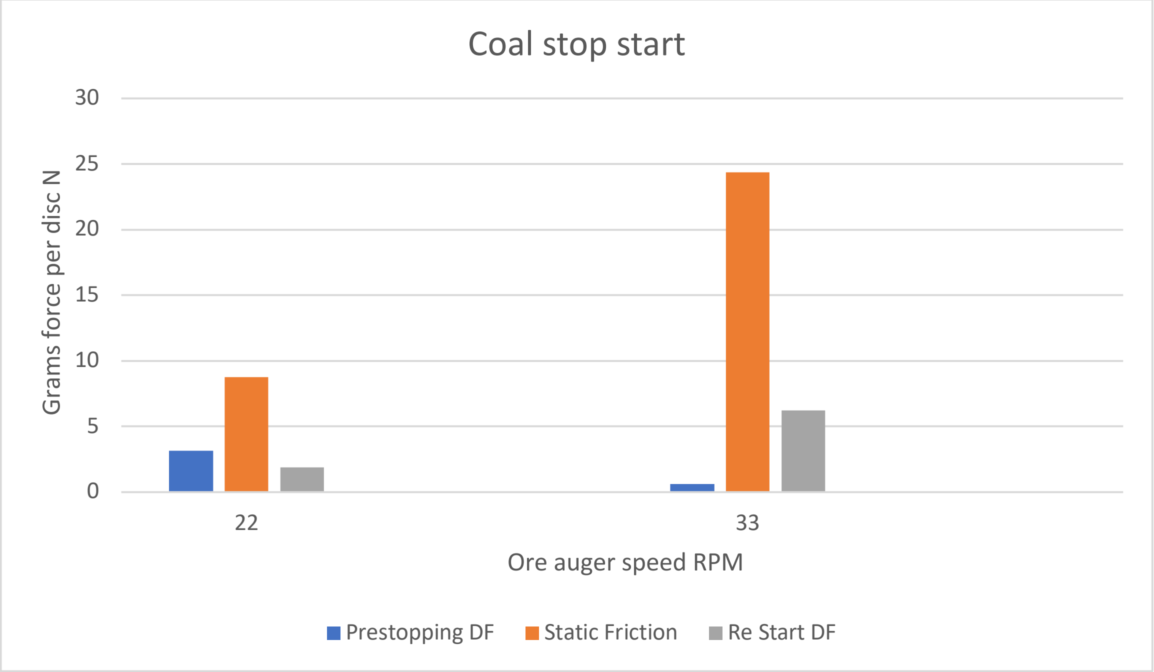
Static friction is tested by stopping the elevator when operating at load, then restarting it again. The static and dynamic frictions are then compared.

Graph 23. Coal. Stop start static friction test. Run number 926, sample 420

The data for Table 71 is from Graph 23.

Table 71. Coal stop start static friction test. Data from Graph 23. Ore rate at speed 22 and 33 RPM. Sample number 420, run number 926

Time of sample reading 24hr time			Activity	Dynamic Friction force in the tube DF		Weight of Ore on the disc		dF	sF	Ore Bin Speed
h	m	s		16 discs kg	Per disc grams	19 discs kg	Per disc grams	N/cm^2	N/cm^2	RPM
14	25	30	Operating stable 22	0.05	3.13	10.04	528.42	0.111		22
14	26	20	Stop							0
14	27	00	Stopped and stable	0.02	1.25	9.69	510.00	0.046		0
14	27	50	Restart	0.14	8.75	10.56	555.79		0.297	22
14	27	50	Operating stable	0.03	1.88	10.22	537.89	0.065		22
14	29	50	Increase ore rate 33							33
14	29	50	Ore-rate 33stable	0.01	0.625	15.69	825.79	0.014		33
14	32	40	Stop							0
14	35	25	Restart	0.39	24.38	17.80	936.84		0.488	33
14	36	30	Operating stable	0.10	6.25	16.75	881.16	0.133		33



Graph 24 Coal. Comparison of the static SF_1 and dynamic friction DF_1. Data taken from Table 75.

6.11 Dynamic Friction Test Rig 2 Results and Calculations for Dynamic Friction and Lifting Height

All the results below are summarised from those recorded in Appendix 3. The results used in this are the average of the averages, the average of the maximums and the average of the minimums that have the same ore bin discharge speed (rpm) and the same cable speed V_2 . Samples discussed in section 6.5 are also included as part of the results in this section.

The ore weight per disc is measured in the test rig from the weight of ore that has been discharged from the ore bin (m_2) and is by default, in the elevator. The weight of ore on a single disc is then calculated by dividing that weight by the number of discs in the elevator that is lifting the ore. This number is 19 discs which is displayed in the tables in Appendix 3.

Equation 6.06

$$\text{Ore weight per disc} = \frac{m2}{19}. \quad \text{Kg}$$

Dynamic friction force is calculated from the force that is experienced in the lifting tube which has 16 discs in this tube at any one time. These are shown in the tables in Appendix 3.

Equation 6.07

$$DF_1 = \frac{DF_{16}}{16} \quad \text{N}$$

Dynamic friction df is then calculated. K is selected from Table 67.

Equation 6.31 $\mathrm{df} = \frac{\mathrm{DF}}{\mathrm{m}}\ \mathrm{K_{ore}}\ 0.00981 \quad \mathrm{N/cm^2}$

Tension for lift against gravity $\mathrm{T_e^L}$.

Equation 6.14 $\mathrm{T_e^L} = \mathrm{m.g} \quad \mathrm{N}$

Tension resulting from acceleration $\mathrm{T_e^a}$ is calculated from Table 60 based on the selected elevator cable speed $\mathrm{V_2}$.

6.11.1 Coal

The dynamic friction is calculated using equation 6.09. K from Table 63 is 1.91 for coal. The amount of ore being transferred is calculated from the weight of ore on the disc and the number of discs passing a particular point per second.

6.11.1.1 Coal. Ore Bin Auger Speed 11 RPM, with Variable Elevator Speed.

In Table 68, the ore weight per disc is summarised from Table 70 and Appendix 3, Tables 188, 189, 191, 192, 193, and 194

Table 72. Coal 2mm, ore bin rate 11RPM. Variable elevator cable speed at 1.5, 1.75, 2.0, 3.0 and 3.5 m/s

1Elevator speed RPM.		60		70		80		100		120		140	
Elevator cable speed m/s		1.5		1.75		2.0		2.5		3.0		3.5	
Ore weight (m) per disc. g Eqn. (6.06)	Avg.	664.48		324.74		227.24		235.00		156.84		181.11	
	Max.	672.37		336.84		246.58		255.00		177.50		216.85	
	Min	640.53		307.37		203.29		203.69		134.87		153.42	
Dynamic friction force. DF_1. Eqn. (6.07)		N	g	N	g	N	g	N	g	N	g	N	g
	Avg.	1.49	151.57	0.29	30.00	0.29	29.22	0.32	32.51	0.27	27.35	0.37	37.82
	Max.	1.93	196.44	0.69	70.63	0.42	42.68	0.52	52.51	0.47	47.82	0.52	53.13
	Min.	1.08	110.00	0.09	9.38	0.14	14.22	0.31	31.88	0.12	12.73	0.22	22.82
Dynamic friction. df $N/cm^2 \times 10^{-3}$ Eqn. (6.31)	Avg.	4.27		1.73		2.41		2.59		3.27		3.90	
	Max.	5.47		3.93		3.24		3.86		5.05		4.59	
	Min.	3.21		0.59		1.31		2.93		1.76		2.79	
T_e^L one disc m x 0.00981 N	Avg.	6.52		3.19		2.23		2.31		1.54		1.78	
	Max.	6.60		3.30		2.42		2.50		1.74		1.76	
	Min.	6.28		3.02		1.99		2.00		1.32		1.51	

6.11.1.2 Coal. Ore Bin Auger Speed 22 RPM, with Variable Elevator Speed

Data is taken from Table 69 and 70, plus Appendix 3, Tables 189, 191, 192, 193, 195, 199, 200, 201, 209, and 210.

Table 73. Coal 2mm, ore bin speed rate at 22 RPM. Variable elevator cable speed 1.75, 2.0, 2.5, 3.0 and 3.5 m/s

Elevator speed RPM.		70		80		100		120		140	
Elevator cable speed m/s		1.75		2.0		2.5		3.0		3.5	
Ore weight (m) per disc . g Eqn. (6.06)	Avg	825.26		455.15		468.25		313.47		219.12	
	Max.	855.79		539.27		490.33		334.21		250.88	
	Min.	802.11		442.74		442.46		288.16		195.79	
Dynamic friction force DF_1.. Eqn. (6.07)		N	g	N	g	N	g	N	g	N	g
	Avg.	1.02	104.38	0.41	41.50	0.35	36.04	0.34	34.69	0.33	33.13
	Max.	1.28	130.00	0.64	65.50	0.69	70.00	0.66	67.51	0.55	56.24
	Min.	0.48	49.38	0.22	22.76	0.16	16.04	0.11	11.26	0.18	18.75
Dynamic friction. df $N/cm^2 \times 10^{-3}$ Eqn. (6.31)	Avg.	2.37		1.71		1.44		2.07		2.83	
	Max.	2.84		2.28		2.67		3.78		4.20	
	Min.	1.15		0.96		0.68		0.73		1.79	
T_e^L one disc m x 0.00981 N	Avg	8.10		4.47		4.59		3.08		2.15	
	Max.	8.40		5.29		4.81		3.28		2.46	
	Min.	7.87		4.34		4.34		2.83		1.92	

6.11.1.3 Coal. Ore Bin Auger Speed 33RPM, with Variable Elevator Speed.

Data is taken from Table 70, and Appendix 3, Tables 189, 191, 192, 193, 196, and 209.

Table 74. Coal 2mm, ore bin speed 33 RPM. Variable elevator cable speed 1.75, 2.0, 2.5, 3.0, and 3.5 m/s

Elevator speed RPM.		70		80		100		120		140	
Elevator cable speed m/s		1.75		2.0		2.5		3.0		3.5	
Ore weight (m) per disc. g Eqn. (6.06).	Avg	1147.30		636.84		469.47		591.32		373.11	
	Max	1212.11		663.86		501.84		620.79		400.00	
	Min.	1069.84		614.21		442.63		549.95		346.58	
Dynamic friction force. DF_1. Eqn. (6.07)		N	g	N	g	N	g	N	g	N	g
	Avg.	1.22	124.38	0.99	100.63	0.45	45.94	0.31	31.88	0.44	45.32
	Max.	1.58	161.25	1.33	135.21	0.64	65.32	0.59	60.63	0.63	64.33
	Min.	1.07	108.75	0.73	74.59	0.30	30.94	0.11	11.25	0.29	29.07
Dynamic friction. df N/cm^2 x 10^{-3} Eqn. (6.31)	Avg.	2.04		2.96		1.83		1.01		2.27	
	Max.	2.49		3.82		2.44		1.83		3.01	
	Min.	1.90		2.28		1.31		0.38		1.57	
T_e^L one disc m x 0.00981 N	Avg	11.26		6.25		4.61		5.80		3.66	
	Max	11.89		6.51		4.92		6.09		3.92	
	Min.	10.50		6.03		4.34		5.40		3.40	

6.11.1.4 Coal. Ore Bin Auger Speed 44 RPM, with Variable Elevator Speed.

Data is taken from Table 66, and Appendix 3, Tables 189, 190, 191, 192, 193, 197, and 209.

Table 75. Coal 2mm, ore bin speed 44RPM. Variable cable speed 2.0, 2.5, 3.0 and 3.5m/s

Elevator speed RPM.		80		100		120		140	
Elevator cable speed m/s		2.0		2.5		3.0		3.5	
Ore weight (m) per disc. g Eqn. (6.06)	Avg.	777.89		632.11		581.05		641.75	
	Max.	811.84		650.35		641.75		701.05	
	Min.	744.46		601.32		559.12		609.00	
Dynamic friction force. DF_1. Eqn. (6.07)		N	g	N	g	N	g	N	g
	Avg.	1.15	117.66	0.64	65.00	0.59	60.42	0.43	43.34
	Max.	1.47	149.69	1.00	101.88	0.88	89.79.	0.63	64.59
	Min.	0.88	89.22	0.46	46.88	0.42	43.28	0.26	26.17
Dynamic friction. df N/cm^2 x 10^{-3}. Eqn. (6.31)	Avg.	2.83		1.93		1.95		1.27	
	Max.	3.45		2.94		2.62		1.72	
	Min.	2.25		1.46		1.45		0.81	
T_e^L one disc m x 0.00981 N	Avg.	7.63		6.20		5.70		6.30	
	Max.	7.96		6.38		6.30		6.88	
	Min.	7.30		5.90		5.84		5.97	

6.11.2 Gravel

6.11.2.1 Gravel. Ore Bin Auger Speed 11RPM, with Variable Elevator Speed

Data is taken from Table 64 and Appendix 3, Tables 198, 199, 200, 201, and 208.

Table 76. Gravel 2mm, ore bin speed 11 RPM. Variable elevator cable speed 2.0, 2.5, 3.0 and 3.5 m/s

Elevator speed RPM.		80		100		120		140	
Elevator cable speed m/s		2.0		2.5		3.0		3.5	
Ore weight (m) per disc. g Eqn. (6.06)	Avg	1089.46		535.26		312.98		366.32	
	Max	1131.58		587.89		352.53		427.37	
	Min.	1042.11		524.21		240.07		314.74	
Dynamic friction force. DF_1, Eqn. (6.07)		N	g	N	g	N	g	N	g
	Avg.	2.64	269.50	0.86	88.13	0.75	76.46	0.77	78.75
	Max.	3.93	400.63	1.45	148.13	1.07	108.75	1.02	104.38
	Min.	2.27	230.94	0.28	28.13	0.12	12.54	0.35	35.63
Dynamic friction. df N/cm^2 x 10^{-3} Eqn. (6.31)	Avg.	10.55		7.03		10.42		9.17	
	Max.	15.11		10.75		13.16		10.42	
	Min.	9.46		2.29		2.23		4.83	
T_e^L one disc m x 0.00981 N	Avg.	10.69		5.25		3.07		3.59	
	Max.	11.10		5.77		3.46		4.19	
	Min.	10.22		5.14		2.36		3.09	

6.11.2.2 Gravel. Ore Bin Auger Speed 22 RPM, with Variable Elevator Speed

Data is taken from Table 63 and 64, then Appendix 3, Tables 199, 200, 201, 207, and 208.

Table 77. Gravel 2mm, ore bin speed 22 RPM. Variable elevator cable speed 2.0,2.5, 3.0 and 3.5 m/s

Elevator speed RPM.		80		100		120		140	
Elevator cable speed m/s		2.0		2.5		3.0		3.5	
Ore weight (m) per disc. g Eqn. (6.06)	Avg	1066.32		789.21		563.68		526.84	
	Max.	1080.53		821.58		589.12		563.42	
	Min	1052.63		760.27		516.67		486.84	
Dynamic friction force. DF_1 Eqn. (6.07)		N	g	N	g	N	g	N	g
	Avg	2.27	231.88	1.09	110.63	0.77	78.75	0.49	49.69
	Max.	2.84	290.00	1.41	143.44	1.07	108.75	0.81	82.50
	Min.	1.83	186.88	0.81	82.82	0.50	50.50	0.18	18.76
Dynamic friction. df N/cm^2 x 10^{-3} Eqn. (6.31)	Avg.	9.28		5.98		5.96		4.02	
	Max.	11.45		7.45		7.88		6.25	
	Min.	7.58		4.65		4.17		1.64	
T_e^L one disc m x 0.00981 N	Avg.	10.46		7.74		5.53		5.17	
	Max.	10.60		8.06		5.78		5.53	
	Min.	10.33		7.46		5.07		4.78	

6.11.2.3 Gravel. Ore Bin Auger Speed 33 RPM, with Variable Elevator Speed

Data is taken from Table 64, and Appendix 3, Tables 199, 200, 201, and 208.

Table 78. Gravel 2mm, ore bin speed 33RPM. Variable elevator cable speed 2.0, 2.5, 3.0 and 3.5 m/s

Elevator speed RPM.		80		100		120		140	
Elevator cable speed m/s		2.0		2.5		3.0		3.5	
Ore weight (m) per disc. g Eqn. (6.06).	Avg.	1618.77		1127.37		880.00		846.84	
	Max	1631.64		1177.89		926.05		908.95	
	Min	1509.12		1047.89		828.42		780.53	
Dynamic friction force. DF_1 Eqn. (6.07)		N	g	N	g	N	g	N	g
	Avg.	2.94	299.52	2.14	218.13	1.63	166.26	1.02	103.75
	Max.	3.40	346.12	2.56	260.63	1.92	195.32	1.42	145.00
	Min.	2.46	251.07	1.88	191.25	1.06	108.13	0.52	53.13
Dynamic friction. df N/cm^2 x 10^{-3} Eqn. (6.31)	Avg.	10.31		8.26		8.06		5.23	
	Max.	11.82		9.44		9.00		6.81	
	Min.	9.27		7.79		5.57		2.90	
T_e^L one disc m x 0.00981 N	Avg.	15.88		11.06		8.63		8.31	
	Max.	16.01		11.56		9.08		8.92	
	Min.	14.80		10.28		8.13		7.66	

6.11.2.4 Gravel. Ore Bin Auger Speed 44 RPM, with Variable Elevator Speed

Data is taken from Table 64, and Appendix 3, Tables 200, 201, 202, 208, and 209.

Table 79. Gravel 2mm, ore bin speed 44 RPM. Variable elevator cable speed 2.0, 2.5, 3.0 and 3.5 m/s

Elevator speed RPM.		80		100		120		140	
Elevator cable speed m/s		2.0		2.5		3.0		3.5	
Ore weight (m) per disc. g Eqn. (6.06).	Avg.	1813.93		1500.53		1171.93		1044.74	
	Max	1867.16		1551.05		1255.26		1126.58	
	Min	1749.84		1459.47		1114.93		956.06	
Dynamic friction force. DF_1 Eqn. (6.07)		N	g	N	g	N	g	N	g
	Avg.	5.08	517.78	3.28	334.38	2.25	229.59	1.33	135.32
	Max.	6.47	659.44	4.41	449.38	3.01	306.88	1.85	189.07
	Min.	4.68	477.34	2.52	256.88	1.65	167.71	0.51	51.57
Dynamic friction. df N/cm^2 x 10^{-3} Eqn. (6.31)	Avg.	12.18		9.51		8.36		5.53	
	Max.	15.07		13.74		10.43		7.16	
	Min.	11.64		7.51		6.42		2.30	
T_e^L one disc m x 0.00981 N	Avg.	17.79		14.72		11.50		10.25	
	Max.	18.32		15.22		12.31		11.05	
	Min.	17.17		14.32		10.94		9.38	

6.11.3 Granite

6.11.3.1 Granite. Ore Bin Auger Speed 11 RPM, with Variable Elevator Speed.

Data is taken from Table 67, and Appendix 3, Tables, 203, and 204.

Table 80. Granite 2mm, ore bin speed 11 RPM. Variable elevator speed 2.0, 2.5, 3.0 and 3.5 m/s

<table>
<tr><td colspan="2">Elevator speed RPM.</td><td colspan="2">80</td><td colspan="2">100</td><td colspan="2">120</td><td colspan="2">140</td></tr>
<tr><td colspan="2">Elevator cable speed m/s</td><td colspan="2">2.0</td><td colspan="2">2.5</td><td colspan="2">3.0</td><td colspan="2">3.5</td></tr>
<tr><td rowspan="3">Ore weight(m) per disc. g Eqn. (6.06).</td><td>Avg</td><td colspan="2">917.37</td><td colspan="2">618.16</td><td colspan="2">590.53</td><td colspan="2">505.79</td></tr>
<tr><td>Max</td><td colspan="2">950.00</td><td colspan="2">648.69</td><td colspan="2">623.16</td><td colspan="2">567.89</td></tr>
<tr><td>Min</td><td colspan="2">884.21</td><td colspan="2">580.00</td><td colspan="2">554.21</td><td colspan="2">467.89</td></tr>
<tr><td rowspan="4">Dynamic friction force DF_1. Eqn. (6.07)</td><td></td><td>N</td><td>g</td><td>N</td><td>g</td><td>N</td><td>g</td><td>N</td><td>g</td></tr>
<tr><td>Avg.</td><td>0.63</td><td>63.75</td><td>0.49</td><td>50.00</td><td>0.71</td><td>71.88</td><td>0.60</td><td>61.25</td></tr>
<tr><td>Max.</td><td>1.31</td><td>133.75</td><td>0.86</td><td>87.19</td><td>1.06</td><td>108.13</td><td>0.86</td><td>88.13</td></tr>
<tr><td>Min.</td><td>0.02</td><td>1.88</td><td>0.14</td><td>14.38</td><td>0.38</td><td>38.75</td><td>0.37</td><td>37.50</td></tr>
<tr><td rowspan="3">Dynamic friction. df N/cm^2 x 10^{-3} Eqn. (6.31)</td><td>Avg.</td><td colspan="2">3.87</td><td colspan="2">4.51</td><td colspan="2">6.78</td><td colspan="2">6.75</td></tr>
<tr><td>Max.</td><td colspan="2">7.84</td><td colspan="2">7.49</td><td colspan="2">9.67</td><td colspan="2">8.65</td></tr>
<tr><td>Min.</td><td colspan="2">0.12</td><td colspan="2">1.38</td><td colspan="2">3.90</td><td colspan="2">4.47</td></tr>
<tr><td rowspan="3">T_e^L one disc m x 0.00981 N</td><td>Avg</td><td colspan="2">9.00</td><td colspan="2">6.06</td><td colspan="2">5.79</td><td colspan="2">4.96</td></tr>
<tr><td>Max.</td><td colspan="2">9.34</td><td colspan="2">6.36</td><td colspan="2">6.11</td><td colspan="2">5.57</td></tr>
<tr><td>Min.</td><td colspan="2">8.67</td><td colspan="2">5.69</td><td colspan="2">5.44</td><td colspan="2">4.59</td></tr>
</table>

6.11.3.2 Granite. Ore Bin Auger Speed 22 RPM, with Variable Elevator Speed

Data is taken from Table 66, and 67, then Appendix Tables 204 and 205.

Table 81. Granite 2mm, ore bin speed 22 RPM. Variable elevator cable speed 2.0, 2.5, 3.0 and 3.5 m/s

Elevator speed RPM.		80		100		120		140	
Elevator cable speed m/s		2.0		2.5		3.0		3.5	
Ore weight (m)per disc. g Eqn. (6.06).	Avg	1637.68		868.34		791.03		687.32	
	Max	1811.73		902.81		813.72		712.18	
	Min.	1596.49		807.56		752.34		644.44	
Dynamic friction force. DF_1 Eqn. (6.07)		N	g	N	g	N	g	N	g
	Avg	2.68	272.75	0.61	62.59	0.63	64.17	0.46	47.00
	Max.	3.35	341.74	0.83	84.59	0.90	91.33	0.62	63.07
	Min.	2.28	232.37	0.37	37.29	0.41	42.28	0.30	30.36
Dynamic friction. df N/cm^2 x 10^{-3} Eqn. (6.31)	Avg	9.28		4.35		4.52		3.81	
	Max.	10.51		5.22		6.25		4.93	
	Min.	8.11		2.59		3.13		2.63	
T_e^L one disc m x 0.00981 N	Avg	16.07		8.52		7.76		6.74	
	Max.	17.77		8.86		7.98		6.99	
	Min.	15.66		7.92		7.39		6.32	

6.11.3.3 Granite. Ore Bin Auger Speed 33 RPM, with Variable Elevator Speed.

Data is taken from Table 67, and Appendix Tables, 204.

Table 82. Granite 2mm, ore bin speed 33RPM. Variable elevator speed 2.0, 2.5, 3.0 and 3.5 m/s

Elevator speed RPM.		80		100		120		140	
Elevator cable speed m/s		2.0		2.5		3.0		3.5	
Ore weight (m)per disc. g Eqn. (6.06).	Avg.	1870.14		1105.79		827.38		747.69	
	Max	1927.64		1211.58		897.44		876.57	
	Min	1793.53		982.11		792.69		701.06	
Dynamic friction force. DF_1 Eqn. (6.07)		N	g	N	g	N	g	N	g
	Avg.	2.44	248.70	1.12	113.75	0.83	84.34	0.76	77.96
	Max.	3.39	345.95	1.98	201.88	0.96	98.23	0.94	95.96
	Min.	2.15	219.52	0.50	50.63	0.72	73.57	0.68	69.70
Dynamic friction. dF N/cm^2 x 10^{-3} Eqn. (6.31)	Avg.	7.41		5.73		5.68		5.81	
	Max.	10.00		9.28		6.13		6.10	
	Min.	6.82		2.87		5.17		5.54	
T_e^L one disc m x 0.00981	Avg.	18.35		10.85		8.12		7.33	
	Max.	18.91		11.89		8.80		8.60	
	Min.	17.59		9.63		7.78		6.88	

6.11.3.4 Granite. Ore Bin Auger Speed 44 RPM, with Variable Elevator Speed.

Data taken from Table 67, and Appendix 3, Tables 206, and 204.

Table 83. Granite 2mm, ore bin speed 44RPM. Variable elevator speed 2.0, 2.5, 3.0 and 3.5 m/s

Elevator speed RPM.		100		120		140	
Elevator cable speed m/s		2.5		3.0		3.5	
Ore weight (m)per disc. g Eqn. (6.06).	Avg.	1964.47		1517.89		1311.58	
	Max	2017.64		1596.32		1443.68	
	Min.	1886.11		1455.26		1233.16	
Dynamic friction force. . DF$_1$ Eqn. (6.07)		N	g	N	g	N	g
	Avg.	3.68	375.32	2.67	271.88	2.02	205.63
	Max.	4.25	432.82	3.02	308.13	2.83	288.13
	Min..	3.20	326.57	2.41	245.63	1.79	182.50
Dynamic friction. dF N/cm^2 x 10^{-3} Eqn. (6.31)	Avg.	10.65		9.98		8.74	
	Max.	11.95		10.76		11.12	
	Min.	9.65		9.40		8.25	
T_e^Lone disc m x 0.00981	Avg.	19.27		14.89		12.87	
	Max.	19.79		15.40		14.16	
	Min.	18.50		14.28		12.10	

6.12 Comparison of Dynamic and Static Friction

Dynamic friction results are taken from Tables 68 to 83. The static friction is taken from Table 42 for ore of 1000 grams on the disc.

Table 84. Dynamic and static friction for ore less than 2mm

Cable speed		2.0	2.5	3.0	3.5
	Static Friction T_{sf} N/cm^2 Table 46	Average dynamic friction df N/cm^2 x 10^{-3} Tables 72-84			
Gravel	0.19	10.58	7.76	8.20	5.53
Granite	0.18	6.85	3.65	6.74	6.28
Coal	0.02	2.41	1.70	2.08	2.57

6.13 Lifting Distance That Could Be Achieved.

The lifting distance that the cable can lift is determined by a number of parameters.

6.13.1 Factor of Safety (FoS).

As observed in Chapter 5 the FoS 6.67. This brings the FoS into conformance with the overland conveyor belt and elevator belt applications used in the mining industry for ore haulage.

6.13.2 Selected Cable Size

The cable size for the 5-inch cable disc elevator for these calculations is a 40mm diameter Bridon Cable Endurance Dyform 34 LR of known strength. The capability of the cable is 219 kilo Newton's at a FoS of 6.67.

Data for this cable selected is taken from Tables 4. The minimum breaking force EIPS/1960 grade cabling is 1468kN. This would give the cable a characteristic vertical length of 16,625 metres. i.e. where the cable is only lifting itself and the factor of safety is not considered. Where the factor of safety is 6.67 the lifting distance is 2500 metres when there is no ore on the cable.

These calculations also show what cable strength would be necessary to achieve a lift for 1000metres. Other specialised cables may be more suitable.

Using equation 6.10 $$T_1 = T_e + T_2$$

Where T_e is the working force required to overcome the friction, lift the ore and, and accelerate it to V_2. T_2 results from the weight of the cable on the return side of the elevator, and T_1 is the maximum tension that the lifting cable can carry using the factor of safety of 6.67.

6.13.3 Calculation of T_e^a for Acceleration in this Application for One Disc.

Tension resulting from acceleration is taken from Table 57. This refers to equation numbers 6.17, 6.16, and 6.13. Acceleration of the ore only occurs for 250mm, after which the ore is at the same speed as the cable and no further acceleration takes place. The only time the ore for the whole length of the cable is experiencing acceleration is when the cable has stopped when fully loaded with ore and has to be restarted. The tension needs to then include the effects of the breakfree force and acceleration.

The tension results in Table 85 below, calculations are used in part to calculate the working tension T_e. For this design discs are 250mm apart, meaning that there are 4 per metre. Two examples are used, one when the ore weight is 1kg per disc, and one where the ore cell is 80% full.

Table 85. Tension resulting from ore acceleration T_e^a. Time to accelerate taken from Table 57. The weight of ore per disc is based at 80% cell fill, Data from Table 61

Cable speed m/s		1.00	1.50	2.00	2.50	3.00	3.50
Time to accelerate (6.17) Seconds		0.250	0.167	0.125	0.100	0.083	0.071
Acceleration (a) (6.16) m/s^2		8.00	17.99	32.05	50.00	72.56	99.21
Tension T_e^a to accelerate N (6.13)	m = ore mass kg	8.00 x m	17.99 x m	32.05 x m	50.00 x m	72.56 x m	99.21 x m
Tension T_e^a to accelerate N (6.13) were m = **1kg**	Gravel and Granite	8.00	17.99	32.05	50.00	72.56	99.21
Tension T_e^a to accelerate N (6.13) were m = **3.13kg**	Gravel	25.04	56.31	100.32	156.5	227.11	310.53
Tension T_e^a to accelerate N (6.13) were m = **4.09kg**	Granite	32.72	73.58	131.08	204.50	296.77	405.77
Tension T_e^a to accelerate N (6.13) were m = **1.37kg**	Coal	13.36	30.04	53.52	83.50	121.18	165.68

6.13.4 Calculation of $\mathrm{T_e^L}$.for Lifting the Ore in this Application

Tension for lifting ore that is on the discs is calculated from equation 6.14 where $\mathrm{T_e^L}$ results is from the effect of gravity.

Effect of gravity
$$\mathrm{T_e^L = T_g^L = m.\,g} \tag{6.41}$$

When the amount of ore on the disc is 1kg then $\mathrm{T_e^L}$ = 9.81 N per disc.

6.13.5 Calculation of $\mathrm{T_e^f}$.for Friction for the Ore in this Application.

From equation (6.26) the available surface area where the cells are 80% full is 797.96 $\mathrm{cm^2}$.

From Table 61 the surface area for 1kg of gravel is 255.48 $\mathrm{cm^2}$, 1 kg of granite is 195.53 $\mathrm{cm^2}$, and for coal 583.33g the surface area takes up the 80% fill of the cell at 797.96 $\mathrm{cm^2}$. These surface areas are used to calculate the dynamic friction force $\mathrm{T_e^f}$ per disc. The dynamic friction force ($\mathrm{DF_1}$) $\mathrm{T_e^f}$ is calculated from the surface contact area and the average dynamic friction df N/$\mathrm{cm^2}$,eqn.(6.09)

$$\mathrm{df} = \frac{\mathrm{DF_1}}{\mathrm{SA}}\ \mathrm{N/cm^2}$$

Working friction tension $\mathrm{T_e^f}$ N for one disc is calculated when the 40mm cable is used and surface contact area of the ore and the tube is adjusted from the test rig results for the volume of the ore displaced by the cable. In red are the 80% full calculations. The effect of acceleration is not considered in the above graph as acceleration only occurs once during the ore lift regardless of the lifting height. Therefore, acceleration does not take place over each metre.

Table 86. Dynamic friction force for 1000grams, for gravel granite and coal in the 5-inch cable disc elevator with a 40mm lifting cable

Cable speed m/s			2.0	2.5	3.0	3.5
	Ore weight per disc. grams	Ore contact surface area with tube per disc. $\mathrm{cm^2}$	**Average dynamic friction df N/$\mathrm{cm^2}$ x 10^{-3} From Table 85**			
Gravel Dynamic friction force $\mathrm{T_e^f}$ ($\mathrm{DF_1}$) per disc.			**10.58**	**7.76**	**8.20**	**5.53**
	1000	255.48	2.70 N	1.98 N	2.09 N	1.41 N
	3128	798	8.44 N	6.19 N	6.54 N	4.41 N
Granite Dynamic friction force $\mathrm{T_e^f}$ ($\mathrm{DF_1}$) per disc.			**6.85**	**3.65**	**6.74**	**6.28**
	1000	195.53	1.34 N	0.71 N	1.32 N	1.23 N
	4087	798	5.47 N	2.91 N	5.38 N	5.01 N
Coal Dynamic friction force $\mathrm{T_e^f}$ ($\mathrm{DF_1}$) per disc.			**2.41**	**1.70**	**2.08**	**2.57**
	1000	583.33	1.41 N	0.99 N	1.21 N	1.50 N
	1370	798	1.92 N	1.36 N	1.66 N	2.05 N

6.13.6 Calculation of.T_e.for One Metre of Cable for One Metre Lift.

From equation (6.11) the total working force is the sum of the force required to lift against gravity (T_e^L), the force required to accelerate (T_e^a) the ore from stationary to the operating cable velocity V_2 , and the force required to overcome the friction between the ore and the tube (T_e^f).

Total working tension

$$T_e = T_e^L + T_e^a \text{ (one cell)} + T_e^f \qquad 6.42$$

Working tension for one metre of cable represents 4 discs. Data is taken from Table 85, multiplying the dynamic force (DF) T_e^f components are multiplied by 4 as there are 4 discs per metre of cable. The working tension due to gravity is calculated from equation 6.14. These results are shown in Table 87.

Table 87. Dynamic friction force for one metre of cable for the selected ore weights. Data multiplied by 4 from Table 83. By selection, there are 4 discs per metre.

Cable velocity V_2 m/s			2.0	2.5	3.0	3.5
	Ore weight per disc g	Ore weight per metre of cable g and kg	Dynamic friction force T_e^f for 1metre of cable. N	Dynamic friction force T_e^f for 1metre of cable. N	Dynamic friction force T_e^f for 1metre of cable. N	Dynamic friction force T_e^f for 1metre of cable. N
Gravel	1000	4000	10.80	7.92	8.36	5.64
	3128	12.51	33.76	24.76	26.16	17.64
Granite	1000	4000	5.36	2.84	5.28	4.92
	4087	16.35	21.88	11.64	21.52	20.04
Coal	1000	4000	5.64	3.96	4.84	6.00
	1370	5.48	7.68	5.44	6.64	8.20

The tension required to overcome gravity is calculated using equation 6.14.

Lifting tension component per disc.

$$T_e^L = m \times g \qquad (6.14)$$

These results are shown in Table 88.

Table 88. Tension required to overcome gravity for one metre of cable. Equation (6.14)

Cable velocity V_2 m/s			2.0	2.5	3.0	3.5
	Ore weight per disc g	Ore weight per cable metre g and kg	TensionT_e^L against gravity for 1metre of cable. N	Tension T_e^L against gravity for 1metre of cable. N	Tension T_e^L against gravity for 1metre of cable. N	Tension T_e^L against gravity for 1metre of cable. N
Gravel	1000	4000	39.24N	39.24N	39.24N	39.24N
	3128	12.51	122.72N	122.72N	122.72N	122.72N
Granite	1000	4000	39.24N	39.24N	39.24N	39.24N
	4087	16.35	160.39N	160.39N	160.39N	160.39N
Coal	1000	4000	39.24N	39.24N	39.24N	39.24N
	1370	5.48	53.76	53.76	53.76	53.76

The working tension T_e can now be calculated by the sum of the tension from Tables 87, and 88, using equation 6.13 without the effect of acceleration of the ore for one disc. Working tension T_e excluding acceleration T_e^a (one cell).

$$T_e = T_e^L + T_e^f \text{ N} \tag{6.43}$$

Table 89 above in red shows the percentage component of T_e that relates to the dynamic friction force T_e^f from Table 87. The tension required to overcome acceleration for one disc T_e^a (for one disc) is not included.

Table 89. Total working tension force T_e in Newtons for one metre of elevator cable at various cable speeds

Cable velocity V_2 m/s			2.0		2.5		3.0		3.5	
Ore	Ore weight per disc g	Ore weight per cable metre kg	T_e Total working tension for 1metre of cable. N		T_e Total working tension for 1metre of cable. N		T_e Total working tension for 1metre of cable. N		T_e Total working tension for 1metre of cable. N	
			N	%T_e^f	N	%T_e^f	N	%T_e^f	N	%T_e^f
Gravel	1000	4.00	50,04	21.58	47.16	16.79	47.60	17.56	44.88	12.57
	3128	12.51	156.48	21.57	147.48	16.79	148.88	17.57	140.36	12.57
Granite	1000	4.00	44.60	12.02	42.08	6.75	44.52	11.86	44.16	11.14
	4087	16.35	182.27	12.00	172.03	6.77	181.91	11.83	180.43	11.11
Coal	1000	4.00	44.88	12.57	43.20	9.17	44.08	10.98	45.24	13.26
	1370	5.48	61.44	12.50	59.20	9.19	60.40	10.99	61.96	13.23

6.13.7 Dynamic Operation-Calculation for Maximum Lifting Distance using the 40mm Cable for Lift with a Cell Loading of 1 kg of Ore

$$T_e = T_e^L + T_e^a \text{ (One disc)} + T_e^f \tag{6.42}$$

Lifting distance formula T_1 is calculated from (6.09)

$$LD = \frac{\text{Cable tension spec}(CT_{1000}) - T_e^a \text{ (One disc)}}{T_1} \text{ metres} \tag{6.43}$$

Re arranging for cable tension CT.

Cable tension spec. required for a 1000m lift

$$CT_{1000} = LD \times T_1 - T_e^a \text{ (One disc) N} \tag{6.44}$$

- The Bridon 40mm cable selected has a working tension strength of 219kN. (see Table 7).
- T_e^a for one disc where the ore is accelerated is subtracted from the cable strength which then becomes 219,000 N- T_e^a (one disc).
- T_e is the working tension is taken from Table 93 which does not include the tension required to overcome the effects of acceleration.
- T_e^a (one disc) is taken from Table 89.

Ore lifting production is calculated as follows:

$$\text{Production rate} = \frac{m}{1000} D^n V_2 \; 3600 \text{ t/h} \tag{6.45}$$

With a daily operation of 20 hours (h) and an annual production is based on 220 days per year.

The production calculated production rates are shown in Table 90 along with cable tensions where the cell loading is 1kg of ore per disc.

Table 90. Calculation of cable tension T_1, the lifting distance in metres and production capacities for the 5-inch tube elevator

Cable velocity V_2 m/s			2.0	2.5	3.0	3.5
T_e^a (One disc) ore weight is 1kg. T_e^a			32.5 N	50.00 N	72.56 N	99.21 N
Cable	9.0 kg/m	T_2 N/m	88.29	88.29	88.29	88.29
Gravel 1000g per disc	eqn. (6.09) $T_e + T_2$	T_1 N/m	138.33	135.45	135.89	133.17
Lifting distance m for 40mm cable		$\frac{219000 - T_e^a \text{ N}}{T_1 \text{ N/m}}$	**1583**	**1616**	**1611**	**1644**
Lifting cable tension required for 1000m lift. N		eqn. (6.33)	**138,298**	**135,400**	**135,817**	**133,071**
Granite 1000g per disc	eqn. (6.09) $T_e + T_2$	T_1 N/m	132.89	130.37	132.81	132.79
Lifting distance m for 40mm cable		$\frac{219000 - T_e^a \text{N}}{T_1 \text{ N/m}}$	**1648**	**1679**	**1648**	**1648**
Lifting cable tension required for 1000m lift. N		eqn. (6.33)	**132,858**	**130,320**	**132,802**	**132,691**
Coal 1000g per disc	eqn. (6.09) $T_e + T_2$	T_1 N/m	133.17	131.49	132.37	133.53
Lifting distance m for 40mm cable		$\frac{219000 - T_e^a \text{ N}}{T_1 \text{ N/m}}$	**1644**	**1665**	**1654**	**1639**
Lifting cable tension required for 1000m lift. N		eqn. (6.33)	**133,138**	**131,440**	**132,297**	**133,431**
Gravel granite and coal. Production tonnes per hour **(1kg/disc)**			28.8	36.0	43.2	50.4
Production tonnes per 20hr day			576	720	864	1008
Production tonnes per 220 days per year at 20 hours per day			126,720	158,400	190,080	221,760

6.13.8. Dynamic Operation- Calculation for Maximum Lifting Distance using the 40mm Cable for Lift with a 80% Cell Loading Volume

The Bridon 40mm cable selected has a working tension strength of 219kN. T_e^a for one disc where the ore is accelerated is subtracted from the cable strength which then becomes 219,000N- T_e^a (one disc). T_e the working tension is taken from Table 89 which does not include the tension required to overcome the effect of acceleration. T_e^a (one disc) is taken from Table 85. Ore load on the disc in Table 91 is calculated where the volume of the cell between the discs is 80% full.

Table 91. Calculation of the cable tension T_1, the lifting distance in metres, and the production capacities for the 5-inch elevator

Cable velocity V_2 m/s			2.0	2.5	3.0	3.5
T_e^a (One disc) ore weight Gravel 3.13kg			100.32 N	156.50 N	227.11 N	310.53 N
T_e^a (One disc) ore weight Granite 4.09kg			136.08 N	204.50 N	296.77 N	405.77 N
T_e^a (One disc) ore weight Coal 1.67kg			53.52 N	83.50 N	121.18 N	165.68 N
Cable	9.0 kg/m	T_2 N/m	88.29	88.29	88.29	88.29
Gravel	$T_e + T_2$	T_1 N/m	244.77	235.77	237.17	228.65
Lifting distance m		$\frac{219000 - T_e^a N}{T_1\ N/m}$	**894**	**928**	**922**	**956**
Lifting cable tension required for 1000m lift. N		eqn. (6.33)	**244,669**	**235,614**	**236,943**	**228,339**
Granite	$T_e + T_2$	T_1 N/m	270.56	260.33	270.20	268.72
Lifting distance m		$\frac{219000 - T_e^a N}{T_1\ N/m}$	**809**	**840**	**809**	**813**
Lifting cable tension required for 1000m lift. N		eqn. (6.33)	**270,424**	**260,126**	**269,903**	**268,314**
Coal	$T_e + T_2$	T_1 N/m	149.73	147.49	148.69	150.25
Lifting distance m		$\frac{219000\ N}{T_1\ N/m}$	**1462**	**1484**	**1472**	**1456**
Lifting cable tension required for 1000m lift. N		eqn. (6.33)	**149,676**	**147,407**	**148,569**	**150,084**
Gravel. Production tonnes per 220 days per year at 20 hours per day			369,643	477,259	594,950	694,108
Granite. Production tonnes per 220 days per year at 20 hours per day			518,285	635,026	777,427	906,998
Coal. Production tonnes per 220 days per year at 20 hours per day			173,606	217,008	260,410	303,811

6.13.9 Tension Required to Accelerate the Ore from V_1 to the Operating Speed V_2 when Fully Loaded. where V_1 is Zero m/s

When the elevator has stopped during operation and the discs are loaded the forces on the cable when restarting the elevator include the breakfree force required to overcome the static friction and an acceleration force to return the elevator to operational speed V_2 m/s. The acceleration force calculated at constant acceleration. In Tables 90 & 91, the acceleration of the ore is for one cell as the cable disc elevator is in motion. For the elevator to start under a full load every cell is under acceleration.

There are two ways the elevator could be restarted:

- Firstly, as the elevator is restarted there is no ore added and the elevator unloads at the top resulting in the force to lift the ore reducing as the weight of the ore reduces. From equation 2.07:

  $$F = m\,a$$

  Then $$a = \frac{F}{m} \qquad (6.46)$$

  For constant acceleration as the mass of ore on the cable reduces, then the force to lift the ore has to also reduce.

- Secondly, as the elevator starts the ore supply onto the cable resumes. This option to restart maintains the load of the ore on the cable. At constant acceleration, the force will remain constant as there is no change in the ore weight of the ore on the elevator.

Calculations for the tension required to accelerate the ore back to operational speed V_2 considers only the second option where the mass of ore on the elevator is unchanged, i.e. the elevator is loading at the same rate as it is unloading.

The following formulae are used to calculate the data for the following tables.

Acceleration $$a = \frac{V_2 - V_1}{t} \qquad (2.05)$$

Where t is the time to accelerate and V_1 is zero when the elevator is stationary.

The force for this acceleration is calculated from equation 2.07

$$F = m\,a$$

Substituting for acceleration from equation 2.5 and where V_1 is zero, then the force required is;

$$F = m\,\frac{V_2}{t} \qquad (6.47)$$

Then the tension required in the cable for the ore to be accelerated at a constant acceleration is:

$$T_e^a = m\,\frac{V_2}{t}\ \text{N} \qquad (6.48)$$

6.13.9.1 Tension Required to Overcome Acceleration at Various Acceleration Times for 1 kg of Ore on each Disc for a Cable Lift of 1000 Metres

In Table 92 the tension required for acceleration T_e^a is calculated from equation 6.15. There are 4000 discs for the 1000 metre lift elevator.

Table 92. Tension required to accelerate a cable carrying 1000g of ore per disc for 4000 discs to operational speed at a constant acceleration.

Cable speed V_2 m/s		2.0	2.5	3.0	3.5
Time to accelerate seconds	Ore weight per disc g	T_e^a N	T_e^a N	T_e^a N	T_e^a N
120	1000	66.67	83.33	100.00	116.67
180	1000	44.44	55.56	66.67	77.78
240	1000	33.33	41.67	50.00	58.33
300	1000	26.67	33.33	40.00	46.68
480	1000	16.67	20.80	25.00	29.17
600	1000	13.33	16.67	20.00	23.33

6.13.9.2 Tension Required to Overcome Acceleration at Various Acceleration Times for Ore that Occupies 80 % of the Ore Cell Volume for a Cable Lift of 1000 Metres

The acceleration force T_e^a, is calculated from equation (6.15). There are 4000 discs for the 1000m lift elevator where V_1 is zero.

Table 93. Tension required to accelerate the cable carrying 4000 discs to operational speed at constant acceleration where the ore cells are 80% full.

Cable speed V_2 m/s			2.0	2.5	3.0	3.5
Time to accelerate seconds	Ore Type	Ore weight per disc kg	T_e^a N	T_e^a N	T_e^a N	T_e^a N
120	gravel	3.13	208.67	260.83	313.00	365.17
180	gravel	3.13	139.11	173.89	208.67	243.44
300	gravel	3.13	83.47	104.33	125.20	146.07
600	gravel	3.13	41.73	52.17	62.80	73.03
120	granite	4.09	272.67	340.83	405.00	477.17
180	granite	4.09	181.78	227.22	272.67	318.11
300	granite	4.09	109.07	136.33	163.60	190.87
600	granite	4.09	54.53	68.17	81.80	95.43
120	coal	1.37	91.33	114.17	137.00	159.83
180	coal	1.37	60.89	76.11	91.33	106.56
300	coal	1.37	36.53	45.66	54.88	63.93
600	coal	1.37	18.27	22.83	27.40	31.97

6.14 Summary of the Lifting Distance for the 5-Inch Elevator

Lifting distances depend on the balance between the forces resisting lift and the cable tension available to lift the ore and must favour the cable tension. Cable tension capability has an inherent factor of safety of 6.67 and operates at only 15% of its minimum breaking force capability.

In Tables 90 and 91 the lifting distances are based on the Bridon 34LR 40mm cable where the safe maximum tension is 219kN, and for a lifting distance of 1000metres the cable tension requirement has been calculated.

Calculations are based on two ore loadings. In Table 92 the ore cells are carrying 1 kg of ore per disc. In Table 93 the ore cells are carrying the maximum amount of ore that can volumetrically fit into 80% of the volume between the discs, this results in different amounts of ore for different types of ores that have different densities.

$$T_1 = T_e\,(T_e^L + T_e^a + T_e^f) + T_2 \tag{6.49}$$

Where T_1 is the total tension required by the cable, T_e is the total working tension which includes that required to overcome gravity, accelerate the ore to elevator operating speed, and overcome the friction that exists between the ore and the tube. T_2 results from the cable weight.

Lifting distance summary for 1 kg of ore on the disc in the table below data is summarised from Table 90 and 91. In Table 90 the friction is the only variability between the ores. This variability results from the friction relationship between the ore and the tube and is determined by the nature and density of the ore which result in different contact surface areas

Table 94. Lifting distance summary and cable tension required for 1000m lift at 1kg of ore per cell

	Cable speed m/s	2.0	2.5	3.0	3.5
T_1 required for 1000 metre lift N	Gravel	138,289	135,440	135,817	133,071
	Granite	132,858	130,320	132,802	132,691
	Coal	132,858	130,320	132,802	132,691
LD. Lifting distance for 219kN cable LR34, 40mm dia. FoS 6.67 Metres	Gravel	1583	1618	1611	1644
	Granite	1648	1679	1648	1648
	Coal	1644	1665	1654	1639

Table 95. Lifting distance summary and cable tension required for 1000m lift with the cells 80% full

	Cable speed m/s		2.0	2.5	3.0	3.5
T_1 required for 1000 metre lift N	Gravel	3.13 kg per cell	244,669	235,614	236,943	228,339
	Granite	4.09 kg per cell	270,424	260,126	269,903	268,314
	Coal	1.37 kg per cell	149,676	147,407	148,569	150,084
LD. Lifting distance metres. for 219kN cable LR34, 40mm dia. FoS 6.67	Gravel	3.13 kg per cell	894	929	922	956
	Granite	4.09 kg per cell	809	840	809	813
	Coal	1.37 kg per cell	1462	1484	1472	1456

6.15 Summary of the Dynamic Test Rig Friction

- Dynamic friction was measured in Test Rig 2 for gravel, granite and coal and all ores tested had a particle size of 2mm or less. The decision to only test fine ore was based on the results from static friction testing, where particles larger that the gap between the disc and the tube contributed to jamming. In Test Rig 1(section 5.7) for static friction, visual tests with ungraded ore showed that the disc jammed, and the test rig would not have been able to lift this ore any further. The same jamming would result in Test Rig 2, for this reason the decision was made to only test fine product.
- Dynamic friction is less than the static friction was shown in Table 84
- In Table 96 friction T_e^f is shown in red as a percentage of the working tension T_e .T_e^f is also shown in the Table 101 below as a percentage of T_1. The maximum tension T_1.is taken from the average for the ores from Table 91.

Table 96. A comparison between the static and dynamic friction

Cable speed m/s		2.0	2.5	3.0	3.5	Dynamic friction	
	Static Friction T_{sf} N/cm^2 Table 45	Average dynamic friction df N/cm^2 x 10^{-3} Tables 68-80				Avg x 10^{-3}	% of static friction
Gravel	0.19	10.58	7.76	8.20	5.53	8.02	4.20
Granite	0.18	6.85	3.65	6.74	6.28	5.88	3.27
Coal	0.02	2.41	1.70	2.08	2.57	2.19	10.95

Table 97. Dynamic friction force working tension T_e

Ore	Percent range of T_e^f in the maximum tension T_1	Percent range of T_e^f in the working tension T_e
Gravel	10.80-5.64	18.60-8.09
Granite	5.36-2.84	10.19-5.25
Coal	6.00-3.96	10.67-7.17

7.0 Test Rig 3

7.1 A Hybrid Elevator, the Cable Disc Elevator inside a Pipe Conveyor

Test Rig 3 is designed to eliminate friction in the cable disc elevator by replacing the lifting side tube of Test Rig 2 with a pipe conveyor. This research examines what frictions exist and from what depth could this elevator with the pipe conveyor lift ore. An equation is developed to calculate the depth that the elevator could reach. An example is based on using a 40mm diameter Bridon 34LR cable. Another equation is also developed to calculate the tension specification of a cable that would be required for lifting ore from a nominated depth. However, in the calculations the depth selected if for 1000metres, but greater depths could have been selected.

Test Rig 3 is a hybrid elevator combining the cable disc elevator and a pipe conveyor. Each component has a particular function.

- The cable disc elevator lifts the ore.
- The pipe conveyor is in a vertical position and replaces the vertical steel tube of Test Rig 2. Its function is to only to provide a tube that stops ore falling off the cable elevator discs. This vertical pipe conveyor does not have any lifting function other than to lift its own weight.

In this elevator, friction exist where the ore enters the steel pipe that leads into the pipe conveyor belt and the departure from the pipe conveyor belt. For Test Rig 3 both the cable disc elevator and the pipe conveyor are travelling at the same speed, which means there is no relative movement between the two elevators and hence no friction in this section. However, it was possible to run the cable disc elevator at a higher velocity than the pipe conveyor, so this was not done as part of the research into removing friction between the lifting side of the elevator and the ore. To increase the length of the elevator only the combined elevator section is increased in length where there is no relative movement between the ore and the pipe conveyor belt and hence no friction.

In Test Rig 3 the pipe conveyor is distinct from other pipe conveyors, as the section that forms the pipe belt shape is short at 2.0 metres. The reason for the short distance is to keep the elevator short so it can be stood up at the testing facility. The length of the pipe is 6.25 metres plus 2.0 m for pipe forming and 2.0 metres to recover the flat belt shape, plus 1 metre of support frame. This gave an overall height of Test Rig 3 of 11.25 metres. The test rig is free standing. Regardless of the test site restrictions, the sections that contribute to friction are complete and do not change regardless of the test rig height.

7.1.1 Test Rig 3 Equipment

- The pipe conveyor was purpose manufactured by Beijing Haoshen Technology Company Ltd.
- A rubber textile polyester core belt was 600mm wide, and 10mm thick manufactured by Rongcheng Huacheng Rubber Co., ltd.
- The cable disc elevator torque arm on the motor has a weigh load cell Gedge GK2107GIP67/IP68 shear beam weigh load cell.
- Motor drive on the belt conveyor torque arm has a Gedge GK2107GIP67/IP68 shear beam weigh load cell.

- There are four load cell indicators GS100P-HV4 panel mount RS485 indicators. One each for the cable disc elevator motor and one for the pipe conveyor motor.
- RPM meters
- Electrical current meter 0.1 amp to 200amp range for each motor.
- Computer software operating system supplied by Australian Weighing P/L
- Mechanical components were manufactured in-house including swaging for the disc attachments and some machining of the discs, and fitting the cable disc elevator to integrate with the pipe conveyor
- The ore bin is the bin from Test Rig 2.
- The centre panel roller set is mounted on four shear beam weigh load cells model Gedge GK 2107 G1, capacity 0-100kg
- Supply of the cast nylon discs was purposed manufactured from Eplas

The authors concept of this test rig is shown in Figure 39 where the pipe conveyor is used as the tube on the lifting side of the elevator. The return side of the elevator is a metal tube. Both the cable disc elevator and the pipe conveyor are driven at the top of the frame. The actual test rig is pictured as a front and side view in Picture 41. Further pictures are in Appendix 7. Figure 39 shows the selected fiction zones and load cell layout.

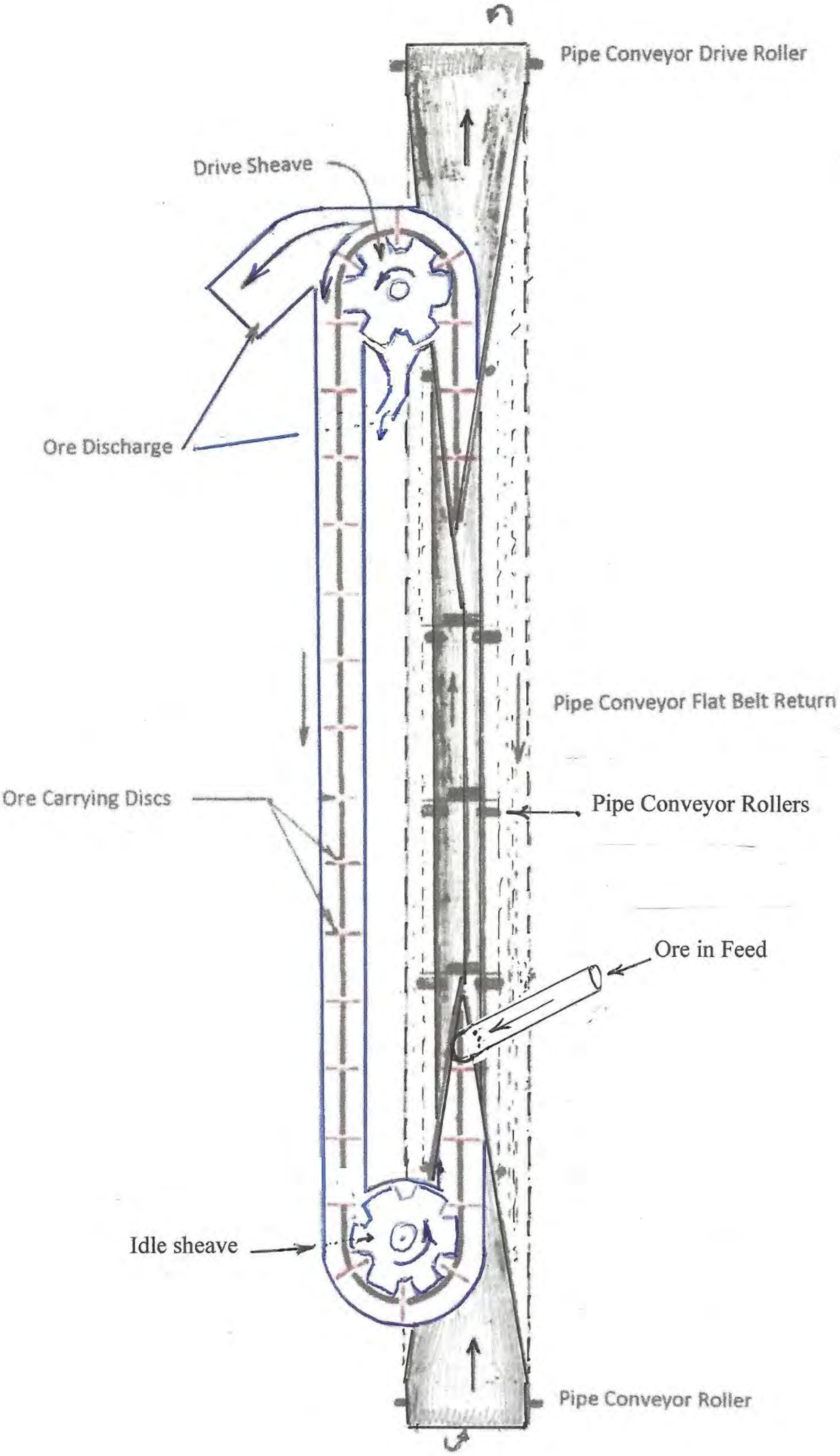


Figure 38. Drawing of Test Rig 3. Cable disc elevator with a pipe conveyor for the lifting tube.

Picture 42. Front and side view of Test Rig 2 without the ore bin

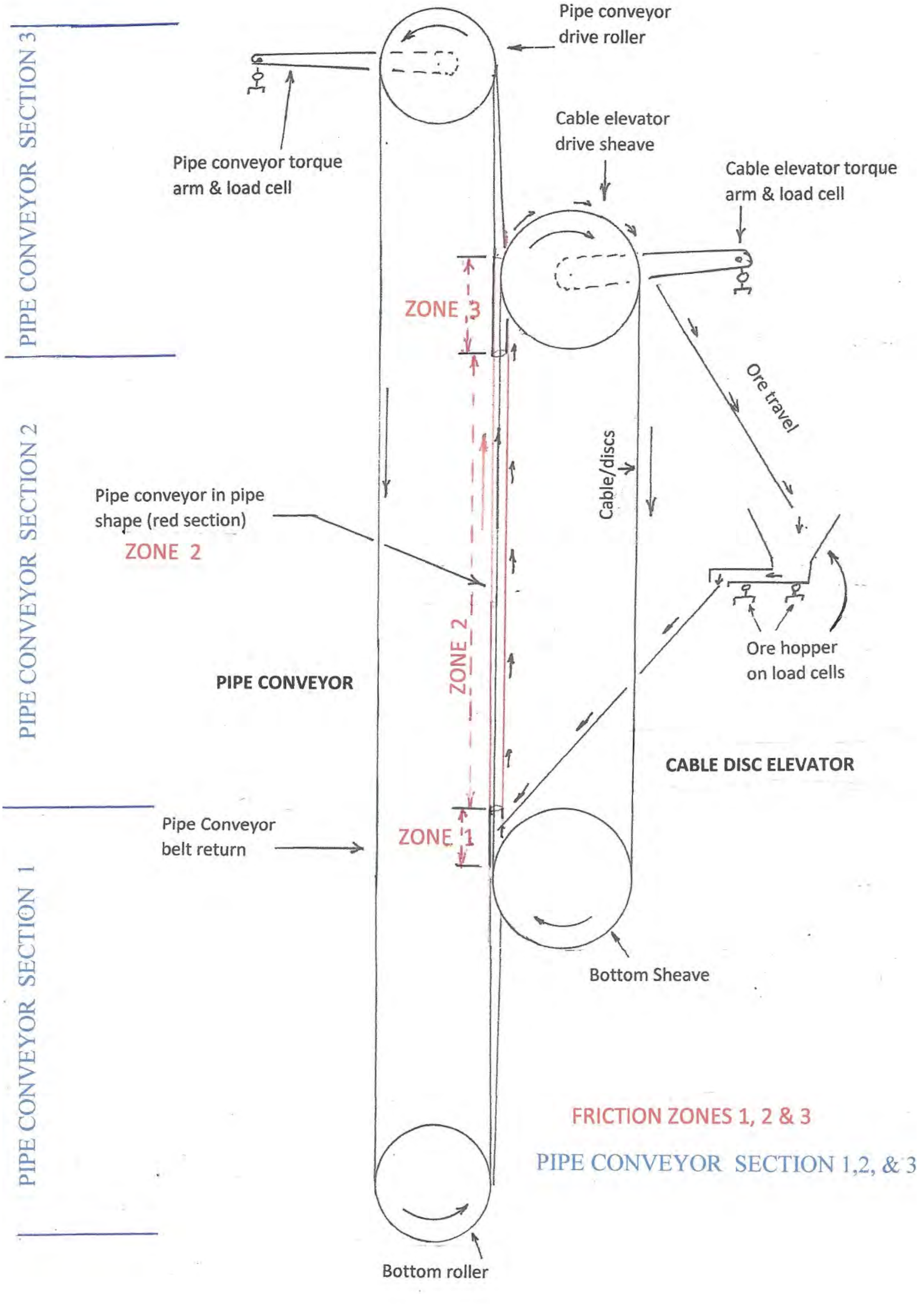


Figure 39. Sketch of Test Rig 3 load cell layout showing ore friction zone

The cable disc elevator disc dimensions are shown in Figure 40. The drive and idle sheave are the same and one is shown in Picture 43 and dimensions in Figure 41. Other pictures are in Appendix 7. The sheave grove for the cable to run in is a European style DIN 15061 design modified to depth that is 0.75% of the standard (DIN 15061, 1977).

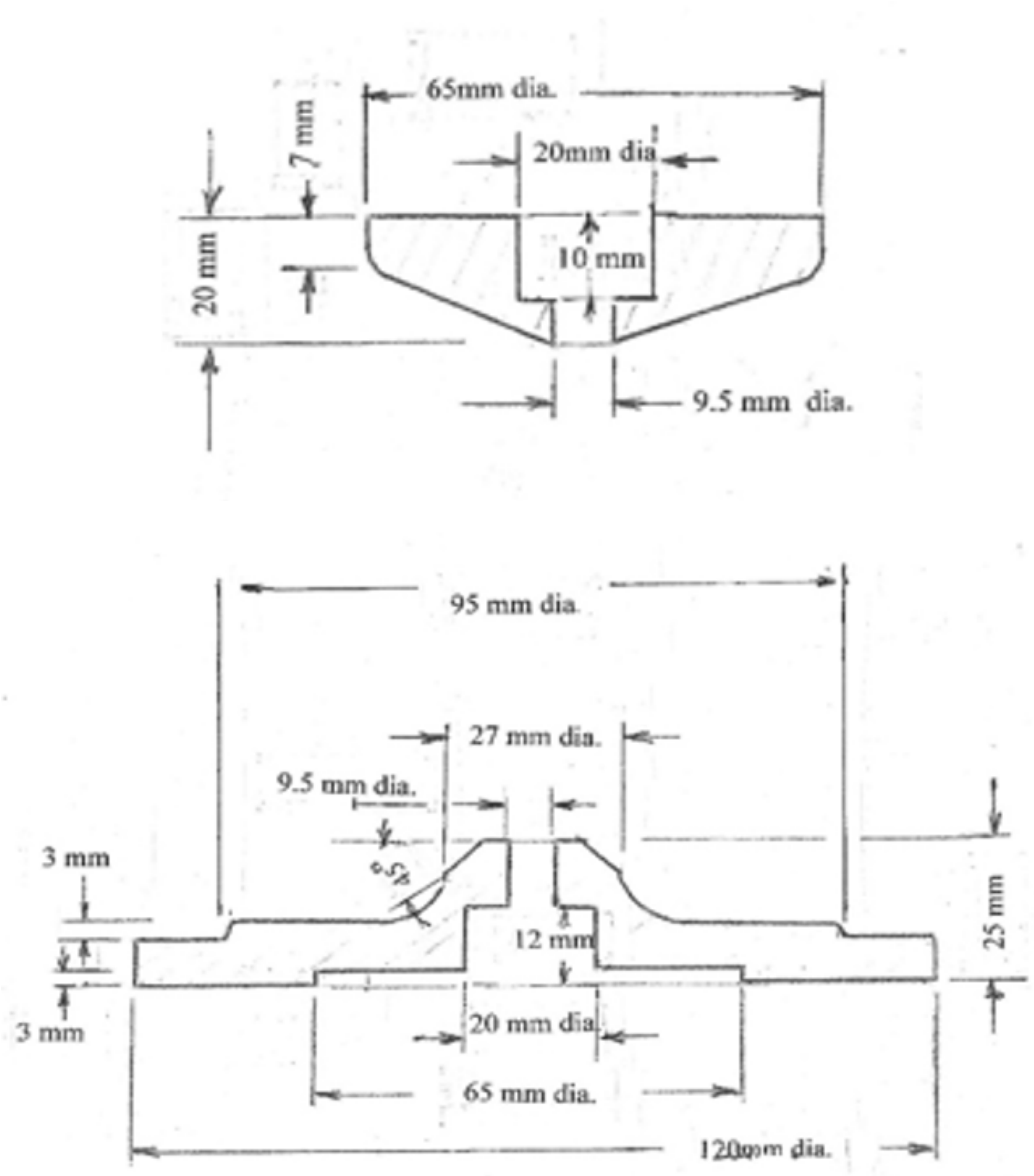
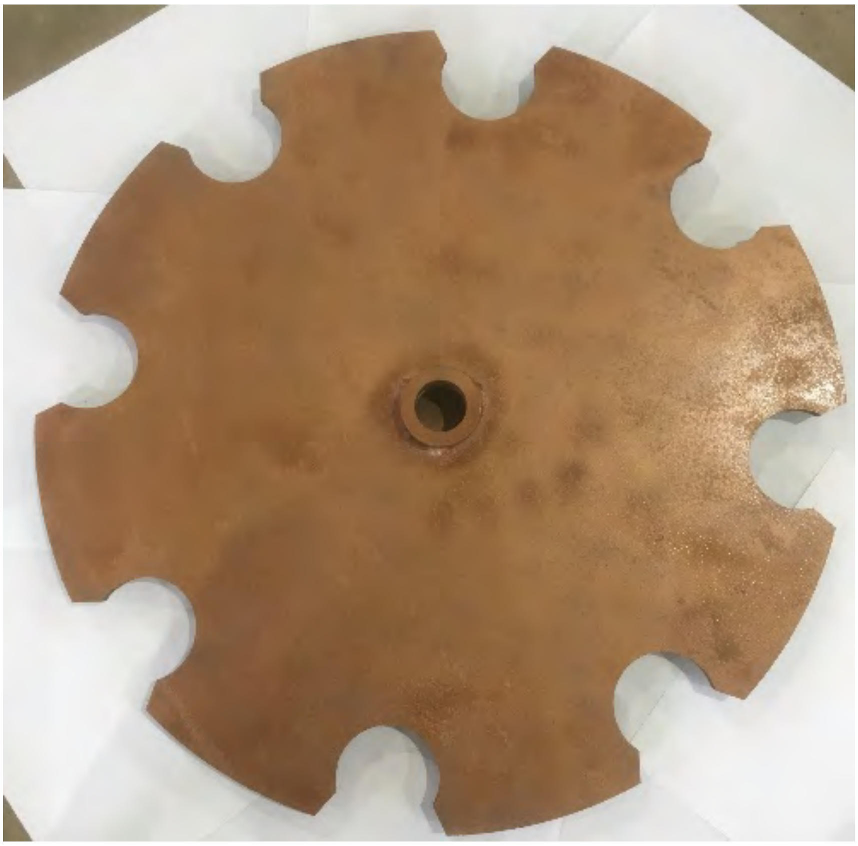


Figure 40. Cable elevator discs. The larger leading disc that carries the ore and the locking disc clamps around the swage



Picture 43. Cable sheave with 8-disc slots, used for the drive and idle sheaves.

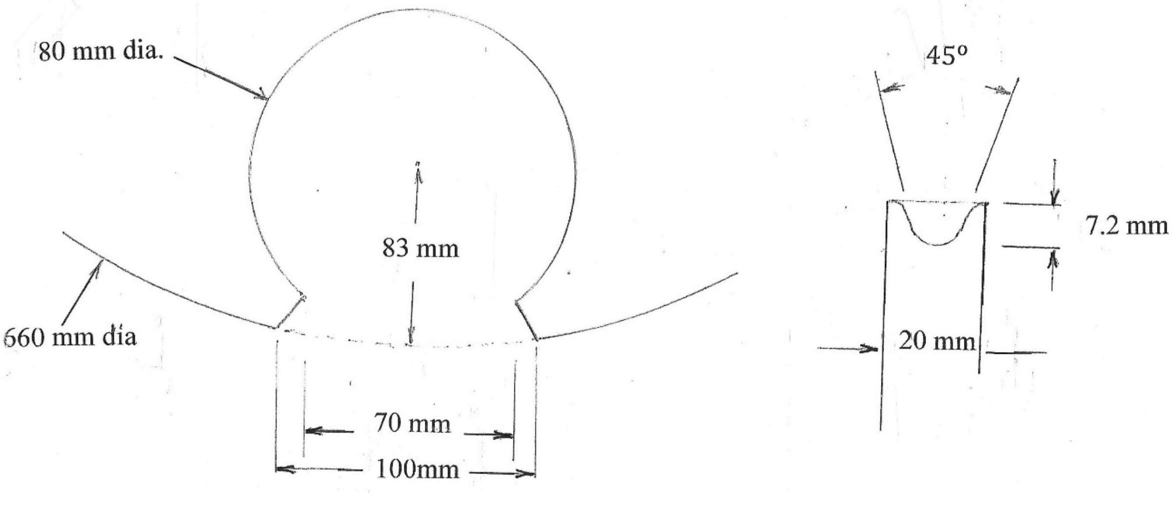


Figure 41. Sheave slot dimensions

Figures 38 and 39 are a sketch of the seal where the ore transitions between the cable disc elevator steel tubes and the pipe conveyor. The sketch in Figure 38 shows the transition where the ore is fed from the ore-infeed tube into zone 1 of the cable disc elevator and is lifted by the cable discs into zone 2. The seal is a simple 2ply poly belt clamped to the cable-disc elevator steel tube which then forms a cone that has full contact with the pipe conveyor belt. Any ore fall back lands back on the seal and falls back on the disc to be elevated. This seal did not leak ore in the tests regardless of the elevator speed. However there is friction between the stationary poly sealing belt material and the pipe conveyor. This force is measured.

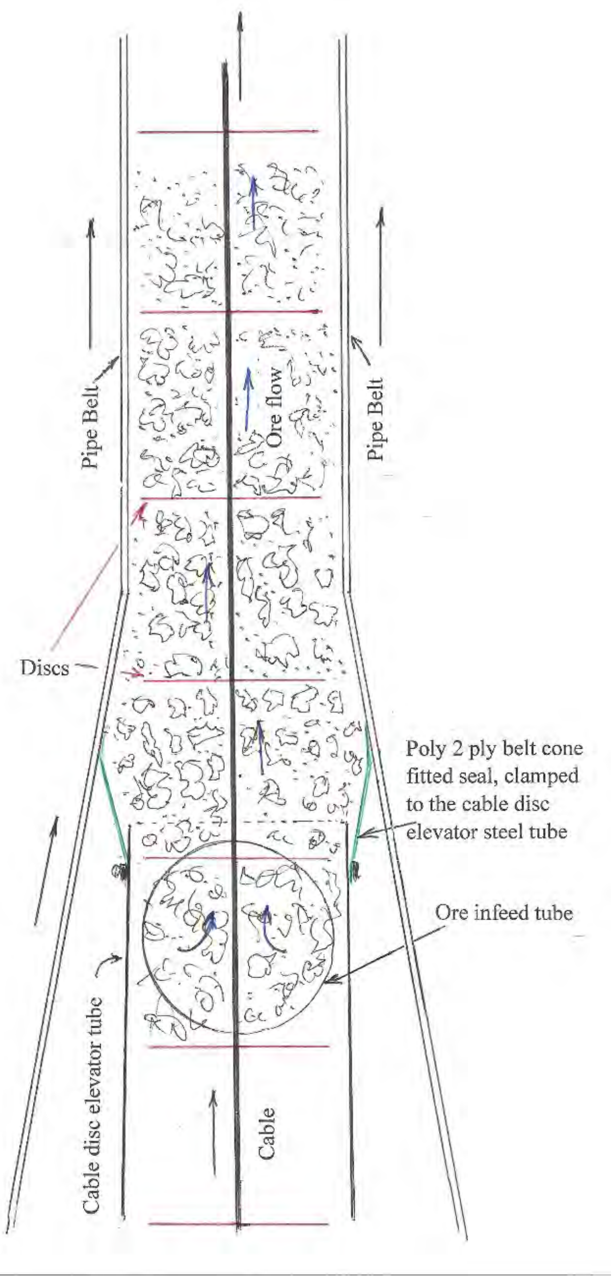


Figure 42. Cable disc elevator tube ore feed to transition to the pipe conveyor at the bottom of the elevator

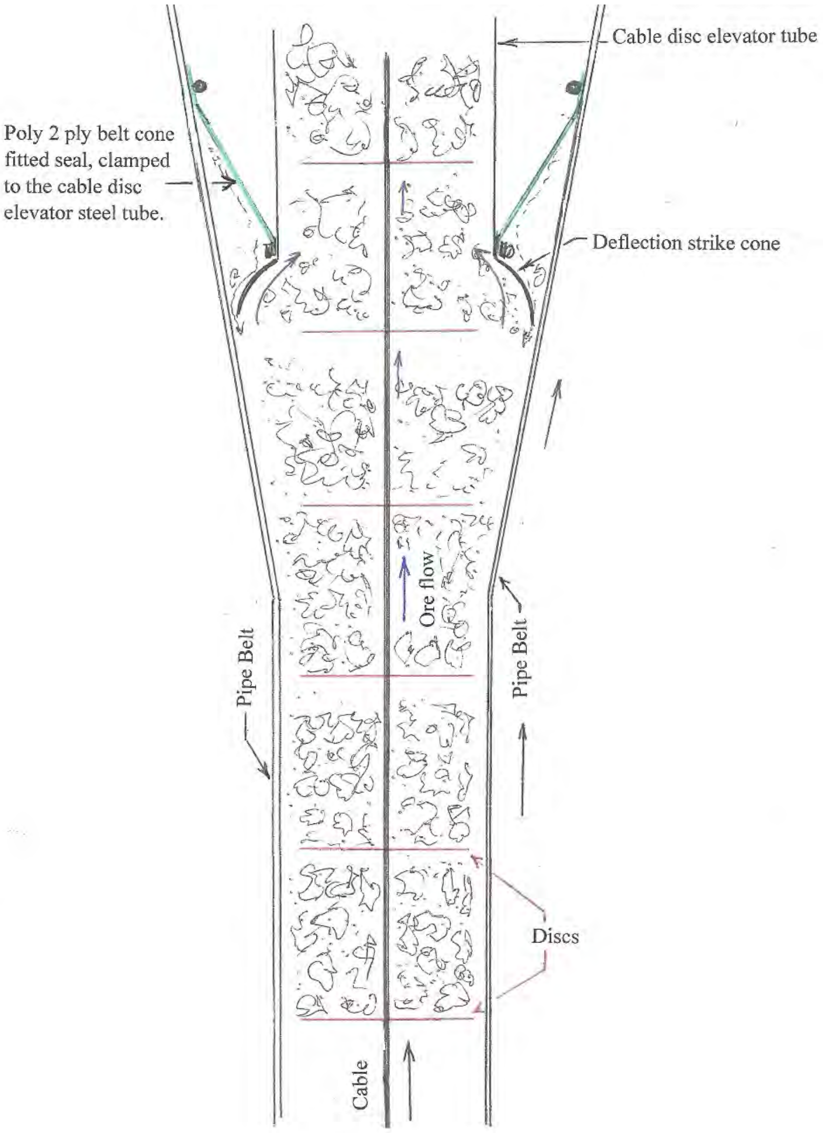


Figure 43. Pipe conveyor transition of the ore into the cable disc elevator at the top of the elevator

For the top seal where the ore is leaving the pipe conveyor section the cable disc elevator has a deflection coned flange attached. The stationary sealing poly belting (green) is clamped to the cable disc elevator to form a cone shape that has a firm contact with the pipe conveyor belt. The seal is a one-off design, as there are no such seals available commercially.

This seal was sensitive to elevator velocity. At slow speeds below 2m/s the seal leaked, however at higher velocities the ore stayed in the elevator and transitioned without leaking past the seal. There was no way of visually observing the interaction in the transfer of ore from the belt to the steel tube except to observe that the seal leaked at slow speed below 2.0 m/s. At the higher speed the ore is thrown forward and does not have enough time to spread to the wider section. Pressure set between the poly sealing belt and the pipe conveyor belt contributed to friction. The friction from the seals is measured for each seal.

7.1.2 Centre Panel and Tube Disc Gap for a Combined Cable Disc Elevator

Figure 44 is a sketch of the cross section of the elevator showing the pipe belt forming rollers, the conveyor belt roll shape and belt overlap, the lifting disc and the cable in the centre of the lifting disc.

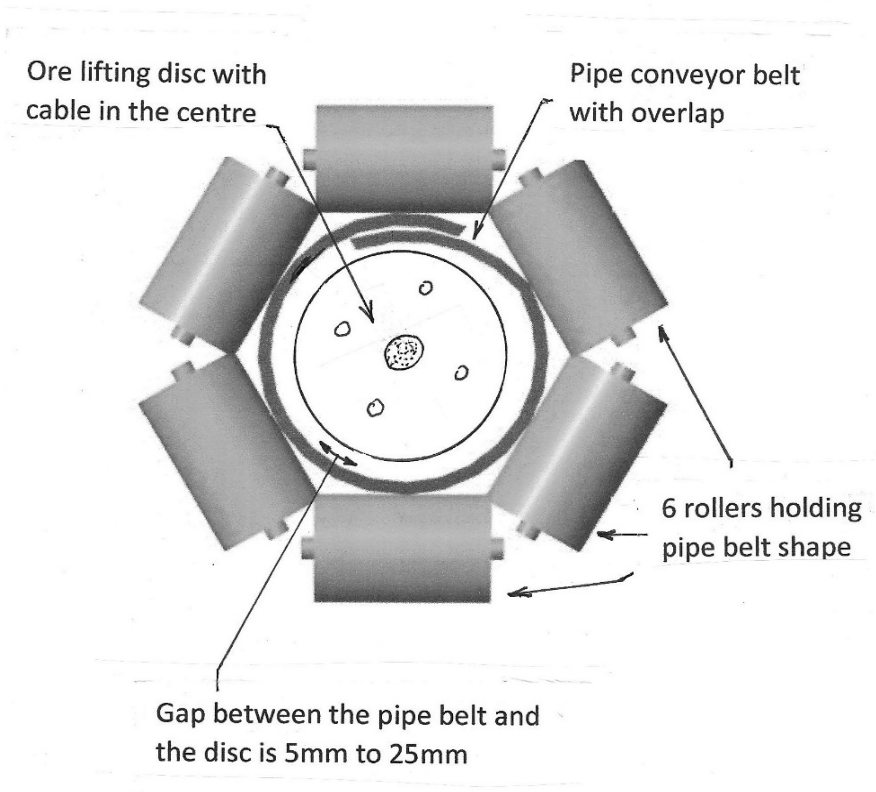


Figure 44. Drawing of the pipe conveyor section with the cable elevator disc in the centre.

This elevator size is referred as a 5-inch elevator; however, the discs are 120mm in diameter, and the gap between the disc and the pipe conveyor varies between 5 and 25mm. The average gap is estimated at 12.5mm. The outside diameter of the pipe as set by the rollers is 165mm and the overlap of the belt is 82 mm.

7.1.3 Ore Friction Zones

There are three friction zones in this test rig shown in Figure 39, however the measuring equipment only has the ability to measure the combined friction of the three zones. Zone 1 and 3 have been minimized in size to have the least effect on testing results. Other elevator friction forces such as those associated with the sheave bearings, cable sheave interaction is cancelled out by testing of the elevator with no load present. Blank tests are also run with no ore for the start-up of each test before ore starts to enter the elevator.

The zones are described as:

- Zone 2. This is the section of the elevator where the lifting side tube is the pipe conveyor. The cable disc elevator in zone 2 has 22 cable discs pulling ore through at any one time. Both elevators travel at the same velocity and there is no relative movement between the pipe conveyor and the cable disc elevator. In this zone, the gap between the pipe conveyor and the disc is variable as the pipe conveyor tube is not a perfect circle and the gap ranges from 5mm to 25mm as shown in Figure 44. This exposes the elevator to ore fall back of fine particles if the combined system does not have sufficient velocity. When the elevator is stopped, some fine particles trickle down, but eventually ore tends to bridge the gap. This results in more fine ore in the lower cells than the upper ones and some ore in the bottom cable disc elevator bottom sheave into zone 1

- Zone 3. In the short steel tube section above the pipe conveyor zone 3 there is no jamming between the steel tube for the ores selected in the tests. The gap between the discs and the fixed steel tube in this zone is 12.5mm. However, this is a very short distance of 400 mm long and all of the ore is less than 12.5 mm in size. The visual tests depicted in Pictures 31 to 35 where the gap was 2.5mm showed wedging of the rock that stopped the test at 1500mm. For this test rig, when there was a larger disc to tube gap, jamming did not happen. It is also the case (although this was not quantified) that the ore had momentum when it reaches zone 3 that may positively help product through the short distance of 400mm. Pictures 36-40 show the effect of ore falling off the disc with a disc to tube gap of 12.5mm, to minimize this effect zone three is as short as possible so that the momentum of the ore can carry through.

- Zone 1. This section is only 240mm long, hence there is just one disc at any one time in this zone. The disc gap is the same as for zone 3. Ore is added at the top of this zone. There was a vulnerability to the elevator when the elevator was stopped with loaded ore, where in some of the ore trickled back past the disc. This may not have happened if this tube is longer, and the disc tube gap is 2.5 mm as in Test Rig 2 because leaving a smaller gap that bridges more easily and cannot let large particles fall past into the lower sheave, plus more lower discs assist in sealing the gap. This was only a problem for the larger particles trickling back into the bottom sheave when the elevator was stopped loaded with ore. When the elevator is operating ore lands on the disc at the top of this zone.

When lifting for coal and gravel those ores sheared and the large particles disintegrated such that after three minutes of operation the particle size was less than one millimetre. In the test rig, ore recirculates back to the feed bin. A reduction in particle size did not happen for granite so there was no change in particle size distribution.

In this section the symbols T^P refers to the tensions associated with the pipe conveyor and T^c refers to the tensions associated with the cable disc elevator.

7.1.4 Forces Being Measured

There are three weigh load cell measuring sections:

- The amount of ore in the elevator. The ore bin is the same ore bin used in Test Rig 2 and has 4 load cells. The significance of the ore bin weight is that the amount of ore taken out of the bin is the quantity of ore in the elevator. Ore that the elevator lifts is returned to the ore bin. The ore being elevated is in a closed circuit. This bin is set on a frame and is lifted into position using the forklift. The bin is lifted down for convenience when changing ore samples. The load bin is shown in Picture 45.

- The force that is applied to lift the cable disc elevator cable is measured by the motor torque arm load cell. The force measured can be divided by the number of discs in the lifting side of the cable disc elevator, resulting in the force per disc calculation. The cable disc elevator motor has a torque arm that directly measures the force on the elevator cable. This can be seen in Picture 44.

- A load cell is mounted on the torque arm of the pipe conveyor belt drive and works on the same principle as the cable disc elevator drive motor. This weigh load cell measures the force needed to rotate the pipe conveyor belt. This is the force required to overcome the roller resistances and friction associated with the rotation of the belt. This is not a force relating to the ore friction. Also seen on the upper left top of Picture 44.

Picture 44 Test Rig 3 head drives with torque arms

Picture 45. The ore bin.

7.2 Ores Tested for Test Rig 3

The ores tested are from the same source as the three ores used in Test Rig 1 (gravel, granite and coal):

- Ungraded gravel, with the particle size shown in Table 11.
- Ungraded granite, with the particle size distribution shown in Table 10.
- Course coal as per the size outlined in Table 9.

The particles size is relevant for granite only, as this ore was the only one that did not disintegrate during testing. Coal and gravel reduced in size to less than 1mm during elevation. Crushed ungraded granite particle size mixed but less than 25mm in Picture 46 and sieve size in Table 98.

Picture 46. Crushed ungraded granite.

Table 98. (from Table 10). Granite particle size distribution

Sieve aperture size mm	Retention % per sieve	Total retention above sieve %
9.5	20.7	20.7
5.0	23.4	44.1
2.5	23.5	67.6
2.0	4.2	71.8
1.0	14.3	86.1
Pan	13.9	

A second sample of granite where the particles are between 5.0mm and 9.5mm are shown in Picture 46

Picture 47. Granite particle size less than 9.5mm greater than 5mm. No fines.

The granite in Picture 47 contains no particles smaller than 5.0mm, and no particles greater than 9.5mm. Samples of granite used in Pictures 46 and 47 would lead to jamming in Test Rig 1 and 2. These samples are used to test the ability of the hybrid elevator to use course product and variable topography.

7.3 Test Rig 3 The Pipe Conveyor Component

The function of the pipe conveyor is to hold ore on the discs of the cable disc elevator. This test rig is operated so that all the lifting is done by the cable disc elevator and there was no ore lifting force for the pipe conveyor. Calculations for the pipe conveyor are made on this basis. This section describes the pipe conveyor pictorially and detailed specifications for the belt that is used for this test rig. Further pictures of the pipe conveyor and the frame are in Appendix 7.

Testing of the belt is to establish the main forces that are exerted on this belt. This enables predictions to be made as to the vertical height that this belt could reach. To derive the data needed to calculate the potential length, the force required for the belt to rotate is measured using a load cell mounted on the torque arm of the motor drive, and one central panel of shape holding rollers mounted on four load cells. This data allows for the calculation of the total resistance of all the rollers, the shape forming and relaxing of the belt, and the resistance that was exerted by the seals that stopped ore from leaking out of the test rig, plus other miscellaneous forces including friction at the large drive and idle rollers at each end of the conveyor.

7.3.1 Pipe Conveyor Sections

The pipe conveyor is depicted in Figure 39 and is discussed below:

- Section 3 (in Figure 39). This section provides the power required to drive the pipe conveyor roller. The roller is 420mm in diameter and is driven by a 11-kw hollow shaft motor mounted on the roller shaft and supported by a torque arm attached to a load cell to measure the force being applied to the belt. The roller is rubber-coated to improve traction with the pipe conveyor belt. The motor drive is powered through a variable frequency controller that allows adjustment of the belt speed so that it can match the velocity of the cable disc elevator.
- Section 2 is the part of the pipe conveyor that has been formed into a tube and replaces the steel tube used in Test Rig 2. This holds the ore on the cable disc elevator discs. The objective of this section is that it travels at the same speed as the cable disc elevator cable so the only interaction between the discs, ore and tube is static with no relative motion.
- Section 1 has the idle roller at the bottom of the pipe conveyor and rotates freely with the belt, which is also covered in rubber to encourage good traction connection with the belt.
- The belt structure has a 3-layer textile core with a rubber infusion and covers on each side. It has a belt rating of ST1400. (see Table 4, AS1333-1994).
- Conveyor pipe framing consists of 11 pipe panels with infeed pipe belt shaping and out feed in sections 1 and 3.

7.3.2 Pictorial View of The Pipe Conveyor

Section 1. The pipe-shape forms from a flat belt and shifts to a tube shape. (Gabriel, 2012). This infeed shaping section should be 40 to 60 times the belt diameter of the external pipe belt for steel wire cable belts. However, this was not practical for the test rig as there were height restrictions at the test site that the pipe conveyor. Hence, the belt used is a textile belt like that in Figure 6, rather than a steel cable reinforced belt that cannot stretch the cables over a short distance (Cable steel wire characteristics in section 2.8). The short belt forming section can be seen in Picture 48.

Picture 48. Test rig 3. Pipe conveyor, tube forming end section 1.

Section 2. The pipe conveyor in this section is already in the pipe shape and is maintained in that shape by 11 panels of 6 rollers as shown in Picture 48. The two end panels are where the belt finally forms. This results in 9 centre panels 500mm apart that are used to maintain the belt's pipe shape. This is the section in which the ore is lifted by the cable disc elevator and is the longest section in the test rig and would be the longest section in any production elevator.

The six rollers on each panel are mounted with three rollers on each side of the panel. This allows the rollers to be longer, effectively overlapping each other and reducing any chance of the belt overlapping edge wedging between roller edges.

Section 3. This is the top end of the pipe conveyor where the belt is allowed to relax back to a flat belt before going over the drive roller. The belt is driven from that end when in the vertical position.

Section 4 is the return belt going back down the elevator to the idle roller. The flat belt return can be seen sagging under section 2 of the pipe conveyor in Picture 49. There are 3 rollers supporting the return belt while the pipe conveyor is in the horizontal position. These rollers have no function in the vertical position for the test rig, however in a long vertical elevator they stop the belt from whipping.

Picture 49. Test Rig 3. This shows all sections including section 4, which is the return of the belt to the lower idle roller under the pipe conveyor.

7.3.3 Test Rig 3, Pipe Belt Specifications

Table 99. Test Rig 3. Pipe conveyor belt specifications

Component	Dimensions
Belt width	600mm
Number of ply's	4
Cord material	Polyester
Covers	Transverse directly reinforced inside top cover
Covers grade	DIN W
Belt thickness	10mm
ST Rating	ST1400
Nominal mass length. kg/m	18 kg/m
Minimum breaking force.	1400N/mm
Operational strength F.o.S 6.67	210 N/mm
Belt length	24.4m (22.9m after joining)
Join	Cold join spice
Joining adhesive	Rema Tip Top, Cement SC 4000
Belt diameter	165mm (O.D.)

7.3.4 Belt Dynamics.

Abbreviations used for the pipe conveyor. This allows the formulae to be easily distinguished from that of those abbreviations for the cable disc elevator component.

Table 100. Symbols used for the pipe conveyor calculations

Symbol	item	Unit of measure
T_1^P	Maximum belt tension required	N, kN
T_2^P	Tension return belt	N, kN
T_e^P	Working tension	N, kN
T_e^{pctr}	Tension at the central idle panel roller resistance.	N, kN
T_2^{pTs}	Tension from the top seal	N, kN
T_2^{pBs}	Tension from the bottom seal	N, kN
LD	Lifting distance	m (metres)
D_n^P	Number of idler roller panels per metre	no unit.
BW	Belt lineal weight/ distance	kg/m
CW	Assembled cable weight per lineal metre	kg/m
T_e^{ps}	Tension to form pipe shape	N, kN
T_{sf}	Tension for shape recovery	N, kN

Using a standard equation for a drive roller on a conveyor from Metlikovic (2006)

eqn. 3.01 $$T_1^P = T_2^p + T_e^P \qquad (7.01)$$

Where T_2^p is the tension from the weight of the return belt.

T_e^P is the working tension in sections 1,2, and 3. This can be divided up into individual friction sections. These are the:

- Friction resulting from the top seal between the pipe conveyor and the cable disc elevator: T_e^{PTs}
- Friction resulting from the bottom seal: T_e^{PBs}
- Friction resistance from the pipe intermediate centre roller panels: T_e^{pctr}
- Friction from the pipe forming transition ends, drive and idle roller ends, plus the return belt idler rollers: T_e^{Ps}.

As noted above the return belt rollers have no input resistance when the pipe conveyor is in a vertical position.

T_e^p is the sum of all the resistances to motion (Harrison 2009) in the conveyor belt.

$$T_e^p = T_e^{PTs} + T_e^{PBs} + T_e^{pctr} + T_e^{Ps} \qquad (7.02)$$

7.3.5 Test Rig 3 Working Tensions Measured T_e^p

The purpose of the following tests is to establish the resistance to movement for T_e^p, by isolating the individual friction components in equation (7.02)

Tests are run with no ore present before being repeated with the top seal removed, then the bottom seal removed. The intermediate panel is held by weigh-load cells, which record the roller resistance for the six rollers on the panel. The final resistance without the seals and the roller panel resistance subtracted, is T_e^{Ps} which includes all other miscellaneous resistances, but mainly those that result from the pipe shaping.

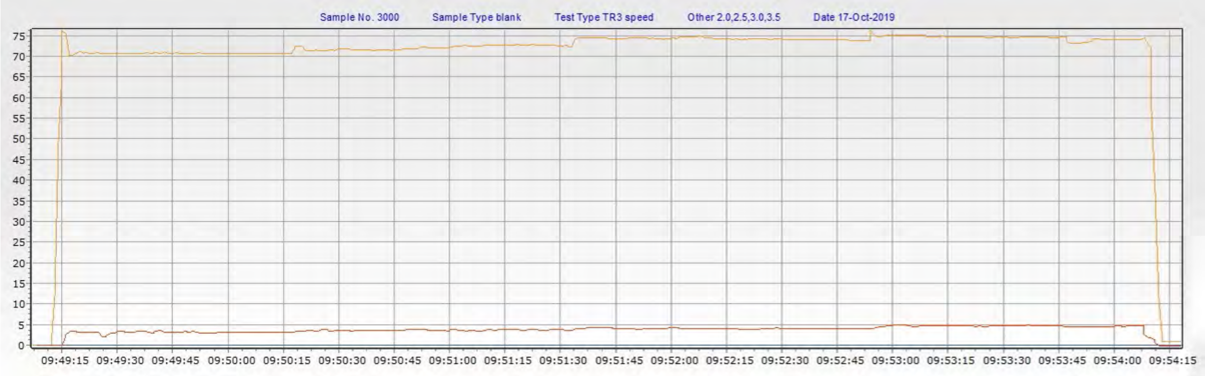
This data is later used in comparison with the data obtained when ore is lifted in the elevator. Any increase in effort will be considered to be a result of friction, any reduction in effort of the pipe conveyor will be considered lift from the cable disc elevator connected with the pipe conveyor belt by the ore.

The theoretical projection of a longer elevator will be considered that the only variable will be the increase in the number of centre roller panels. The other frictions will be assumed stay the same.

7.3.6 Test Rig 3 Pipe Conveyor Resistance with No Ore at 4 Different Speeds

This section measures the data for the pipe conveyor and the cable disc elevator under the conditions where there is no ore and the elevator is operated at 4 different speeds.

In this blank trial with no ore present in the elevator, and various operating speeds, the cable disc elevator and the pipe conveyor travel at the same speed. These speeds are 2.0m/s, 2.5m/s, 3.0 m/s, and 3.5 m/s. The force required to rotate the pipe conveyor belt is the sum of the rolling resistance, as in equation 7.02. This result is shown below in Graph 25 from test in Appendix 4 Table 420 run number 100. The measurements are taken from the torque arms of both motor drives. Note: the straight blue line for the ore bin is on the zero line and hence, demonstrates that no ore was discharged.



Graph 25. Test Rig 3 operating at various speeds with no ore present. Traces for the pipe conveyor and cable disc elevator. Appendix 4 Graph 420 test run number 100.

The data summary for Graph 23 is listed in Table 101.

Table 101. Test Rig 3 operating with no ore on the discs. Appendix 4 Table 420 run number 100

Time at measurement am.	Elevator velocity m/s	Avg. pipe conveyor tension kg	Avg. pipe conveyor tension T_e^p N	Avg. cable disc elevator tension kg	Avg. cable disc elevator tension T_e^C N
9.49.20 to 9.50.15	2.0	70.73	693.87	3.01	29.53
9.50.30 to 9.51.15	2.5	72.15	707.79	3.67	36.00
9.51.45 to 9.52.30	3.0	74.13	727.22	4.06	39.83
9.53.15 to 9.54.00	3.5	74.59	731.73	4.77	46.79

7.3.7 Test Rig 3 The Centre-Panel Roller Resistance, at 4 Different Speeds, Without Ore

The centre panel is shown in Figure 44 and Appendix 7 Picture 3B and 3C. This one roller panel is one of 9 such panels for the test rig. Only one panel is measured for roller resistance, however it is taken as representative of all the panels whether 9 or expanded to a thousand panels.

The centre panel resistance (T_e^{pctr}) is measured using four weigh load cells and with the pipe conveyor belt operating at different speeds. The importance of understanding the panel's resistance is to calculate the total resistance required for long distances by multiplying the result by the number of panels required. The resistance for the shape forming and deforming are the same as there is only one of those per elevator regardless of the conveyor length. The data in Table 106 below is from Appendix 4 Graph and Table 423, test run number 104. In this test only one panel of rollers is used to measure the roller resistance. There are 9 similar panels in the test rig.

As shown in Table 102 below, within the range of the test rig, the roller resistance reduced as the speed increased from 2.0 m/s to 3.5 m/s. The maximum speed specified by the manufacturer was 4.5 m/s that this pipe belt was not to exceed, however the rig was limited to 3.5m/s.

Table 102. Pipe conveyor centre panel roller resistance. No Ore present. Appendix 4 graph and table run number 422 and run number104

Time at measurement am.	Elevator velocity m/s	Avg. pipe conveyor tension kg	Avg. pipe conveyor tension T_e^p N	Avg. centre roller panel resistance measured for one panel. kg	Avg. centre roller panel resistance force for one panel T_e^{Pctr} N	Centre roller panel resistance calculated for 9 panels T_e^{Pctr} N	By difference all other resistances -shape forming -bottom and top seals -miscellaneous N
10:02:10 – 10:02:25	2.0	70.37	690.33	1.89	18.54	166.86	523.47
10:03:30 – 10:04:15	2.5	71.44	700.83	2.18	21.39	209.84	490.99
10:04:40 – 10:05:25	3.0	72.98	715,93	2.40	23.54	230.93	485.00
10:05:40 – 10:06:25	3.5	73.69	722.90	2.59	25.41	288.67	434.23

7.3.8 Test Rig 3. Testing the Pipe Conveyor Frictions

The elevator has seals at the transition points where the cable lifting the ore moves out of zone 1 into zone 2, and out of zone 2 into zone 3. These seals are stationary and press hard onto the pipe conveyor belt, which results in friction between the seal and the belt. Tests are used to measure the friction of both seals at the transition points. (See Figure 39 for the sections and Figures 42 and 43 for the seals). These seals have some pressure onto the pipe conveyor belt which results in fiction drag on the belt. The friction resulting from the seals is measured from blank runs with no ore present and, the results are determined by difference. This friction is a force that the pipe conveyor belt must overcome and therefore must be part of the pipe conveyor tension strength.

Regardless of how long the pipe conveyor is the seals are the same and the resistance is the same as the seals do not increase based on the length of the conveyor, only zone 2 increases in length.

The seal frictions are derived by measuring the tension of the blank no ore test, and by removing one seal at a time to measure the reduction in belt tension when the seals are removed.

- Determining the friction of the top seal using a blank run shown in Table 101 for the pipe conveyor run number 100 on Table 420 in Appendix 4. The top seal is then removed, and the test rig is run again with no ore under the same conditions. These results are in Appendix 4 Table 421 run number 105.The difference between the two results is from the friction of that top seal, T_e^{PTs}, where the superscript Ts is the top seal. This test in shown in Table 103.

- Determining the friction of the bottom seal T_e^{PBs} is done by using the results of the test rig in Appendix 4 Table 421 run number 105 with the top seal missing as the reference friction. The bottom seal was then removed, and the test rig is run under the same conditions now with no seals, for which the results are in Appendix 4 Table 422 run number 106 and the results by difference is the friction relating to the bottom seal, T_e^{PBs}.The subscript Bs refers to the bottom seal. The results for the bottom seal friction T_e^{PBs} are shown in Table 104.

- All other resistances in the pipe conveyor can then be calculated by difference. These are the pipe shape forming and relaxing, the resistances of the drive and idle rollers and other miscellaneous frictions. This is represented by the tension as T_e^{ps} and shown in Table 105.

Table 103. Test Rig 3 , top seal friction T_e^{PTs}. No ore present

Time at measurement am. run number 100 All seals in place	Elevator velocity m/s	Avg. pipe conveyor tension with the seals in place. Run Number 100 kg	Avg. pipe conveyor tension with the seals in place. N	Time at measurement am. run number 105 Top seal removed	Avg. pipe conveyor tension with the top seal removed. kg Run Number 105	Avg. pipe conveyor tension with the top seal removed. N	Friction from the top seal by difference T_e^{PTs} N
9.49.20 to 9.50.10 am	2.0	70.73	693.87	10.13.45-10.14.30	54.33	532.98	160.89
9.50.30 to 9.51.15 am	2.5	72.15	707.79	10.15.00-10.15.45	57.11	560.25	147.54
9.51.45 to 9.52.30 am	3.0	74.13	727.22	10.16.00-10.17.00	58.99	578.69	148.53
9.53.10 to 9.54.00 am	3.5	74.59	731.73	10.17.15-10.18.00	60.44	592.92	138.81

Table 104. Test Rig 3 Bottom seal friction T_e^{PBs}. No ore present

Time at measurement am. For run number 105	Elevator velocity m/s	Avg. pipe conveyor tension with only the bottom seal. Run Number. 105 N	Time at measurement am. run number with the top and bottom seal removed.	Avg. pipe conveyor tension with no seals. Run Number 106 kg	Avg. pipe conveyor tension with no seals. N	Friction from the bottom seal by difference T_e^{PBs} N
9.49.33 to 9.50.10 am	2.0	532.98	10.22.45-10.24.00	53.97	529.94	3.04
9.50.30 to 9.51.15 am	2.5	560.25	10.24.30-10.25.15	56.14	550.73	9.52
9.51.45 to 9.52.30 am	3.0	578.69	10.25.30-10.26.15	58.13	570.26	8.43
9.53.10 to 9.54.00 am	3.5	592.92	10.26.45-10.27.30	60.42	592.72	0.02

Table 105. Summary of the pipe conveyor tensions

Friction source	Avg. pipe conveyor tension T_e^p N	Avg. centre roller panel resistance T_e^{pctr} N		Friction from the top seal by difference T_e^{PTs} N	Friction from the bottom seal by difference T_e^{PBs} N	By difference all other resistances T_e^{ps} -shape forming -miscellaneous - drive and idle roller. N
		One panel	Nine panels			
Table that data was taken from Table number	101	102	102	103	104	Calculated
Elevator speed m/s						
2.0	693.87	18.54	166.86	160.89	3.04	363.08
2.5	707.79	21.39	209.84	147.54	9.52	340.89
3.0	727.22	23.54	230.93	148.53	8.43	339,33
3.5	731.73	25.41	228.67	138.81	0.02	304.23
	Working tension T_e^p N	One centre panel T_e^{pctr} N	Nine centre panels T_e^{pctr} N	Top seal friction T_e^{pTs} N	Bottom seal friction T_e^{pBs} N	Other frictions T_e^{ps} N
Maximum tensions	731.73	25.41	228.67	160.89	9.52	363.08

7.3.9 Pipe Conveyor Expansion to Greater Lengths

Using the data from Table 105 to calculate the distance this elevator belt can carry its own weight and overcome friction is based on the maximum frictions from Table 105. There were changes in friction at different speeds. When the elevator achieves the maximum speed of 3.5 m/s the elevator velocity would have transitioned through all speeds between 2.0-3.5 m/s. The speed of 3.5m/s was the maximum speed at which the test rig could operate.

Using equation 7.01 $\quad T_1^P = T_2^p + T_e^P$

Substituting for T_e^P from equation 7.02

Then $$T_1^P = T_2^p + T_e^{pTs} + T_e^{pBs} + T_e^{Pctr} + T_e^{Ps} \qquad (7.03)$$

For an elevator with lifting distance LD, with two centre panels per meter, and a belt weight (BW) of 18kg/m, the total tension required for the pipe conveyor belt is calculated as:

$$T_1^P = BW \, x \, LD \, x \, 9.81 + T_e^{pTs} + T_e^{pBs} + (T_e^{Pctr} \, x \, LD \, x \, D_n^P) + T_e^{Ps} \quad (7.04)$$

Substituting the maximum values from Table 105 and a LD of 1000m.

$$T_1^P = 18 \, x \, 1000 \, x \, 9.81 + 160.89 + 9.52 + (228.67 \, x \, 1000 \text{ x } 2) + 363.08$$

Then, for a 1000m lift, the belt tension requirement for this diameter pipe conveyor would be:

$$T_1^p = 322 \text{ kN}$$

The test rig belt has a safe tension capacity of 210N/mm and is 600mm wide. Then the total lifting safe capacity is:

$$T_1^p \;\; 126\text{kN}$$

To achieve a 1000m lift with this conveyor belt, the F.o.S would only be 2.61 or 3.91%.

Alternatively, if the belt were to operate at a F.o.S of 6.67 (15%), this would require a strength of 537N/mm for this size test rig. There are options available for such a belt especially for steel wire cable cord belts, for example the ST 710 steel wire belt with 42 cords for a 600mm wide belt in Table 3, as recorded in AS1333-1994.

For a longer belt than that in the test rig, there will be some increase in pressure on the head roller, and for steel wire cable cord belt, longer belt shaping sections.

The next section is about the cable disc elevator component of the hybrid elevator. It looks at two options. One is where the friction in the fixed tubes in zones 1 and 3 (Figure 39) and calculations are based on the data from Test Rig 2 and the other option of the experimental data from Test Rig 3.

7.4 Test Rig 3 A Cable Disc Elevator Component Modelled on Test Rig 2

In the previous section 7.3 the pipe conveyor was investigated for its frictions. This section is about the cable disc elevator that is inside the pipe conveyor.

The cable disc elevator in zones 1 and 3, shown in Figure 39, have a fixed steel tube, just as in Test Rig 2. Modelling for these zones primarily uses the Test Rig 2 data and examples where there is 1000 grams of ore on the disc, and where the ore cell volume between the discs is 80% full.

Data used for acceleration T_e^{ca}, lift T_e^{Lc} and friction between the tube and the ore T_e^{Lc} are taken from Tables 81 and 85. A superscript of C or c is used to denote that the symbols relate to the cable disc elevator (in order to distinguish these tensions from the pipe conveyor where the superscript is P or p). In zone-1, there is one disc, and zone 3 there are three discs. Each are, 250mm apart, which represents an equivalent of one metre in Test Rig 2 where acceleration of ore is included.

Zone-2 is only considered for the effect of gravity as the pipe conveyor belt and the cable disc elevator are travelling at the same speed, meaning there is no relative movement between these and hence that there is no friction.

7.4.1 Calculation of Tension for Acceleration in this Application for One Disc. From Section 6.10.3

Tension resulting from acceleration T_e^a.is taken from Table 85. (Using equations 6.13, 6.16, and 6.17). Acceleration of the ore only occurs for 250mm after which the ore is at the same speed as the cable and no further acceleration takes place. The only time the ore for the whole length of the cable is experiencing acceleration is when the cable has stopped fully loaded with ore and has to be restarted. The tension needs to then include the effects of the breakfree force and acceleration. For Test Rig 3 the ore is accelerated in zone 1.

The tension T_e^{ca} below in Table 106 are those that result from accelerating the ore from V_1.which is zero m/s to V_2 which is the cable operating velocity. These calculations are from Table 85 for 1kg of ore on the disc and for the amount of ore on the disc when the volume between the discs is 80% full.

Table 106. Cable tensions resulting from ore acceleration. Data taken from Table 85

Cable speed m/s		2.00	2.50	3.00	3.50
Time to accelerate (6.17) Seconds		0.125	0.100	0.083	0.071
Acceleration (a) (6.16) m/s^2		32.05	50.00	72.56	99.21
Tension T_e^{ca} to accelerate N (6.13)	m = ore mass kg	8.00 x m	12.5 x m	18.15 x m	24.8 x m
Tension T_e^{ca} to accelerate N (6.13) where m = **1kg**	Gravel Granite & Coal	8.00	12.50	18.15	24.80
Tension T_e^{ca} to accelerate N (6.13) were m = **3.13kg**	Gravel	25.04	39.13	56.81	77.62
Tension T_e^{ca} to accelerate N (6.13) were m = **4.09kg**	Granite	32.72	51.13	74.23	98.49
Tension T_e^{ca} to accelerate N (6.13) were m = **1.37kg**	Coal	13.36	20.88	30.31	41.42

7.4.2 Friction and Lift in the Steel Tube for Zones 1and 3

This section uses data from Test Rig 2 for zones 1 and 3 for the cable disc elevator component of the combined elevator.

There are 3 discs in the steel tube in zone 3 and 1 disc in zone1. The closest data to these zones is the data from Test Rig 2. This is not exactly the same as for Test Rig 2 however, this is the data available that measures friction. The main difference between Test Rig 2 and Test Rig 3 in the steel tube sections is the gap between the discs and the tube (12.5mm in Test Rig 3 and 2.5mm in Test Rig 2). For Test Rig 3, as the gap is larger than the ore size there will be no jamming. The data used to measure friction for particles 2mm size in the fixed steel tube and for the lift are taken from Table 89 in Section 6.13, where the calculations are made for 1metre of cable. With a disc separation of 250mm, one metre of cable represents 4 discs, equal to the number of discs combined in zones 1 and 3.

The total working tension T_e^c for 4 discs of ore and, one metre of cable in zones 1 and 3 is shown in Table 107. This includes the tension $T_e^{Lc}$to overcome gravity when lifting the ore 1 metre, taken from Table 88, and the tension to overcome friction T_e^{fc} in one metre of tube.

Table 107. (Based on Table 89). The total working tension force T_e in Newtons for one metre of elevator cable at various cable speeds.

Cable velocity V_2 m/s			2.0	2.5	3.0	3.5
Ore	Ore weight per disc g	Ore weight per cable m kg	$T_e^{fc}+T_e^{Lc}$ working tension for 1m of cable. N	$T_e^{fc}+T_e^{Lc}$ working tension for 1m of cable. N	$T_e^{fc}+T_e^{Lc}$ working tension for 1m of cable. N	$T_e^{fc}+T_e^{Lc}$ working tension for 1m of cable. N
Gravel	1000	4.00	50,04	47.16	47.60	44.88
	3128	12.51	156.48	147.48	148.88	140.36
Granite	1000	4.00	44.60	42.08	44.52	44.16
	4087	16.35	182.27	172.03	181.91	180.43
Coal	1000	4.00	44.88	43.20	44.08	45.24
	1370	5.48	61.44	59.20	60.40	61.96

In Table 107 above, the tension required to overcome acceleration for one disc T_e^{ca} (one disc) is not included.

7.4.3 Tension T_e^C in Zones 1 and 3 as a Constant

Regardless of the length of this elevator the results for the working tension T_e^c for zones 1 and 3 do not change, as these two sections only represent the inlet and outlet of the combined pipe and cable elevator.

These tensions are calculated using data from Test Rig 2, where the cable disc elevator is inside a fixed steel tube, as in zone 1 and 3.

Working tension Zones 1and 3

$$T_e^c = T_e^{fc} + T_e^{Lc} + T_e^{ac} \qquad (7.05)$$

Table 108. Test Rig 3. Zones 1 and 3 friction calculated in the fixed tubes from addition of Tables 106 and 107

Cable velocity V_2 m/s			2.0		2.5		3.0		3.5	
Ore	Ore weight per disc g	Ore weight per cable m kg	T_e^c Total working tension for 1m of cable. N		T_e^c Total working tension for 1m of cable. N		T_e^c Total working tension for 1m of cable. N		T_e^c Total working tension for 1m of cable. N	
			N	$\%T_e^f$	N	$\%T_e^f$	N	$\%T_e^f$	N	$\%T_e^f$
Gravel	1000	4.00	58.04	18.61	59.66	13.28	65.75	12.68	69.68	8.09
	3128	12.51	181.52	18.63	186.61	13.27	205.69	12.72	217.98	8.09
Granite	1000	4.00	52.60	10.19	54.58	5.20	62.67	8.43	68.96	7.13
	4087	16.35	214.99	10.18	223.16	5.22	256.14	8.40	278.92	7.18
Coal	1000	4.00	52.88	10.66	55.70	0.66	62.23	7.78	86.76	6.92
	1370	5.48	74.8	10.27	80.08	6.79	90.71	7.32	103.38	7.93

In Table 108 the numbers in red is the percentage of the working tension T_e^c relating to friction.

7.4.4 Tension in Zone 2 to Overcome Gravity T_e^{cL}

This section of Test Rig 3 is 5.5 metres high and has 22 discs. The force required to lift the ore is given by equation 6.14.

$$T_e^{cL} = m.g$$

Table 109. Calculat of tension T_e^{cL} in the pipe conveyor section Zone 2 to overcome gravity-equation (6.14)

Ore	Ore weight per disc g	Ore weight for 22 discs kg (5.5 m)	TensionT_e^{cL} against gravity for 22 discs. N (5.5 m)	TensionT_e^{cL} against gravity for 1m. N
Gravel	1000	22.00	215.82	39.24
	3128	68.82	675.12	122.75
Granite	1000	22.00	215.82	39.24
	4087	89.91	882.02	160.37
Coal	1000	22.00	215.82	39.24
	1370	30.14	295.67	53.76

7.4.5 Test Rig 3. Total Working Tension T_e^c for Ore in Zones 1,2 and 3 for the Cable Disc Elevator

In sections 7.4.1 to 7.4.4 above the working tension T_e^c is calculated using the friction T_e^{fc} , acceleration T_e^{ca} , and lifting T_e^{cL} required to overcome gravity based on data of Test Rig 2 for zones 1 and 3 over one metre. Zone 2 tension is calculated when lifting without any friction.

For Test Rig 3, the sum of the working tensions T_e^c for zones 1, 2 and 3 are calculated by adding the data from Tables 108 and 109, as shown in Table 110. This table is used to predict the working tension for the cable disc elevator in the combined elevator using data from the trials runs for Test Rig 3. The percentage friction calculation uses the friction over one metre from Table 87.

Note: that the working tensions T_e^c for the cable disc elevator component are fixed for zones 1 and 3. The variable is the working tension for zone 2 when the lifting distance is increased. In Table 110, the influence of friction only comes from zones 1 and 3 and the friction varies between 3.94 and 1.05% and is not relevant to zone 2. Hence, increasing the length of zone 2 does not increase the magnitude of the friction, which results in the overall friction percentage reducing.

Table 110. Test Rig 3 Total working tension T_e^c for the cable disc elevator for one metre

Cable velocity V_2 m/s			2.0		2.5		3.0		3.5	
Ore	Ore weight per disc g	Ore weight per cable metre kg	T_e^cTotal working tension combined zones 1.2& 3 for 1m of lift.		T_e^cTotal working tension combined zones 1.2& 3 for 1m of lift.		T_e^cTotal working tension combined zones 1.2& 3 for 1m of lift.		T_e^c Total working tension combined zones 1.2& 3 for 1m of lift.	
			N	%T_e^f	N	%T_e^f	N	%T_e^f	N	%T_e^f
Gravel	1000	26.00	273.96	3.94	275.48	2.87	281.57	2.97	285.50	1.98
	3128	81.33	856.64	3.94	861.73	2.87	880.81	2.97	893.10	1.98
Granite	1000	26.00	268.42	2.00	270.40	1.05	278.49	1.90	284.78	1.73
	4087	106.26	1096.01	2.00	1105.18	1.05	1138.16	1.89	1160.94	1.73
Coal	1000	26.00	268.70	2.10	271.52	1.46	278.05	1.74	302.58	1.98
	1370	35.62	370.47	2.07	375.75	1.45	386.38	1.72	399.05	2.05

7.4.6 Test Rig 3 Projection of the Cable Disc Elevator Working Tension when Zone 2 is 1000m High

Zone 2 conditions are:

- The test rig discs on the cable are 250mm apart.
- For a 1000m lift there are 4000 discs.
- In zone 2 the cable disc elevator is travelling at the same speed as the pipe conveyor, so fiction is not considered hence the only tension is T_e^{cL}.
- There is no ore acceleration in zone 2, as this happened in zone 1.
- The lifting tension component per disc is calculated using equation 6.14.

$$T_e^{cL} = m.g$$

Table 111. Test Rig 3, zone 2. Tension required to overcome gravity N for 1000 metre of cable. Equation (6.14)

Ore	Ore weight per disc g	Ore weight per cable m g and kg	Ore tension T_e^{cL} against gravity for 1m of cable. N	Ore weight for 1000 metres of cable tonnes	Ore tension T_e^{cL} against gravity for 1000m of cable. kN
Gravel	1000	4000	39.24	4.00	39.24
	3128	12.51	122.72	12.51	122.72
Granite	1000	4000	39.24	4.00	39.24
	4087	16.35	160.39	16.35	160.37
Coal	1000	4000	39.24	4.0	39.24
	1370	5.48	53.76	5.48	53.76

The next Table 112 uses zone two results to expand to 1000m and adds the tensions for zone 1 and 3 in order to have a total working tension T_e^c.

Table 112. Test Rig 3 Calculations for 1000m ore lift and the percent of the tension relating to friction

Ore	Ore weight per disc g	Ore weight per cable m g and kg	TensionT_e^L against gravity for 1m of cable. N	Ore weight for 1000 m of cable tonnes	Tension T_e^L against gravity for 1000m of cable. kN	T_e^c Total working tension combined zones 1.2& 3 for 1m at velocity 3.5 m/s N	T_e^c Total for 1000m lift elevator kN	Friction %
Gravel	1000	4000	39.24N	4.00	39.24	285.5	39.53	0.014
	3128	12.51	122.72N	12.51	122.72	893.1	123.61	0.014
Granite	1000	4000	39.24N	4.00	39.24	284.78	39.52	0.015
	4087	16.35	160.39N	16.35	160.37	1160.94	161.53	0.012
Coal	1000	4000	39.24N	4.0	39.24	302.58	39.54	0.015
	1370	5.48	53.76	5.48	53.76	399.05	54.10	0.015

In the cable disc elevator component, the test results from Test Rig 2 are used for zones 1 and 3. These zones have a friction component T_e^{cL}, and an acceleration T_e^{ca} and lift component T_e^{cL}, all of which are used in these calculations. The theoretical calculations for a projected cable disc elevator and pipe conveyor demonstrate that the effect of the friction from zones 1 and 3 are diluted when zone 2 is added to and lengthened.

Applying equation 3.01 for the cable disc elevator inside Test Rig 3.

$$T_1^c = T_e^c + T_2^c$$

To project the lifting capability the cable disc elevator the tension required to hold the elevator cable assembly T_2^c has to the added. To calculate a theoretical cable tension the Bridon 40mm data is used (Table 4). For the 5-inch elevator the volume displacement was also calculated in Section 5.2 and shown in Figure 32. By using the data from Test Rig 2 for the one metre where the steel tube in zones 1 and 3 the volume displacement has been absorbed into the calculations.

The tension of the return side for a 40mm cable T_2^c is taken from Table 58 in Chapter 6, using the maximum tension T_1^c for the lifting side of the elevator, which can be calculated from equation 3.01 and is shown in Table 113. The friction between the ore and the steel tube is only relevant in zones 1 and 3.

Table 113. Maximum tension T_1^c for the cable disc elevator inside the pipe conveyor at 1000m lift

Ore	Ore weight per disc g	Ore weight per cable metre g and kg	T_e^c Total for 1000m lift elevator kN	T_2 40mm cable Table 58 88.3kN / 1000m	T_1^c kN	Friction % x 10^{-3}
Gravel	1000	4000	39.53	88.3	127.8	4.4
	3128	12.51	123.61	88.3	211.9	8.3
Granite	1000	4000	39.52	88.3	127.7	3.9
	4087	16.35	161.53	88.3	249.8	8..0
Coal	1000	4000	39.54	88.3	127.8	4.7
	1370	5.48	54.10	88.3	142.4	5.7

7.4.7 A Theoretical Formula for the Cable Lift Distance of 1000m Combining Zones 1, 2, and 3

For an elevator based on Test Rig 3 where zone 2 is 1000metres the working tension can be calculated as the sum of all the resistances to motion, as discussed by Harrison (Harrison, 2009). In this example the working tension is that in zone 1 and 3, plus zone 2 at 1000metres.

$$T_e^c = (T_e^{fc} + T_e^{Lc}\,(1\mathrm{m}) + T_e^{ac}) + T_e^{Lc}(1000\mathrm{m}) \qquad (7.06)$$

$$T_e^{Lc}(1000\mathrm{m}) = LD \text{ x } m \text{ x } D^n \text{ x } g \qquad (7.07)$$

and

$$T_2^L = LD \text{ x } CW \text{ x } g \qquad (7.08)$$

using equation 3.01

$$T_1^c = T_e^c + T_2^c$$

substituting with equations 7.05, 7.06 and 7.07

$$. \; T_1^c = (T_e^{fc} + T_e^{Lc}\,(1\mathrm{m}) + T_e^{ac}) + LD \text{ x } m \text{ x} D^n \text{ x } g + LD \text{ x } CW \text{ x } g \qquad (7.09)$$

Resolving for the lifting distance:

$$LD = \frac{T_1^c - (T_e^{fc} + T_e^{Lc}\,(1\mathrm{metre}) + T_e^{ac})}{g\,(m \text{ x } D^n + CW)} \quad \text{metres} \qquad (7.10)$$

Alternatively, for a predetermined lifting height, cable strength required can be calculated by rearranging equation 7.09 for tension T_1^c :

$$T_1^c = LD \times g\,(m \times D^n + CW) + (T_e^{fc} + T_e^{Lc}\,(1m) + T_e^{ac}) \quad N \qquad (7.11)$$

Substituting equation 7.04 where T_e^c is the working tension for zone 1 and 3, plus one metre of lift into equations 7.09 and 7.10:

$$T_e^c = (T_e^{fc} + T_e^{Lc}\,(1\text{metre}) + T_e^{ac}) \quad \text{into equations 7.10 and 7.11:}$$

Then the lifting distance can be calculated as: $$LD = \frac{T_1^c - T_e^c}{g\,(m \times D^n + CW)} \quad \text{metres} \quad (7.12)$$

When there is a predetermined cable tension specification. For a predetermined lifting distance, the required cable tension can be calculated as:

$$T_1^c = LD \times g\,(m \times D^n + CW) + T_e^c \qquad N \qquad (7.13)$$

The calculation in Table 114 below use equations 7.12 and 7.13 to determine the maximum lift using the 40mm cable and the cable tension required for the ore to be lifted for 1000 metres in an elevator in Test Rig 3. For zones 1 and 3, the friction in those tubes, the acceleration of the ore over a distance of 250mm and the vertical lift over one metre are selected from Test Rig 2. The lifting tension in zone 2 is calculated based on there is no friction and no acceleration in this zone.

Table 114 below shows the example where the Bridon 34LR 40mm cable is selected to calculate its lifting height when the lifting height is determined by the capability of the cable of 219kN in the cable disc elevator inside the pipe conveyor when using equations 7.12 and 7.13. Alternatively, when using the same equations and setting the lifting height at 1000m, the required cable tension can be calculated.

Table114. Test Rig 3 lifting distance calculations for a selected 40mm cable. Cable tension required for 1000 metre lift

Ore	m. Ore weight per disc Selected from Table 114 kg	Equation number	T_1^C Specified by cable selection kN	LD Lifting distance Specified m	T_e^c for one metre of lift data from Table 110 Equation 7.04 N	BW 40 mm dia., cable selected from Table 58 at 9.0 kg/m	LD Lifting distance determined by calculation m	Required cable strength for 1000m lift. T_1^C Determined by calculation. kN
Gravel	1.000	7.11	219.0	x	285.50	9.0	1715	x
	3.218	7.11	219.0	x	893.10	9.0	1034	x
	1.000	7.12	x	1000	285.50	9.0	x	127.8
	3.218	7.12	x	1000	893.10	9.0	x	211.9
Granite	1.00	7.11	219.0		284.70	9.0	1715	x
	4.087	7.11	219.0		1160.94	9.0	876	x
	1.000	7.12	x	1000	284.70	9.0		127.8
	4.087	7.12	x	1000	1160.94	9.0		248.7
Coal	1.000	7.11	219.0	x	302.58	9.0	1715	x
	1.370	7.11	219.0	x	399.05	9.0	1534	x
	1.000	7.12	x	1000	302.58	9.0	x	127.5
	1.370	7.12	x	1000	399.05	9.0	x	142.4

Section 7.4 used the friction results for the cable disc elevator from Test Rig 2. Acceleration lift against gravity is the same for Test Rigs 2 and 3.

In the next section friction in the cable disc elevator component of the hybrid elevator is determined by experimentation. The effect of the pipe conveyor is also explored and its relationship, if any, to the cable disc elevator apart from holding the ore on the discs.

7.5 Test rig 3 Combining the Pipe Conveyor and the Cable Disc Elevator.

This section examines the graphs and data from the operation of Test Rig 3 in order, to assess the influence of the pipe conveyor on friction or the resistance to movement of the ore, and the force required to lift the ore through zones 1, 2 and 3. All data used in this section is from the experimental trials conducted using Test Rig 3.

7.5.1 Cable Disc Elevator, Pipe Conveyor and Ore Bin Load Data.

The following tables are a summary of the data that was obtained when operating Test Rig 3. The graphs and data summaries are documented in Appendix 4. Tables below are for:

- Gravel Table 115
- Granite Table 116
- Coal Table 117

There are three data inputs that have the most significance to the operation of Test Rig3 once the elevator velocity has been set:

- The ore bin weight measured by load cells, determines the amount of ore that is in the elevator. Ore is discharged out of the ore bin into the elevator which lifts the ore and the ore is returned to the bin via a chute. This is a closed circuit so the weight of ore missing from the ore bin is the ore in the elevator. This is the same system that was used in Test Rig 2. The ore bin in Picture 45. Further details of the loadcells are pictured in Appendix 7. The elevator ore discharge chute is part of the bin weight.
- The total force on the cable disc elevator cable T_1^C is measured by a weigh load cell holding a motor torque arm shown in Picture 45 on the grey motor.
- The total force on the pipe conveyor T_1^P is also measured by a single weigh load cell shown in Picture 45 on the blue motor.

Table 115. Gravel, data for the combined cable disc and pipe conveyor elevator tensions

Table number Appendix 4	Test run number Appendix 4	Ore type	Elevator speed	Ore bin feed screw speed	Ore weight in the elevator 26 discs		Cable disc elevator tension zone-1-2-3		Pipe conveyor tension.	
			m/s	setting	kg	N	kg	N	kg	N
400	81	gravel	2.0	22	26.49	259.87	27.55	270.27	79.21	777.05
401	82	gravel	2.0	44	52.36	513.65	55.27	542.2	77.84	763.61
402	83	gravel	2.0	44	52.88	518.75	54.16	531.65	71.77	704.06
			0.0	0.00	25.44	249.57	0.03	0.29	0.34	3.33
			2.0	44	52.68	516.79	54.81	498.77	72.12	707.50
403	107	gravel	2.0	22	22.05	216.31	26.42	259.18	70.39	690.53
			2.5	22	18.62	182.66	20.59	201.99	71.56	702.00
			3.0	22	15.62	153.23	17.74	174.03	72.36	709.85
			3.5	22	11.61	113.89	13.47	132.14	73.18	717.90
404	91	gravel	2.0	11	15.21	149.21	17.01	166.87	69.93	686.01
405	92	gravel	2.0	17	19.16	187.96	21.34	209.35	71.18	698.27
406	93	gravel	2.0	44	52.34	513.46	53.67	526.50	71.55	701.91

Table 116. Granite, data for the combined cable disc and pipe conveyor elevator tensions

Table number Appendix 4	Test run number	Ore type	Elevator speed	Ore bin feed screw speed	Ore weight in the elevator 26 discs		Cable disc elevator tension zone-1-2-3		Pipe conveyor tension.	
			m/s	setting	kg	N	kg	N	kg	N
407	88	granite	2.0	11	15.58	152.84	17.13	168.05	70.82	694.74
408	89	granite	2.0	17	19.28	189.14	20.95	205.52	70.98	696.31
409	90	granite	2.0	22	19.74	193.65	24.55	240.84	70.71	693.67
410	108	granite	2.0	22	22.17	217.49	25.93	254.37	70.56	629.19
			2.5	22	18.81	184.53	21.62	212.09	72.01	706.42
			3.0	22	15.69	153.92	17.99	176.48	72.73	713.48
			3.5	22	11.74	115.17	12.89	126.45	73.68	722.80
411	86	granite	2.0	44	52.33	513.36	55.43	543.77	71.46	701.02
			0.0	0.0	26.15	256.53	0.05	0.49	0.01	0.10
			2.0	44	52.45	514.53	55.24	541.90	71.32	699.65
412	87	granite	2.0	44	52.67	516.69	55.42	543.67	70.35	690.13

Table 117. Coal, data for the combined cable disc and pipe conveyor elevator tensions

Table number Appendix 4	Test run number Appendix 4	Ore type	Elevator speed	Ore bin feed screw speed	Ore weight in the elevator 26 discs		Cable disc elevator tension zone -1-2-3		Pipe conveyor tension.	
			m/s	setting	kg	N	kg	N	kg	N
413	94	coal	2.0	11	12.57	123.31	14.15	138.81	70.38	690.42
414	95	coal	2.0	17	18.34	179.92	20.21	198.26	70.49	691.51
415	96	coal	2.0	22	24.32	238.58	26.58	260.75	71.10	697.49
416	97	coal	2.0	17	18.53	181.78	20.26	198.75	70.14	688.07
			3.5	17	8.23	80.74	10.11	99.71	72.71	713.29
417	98	coal	2.0	22	24.86	243.88	26.44	259.38	70.74	693.96
			3.5	22	12.67	124.92	15.67	153.72	73.12	717.31
418	99	coal	2.0	17	18.61	182.56	20.23	198.46	70.68	693.37
			0.0	0.0	10.60	103.99	0.05	0.49	0.12	1.18
			2.0	17	18.27	179.23	20.23	199.34	70.84	694.94
419	109	coal	2.0	22	22.28	218.57	26.23	257.32	71.02	696.71
			2.5	22	18.67	183.15	20.81	204.15	72.72	713.38
			3.0	22	15.56	152.64	17.74	174.03	72.81	714.27
			3.5	22	11.66	114.38	13.44	131.85	72.82	714.36

7.6 The Influence of Ore on the Pipe Conveyor in the Combined Elevator

The influence of the pipe conveyor in this elevator system aims to hold the ore on the discs without creating any friction. This is tested at different speeds, with and without ore, and with different amounts of ore on the discs.

7.6.1 Calculation of the Friction Force between the Seals in Zones 1 and 3 on the Pipe Conveyor Belt

This section examines the friction effect of the seals in zone 1 and 3, the influence on the elevator rolling resistance when there is an increased amount of ore on the discs, and when the elevator is operating at different speeds.

The data for this table is taken from Appendix 4 from the tables numbered and the run numbers. The objective is to demonstrate the influence of the seals on the pipe conveyor tension. The focus is only on top and bottom seals regardless of the conveyor height. The main observation was that the faster the elevator ran; the less work was done by the seals to keep ore in the system. One way to interpret this is that the ore has sufficient momentum to carry through into the steel flanged entrance of the cable disc elevator tube in zone 3. Loosening the seal and operating with ore also confirmed that observation. However, it was not possible to have no seals without experiencing ore loss. The seals and the flanged entrance of the steel tube are shown in Figure 42 and 43.

Table 118. Elevator transition seals in zone 1 and zone 3. Friction between the seal and the pipe conveyor results

Table number Appendix 4	Test run number Appendix 4	Elevator operation	Component tested	Elevator speed	Cable disc elevator tension.		Pipe conveyor tension.	
				m/s	kg	N	kg	N
420	100	No ore	Total pipe conveyor resistance	2.0	3.13	30.71	70.67	693.27
				2.5	3.70	36.30	71.77	704.06
				3.0	4.13	40.52	74.42	730.06
				3.5	4.79	46.99	74.85	734.28
421	105	No ore, no top seal	Pipe conveyor resistance	2.0			54.33	532.98
				2.5			57.11	560.25
				3.0			58.99	578.69
				3.5			60.44	592.92
422	106	No ore, no top seal, no bottom seal	Pipe conveyor resistance	2.0			53.97	529.45
				2.5			56.14	550.73
				3.0			58.13	570.26
				3.5			60.42	592.72
Pipe conveyor tension difference from run numbers 100 - 106		Total seal resistance	Calculation of the seal resistance in the pipe conveyor	2.0				162.82
				2.5				153.33
				3.0				159.80
				3.5				141.56

Calculating the seal resistance as a percentage of the total conveyor belt tension for this test rig is not relevant as the seals are a fixed item at each end of the elevator regardless of elevator lifting height. It can be noted that, as the elevator speed increased there was a consistent increase in the total working tension T_e^p.

7.6.2 Pipe Conveyor and Cable disc Elevator with Small Loads

The following data compares the tension of the cable disc elevator resulting from the ore load, and the tension on the pipe conveyor. Tables 403, 410 and 419 in Appendix 4 show that the force on the cable disc elevator reduces as speed V_2 increases, even when the ore flow rate is constant at 22 rpm as the ore is returned to the ore bin in less time so there is less ore in the elevator. However, the pipe conveyor tension increases with speed, in a similar manner as it does even when there is less ore, or where there is no ore present as shown in Table 420 of Appendix 4.

Table 119. Pipe conveyor tensions and elevator speed with fixed ore flow rate at 22rpm

Table number Appendix 4	Test run number Appendix 4	Ore type	Elevator speed	Ore weight in the elevator 26 discs	Ore force due to gravity in zone 2 for 22 discs	Pipe conveyor tension.
			m/s	kg	N	N
403	107	Gravel	2.0	22.05	183.02	690.53
			2.5	18.62	154.56	702.00
			3.0	15.62	129.66	709.85
			3.5	11.61	96.37	717.90
410	108	Granite	2.0	22.17	184.02	629.19
			2.5	18.81	156.13	706.42
			3.0	15.69	130.23	713.48
			3.5	11.74	97.20	722.80
419	109	Coal	2.0	22.28	184.94	696.71
			2.5	18.67	154.97	713.38
			3.0	15.56	129.16	717.27
			3.5	11.66	96.79	714.36
420	100	No ore	2.0			693.27
			2.5			704.06
			3.0			730.06
			3.5			734.28

7.6.3 Pipe Conveyor and Cable disc Elevator Large Loads

The data for this table is from tests where the ore bin is running at 44 rpm. The pipe conveyor tension can then be compared to that of Table 119 where the ore bin speed is 22 rpm and the elevator speed is increased. It was not possible to deliver coal to the elevator down the slide tube at this ore feed rate. The rate of ore here is at 2.02kg per disc, and the maximum coal that could fill between the discs is 1.37kg at 80% capacity.

Table 120. Pipe conveyor tension with higher ore loads. Ore-bin speed 44 rpm

Table number Appendix 4	Test run number Appendix 4	Ore type	Elevator speed	Ore weight in the elevator 26 discs	Ore force due to gravity in zone 2 for 22 discs	Pipe conveyor tension.
			m/s	kg	N	N
401	82	gravel	2.0	52.36	434.63	763.61
402	83	gravel	2.0	52.88	438.94	704.06
			2.0	52.68	437.28	707.5
406	93	gravel	2.0	52.34	434.46	701.91
411	86	granite	2.0	52.33	434.38	701.02
			2.0	52.45	435.38	699.65
412	87	granite	2.0	52.67	437.02	690.13
420	100	No ore	2.0			693.27
			2.5			704.06
			3.0			730.06
			3.5			734.28

7.6.4 Pipe Conveyor Summary

In Appendix 4 Graphs 400-423 at the start of each test run there is a short time that the elevator operates with no ore, at the moment the pipe conveyor starts it reaches the operating tension. Adding ore into the elevator makes virtually no difference to the pipe conveyor tension. However, when ore is added into the elevator the cable disc elevator tension increases based on the ore load. This proves that the pipe conveyor is not carrying the ore load.

Figure 45 is a summary of some of those tensions.

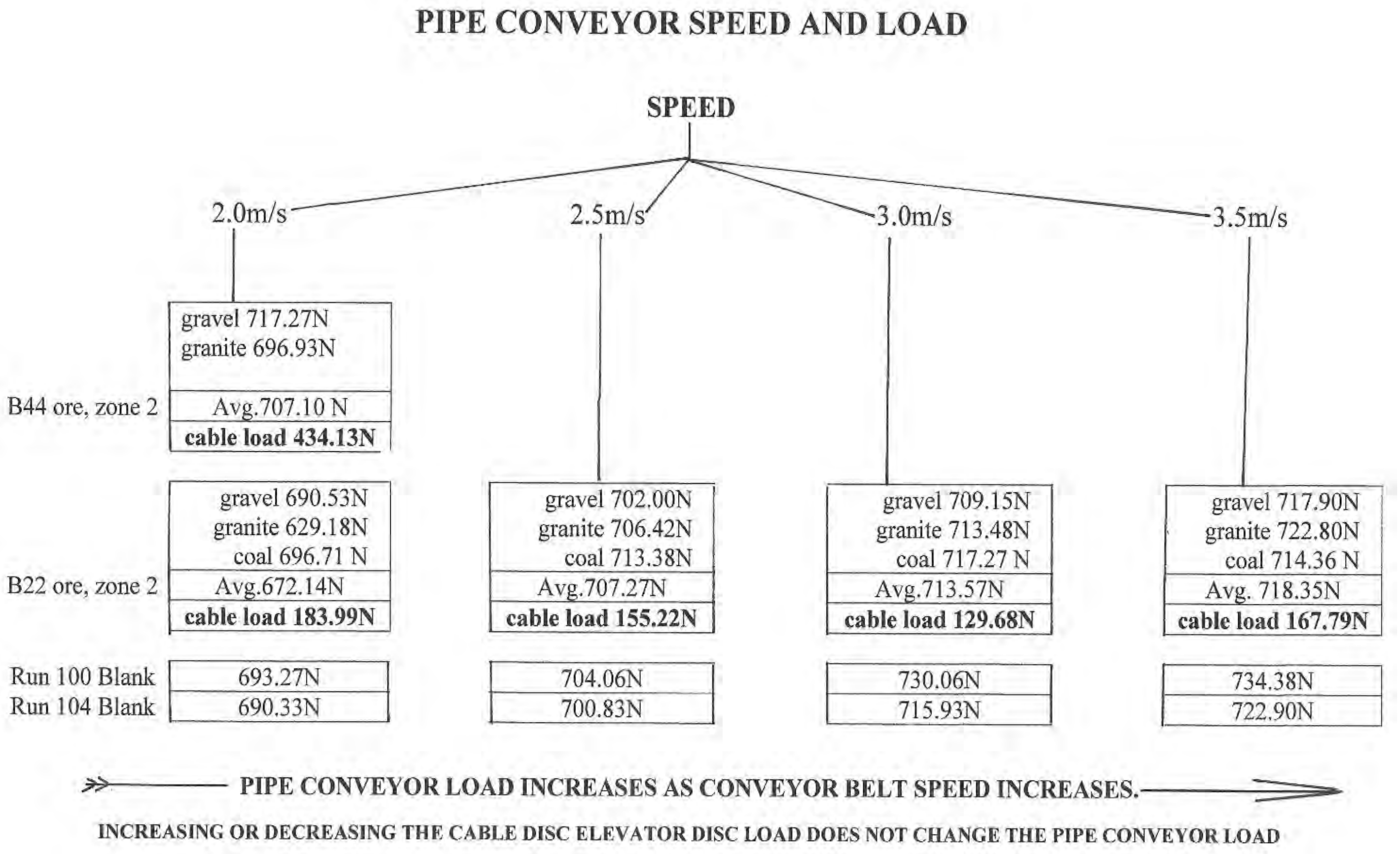


Figure 45. Pipe conveyor loading summary for two ore bin speeds B22 and B44 and an ore loading and pipe belt speed of 2.0-3.5m/s.

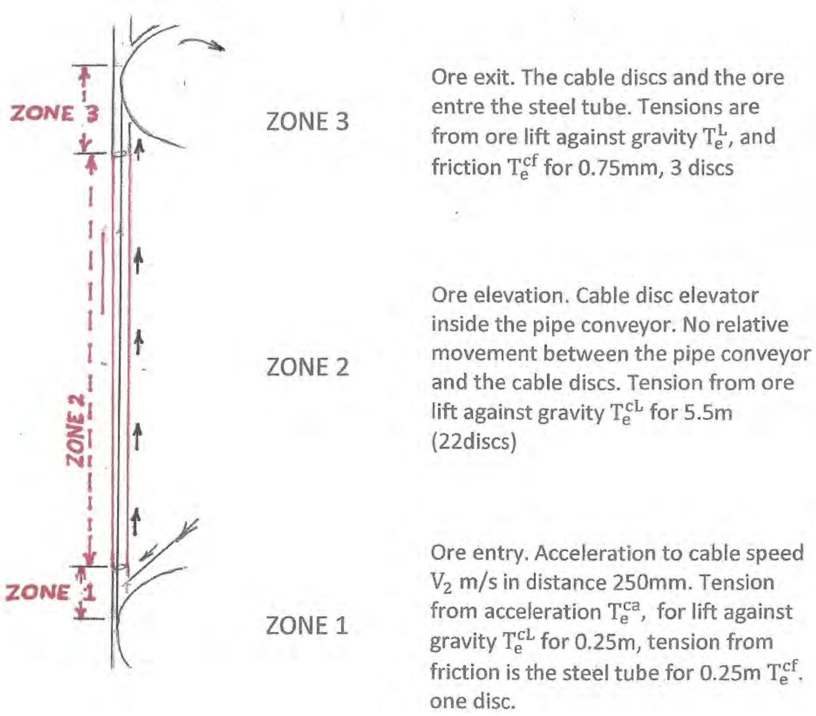
Comparing the data and results presented in Tables 119-120, the variation of the amount of ore on the discs seems to have little or no influence on the tension required when operating the pipe conveyor. The biggest variation in the pipe conveyor tension comes from changes in the speed of the elevator. The average conveyor belt tension was 709.7 N (with variance of between 701.2N and 763.0N), when the ore loading in the elevator was 52.53 kg the ore feed rate is steady with only a slight variation between from 52.33kg to 52.88kg.

Examining the data in Tables 115-120 it can see that the fluctuation of the pipe conveyor tension from the drive does not appear to be related to the amount of ore on the discs. Therefore, it is reasonable to conclude that the pipe conveyor is not a contributor to ore lifting, but rather just acts as a shield to hold the ore onto the elevator discs. By doing this the pipe conveyor has replaced the steel tube that was used in Test Rig 2, and in doing so, the friction between the ore and the tube has been removed in zone 2.

It is therefore reasonable to conclude that the pipe conveyor does not contribute to lifting the ore, and therefore, it is reasonable to consider that there is no friction component between the pipe conveyor and the ore when it is being lifted.

7.7. The Cable Disc Elevator Function in the Combined Elevator.

The purpose of the cable disc elevator is to lift the ore. The purpose of the pipe conveyor is to hold the ore on the discs. There was a lot of attention paid to making sure that both components in the combined elevator had their speed adjusted so that they travelled together with no differential speed. The adjustments were made manually using variable speed drives (VSD). There are 3 zones for this section of the elevator. These are shown below in a section of the drawing taken from Figure 39.



Ore exit. The cable discs and the ore entre the steel tube. Tensions are from ore lift against gravity T_e^L, and friction T_e^{cf} for 0.75mm, 3 discs

Ore elevation. Cable disc elevator inside the pipe conveyor. No relative movement between the pipe conveyor and the cable discs. Tension from ore lift against gravity T_e^{cL} for 5.5m (22discs)

Ore entry. Acceleration to cable speed V_2 m/s in distance 250mm. Tension from acceleration T_e^{ca}, for lift against gravity T_e^{cL} for 0.25m, tension from friction is the steel tube for 0.25m T_e^{cf}. one disc.

Figure 46. Pipe conveyor zone activity descriptions

In this section the cable disc elevator component uses data from experimentation of Test Rig 3, where as in section 7.4.2, the cable disc elevator components in zones 1 and 3 including friction is taken from Test Rig 2 and scaled to 1kg per disc and at 80% ore fill between the discs.

However, for this section, measurements have been taken using the cable disc motor torque arm load cell, which measures the force being applied on the cable and the ore weight on the discs in the elevator from the ore bin load cells.

7.7.1 Working Tension in Zone 2

The working tension for zone-2 T_e^{z2} is the force of gravity on the ore in this zone as there is no friction between the ore on the cable and the pipe conveyor belt. Hence, the working tension can be expressed for the ore being lifted in the rig as:

$$T_e^{z2} = T_e^{L} = \text{ore mass in zone 2 x g} \qquad \text{N} \qquad (7.14)$$

The elevator size in zone 2 is 5.5 metres long and has four discs per metre

$$T_e^{z2} = m \times 4 \times 5.5 \times 9.81 \text{ N}$$

$$T_e^{z2} = m \times 215.82 \qquad \text{N} \qquad (7.15)$$

Where m the mass of ore on each disc in kg.

Table 121. Working tension for lift in Test Rig 3 zone 2

Table number Appendix 4	Test run No. Appendix 4	Ore type and bin auger speed rpm	Ore weight on 26 discs. measured kg	Ore weight on one disc.kg	Tension from ore weight 26 discs N	Tension from ore weight 22 discs. (5.5m lift) T_e^{z2} N Equation 7.14
404	91	gravel 11	15.21	0.59	149.21	126.25
407	88	granite 11	15.58	0.60	152.84	129.33
413	94	coal 11	12.57	0.48	123.31	104.34
405	92	gravel 17	19.16	0.74	197.96	159.04
408	89	granite 17	19.28	0.74	189.14	160.04
416	97	coal 17	18.53	0.71	181.78	153.81
414	95	coal 17	18.34	0.71	179.92	152.25
403	107	gravel 22	22.05	0.85	216.31	183.03
410	108	granite 22	22.17	0.85	217.49	184.03
415	96	coal 22	24.32	0.94	238.58	201.88
401	110	gravel 44	52.36	201	591.84	500.79
412B	112B	granite 44	52.68	203	585.85	495.72

7.7.2 Working Tension in Zone 1

The working Zone 1 tension T_e^{z1} has a lifting distance of 250mm and acceleration to the cable speed V_2 takes place over 250mm in the steel tube before the ore enters Zone 2.

$$T_e^{z1} = T_e^a + T_e^L + T_e^f \qquad (7.16)$$

$$T_e^L = \text{ore mass in zone 1 x g} \qquad (7.17)$$

$$T_e^a = \text{ore mass in zone 1 x a} \qquad (7.18)$$

Where the acceleration of the ore, which for Test Rig 3 takes place in the distance of one cell, i.e. 250mm, which is the distance between the centre of the discs. Acceleration is given by equation 2.5.

$$a = \frac{V_2 - V_1}{t} \qquad \text{m/s}^2 \qquad (2.5)$$

The ore is stationary when it enters the elevator and after the movement of one-disc length it reaches elevator speed, hence V_1 is zero and V_2 is the elevator cable velocity. Acceleration is calculated for the velocities used for Test Rig 3.

Table 122. Ore acceleration time in Test Rig 3 zone 1

Cable speed m/s	2.00	2.50	3.00	3.50
Time to accelerate equals the time for the cable to travel 250mm.seconds	0.125	0.100	0.083	0.071
Acceleration a m/s^2	16.00	25.00	36.14	49.30
Tension T_e^a from accelerate N (6.13)	16.00 x m	25.00 x m	36.14 x m	49.30 x m

The working tension for accelerating the ore to 2.0 m/s over a distance of 0.250m in zone 1 is calculated and shown in Table 123 using equation 7.18.

Table 123. Tension resulting from acceleration in Test Rig 3 for zone 1 with a cable velocity of 2.0 m/s

Table number Appendix 4	Test run number Appendix 4	Ore type and bin auger speed rpm	Ore weight on 26 discs. measured kg	Ore weight on one disc.kg	Tension resulting from Acceleration in zone 1 T_e^{az1} N
404	91	gravel 11	15.21	0.59	9.44
407	88	granite 11	15.58	0.60	9.60
413	94	coal 11	12.57	0.48	7.74
405	92	gravel 17	19.16	0.74	11.80
408	89	granite 17	19.28	0.74	11.80
416	97	coal 17	18.53	0.71	11.36
414	95	coal 17	18.34	0.71	11.36
403	107	gravel 22	22.05	0.85	13.60
410	108	granite 22	22.17	0.85	13.60
415	96	coal 22	24.32	0.94	15.04
401	110	gravel 44	52.36	2.01	32.16
412B	112B	granite 44	52.68	2.03	32.48

Tension for the ore weight resulting from gravity is given in equation 17.17

$$T_e^{Lz1} = \text{ore mass in zone 1 } x \text{ g}$$

The ore mass is only for one disc:

Table 124. Working tension for lift in Test Rig 3 zone 1

Table number Appendix 4	Test run No. Appendix 4	Ore type and bin auger speed rpm	Ore weight on 26 discs. measured kg	Ore weight on one disc.kg	Tension from ore weight on one disc. Zone 1 T_e^{Lz1} N
404	91	gravel 11	15.21	0.59	5.79
407	88	granite 11	15.58	0.60	5.89
413	94	coal 11	12.57	0.48	4.71
405	92	gravel 17	19.16	0.74	7.26
408	89	granite 17	19.28	0.74	7.26
416	97	coal 17	18.53	0.71	6.97
414	95	coal 17	18.34	0.71	6.97
403	107	gravel 22	22.05	0.85	8.34
410	108	granite 22	22.17	0.85	8.34
415	96	coal 22	24.32	0.94	9.22
401	110	gravel 44	52.36	2.01	19.72
412B	112B	granite 44	52.68	2.03	19.91

$$T_e^{z1} = T_e^{az1} + T_e^{Lz1} + T_e^{fz1} \quad (7.19)$$

Resolving for friction, the working tension from friction is then:

$$T_e^{fz1} = T_e^{z1} - (T_e^{a1} + T_e^{Lz1}) \quad (7.20)$$

7.7.3 Working Tension in Zone 3 T_e^{z3}

In zone three, ore enters from the combined pipe conveyor and cable disc elevator zone 2 into zone 3 which is the upper steel tube section of the cable disc elevator. This zone is 750mm long and has three cable discs in use at any one time. In section 7.4.2 calculations for zone 1 and 3 use data from Test Rig 2 for acceleration, lift over one metre and friction. In this section data used for the cable disc elevator is taken from the experimental trials. There is no ore acceleration in zone 3. The tension required by the cable is that required to overcome the weight of the ore and overcome the friction between the ore and the steel tube in zone 3.

Working tension in zone-3 is the sum of the tensions associated with lifting, and friction over 750mm.

$$T_e^{z3} = T_e^{Lz3} + T_e^{fz3} \quad (7.10)$$

From equation 7.16

$$T_e^{Lz3} = \text{ore mass in zone 3} \times g$$

$$T_e^{z3} = m \times D^n \times LD \times g + T_e^{fz3} \qquad (7.22)$$

Table 125. Working tension for the cable disc elevator for lift in Test Rig 3 zone 3

Table number Appendix 4	Test run No. Appendix 4	Ore type and bin auger speed rpm	Ore weight on 26 discs. measured kg	Ore weight on three discs.kg	Tension from ore weight on one disc. Zone 3 T_e^{Lz3} N
404	91	Gravel 11	15.21	1.76	17.27
407	88	Granite 11	15.58	1.80	17.66
413	94	Coal 11	12.57	1.45	14.22
405	92	Gravel 17	19.16	2.21	21.68
408	89	Granite 17	19.28	2.22	21.78
416	97	Coal 17	18.53	2.14	20.99
414	95	Coal 17	18.34	2.12	20.80
403	107	Gravel 22	22.05	2.54	24.92
410	108	Granite 22	22.17	2.56	25.11
415	96	Coal 22	24.32	2.81	27.53
401	110	Gravel 44	52.36	6.04	59.25
412B	112B	Granite 44	52.68	6.09	59.74

From equation 7.19 for friction

$$T_e^{fz3} = T_e^{z3} - T_e^{Lz3} \qquad (7.23)$$

7.7.4 Zone 1 and 3 Combined

Zone 1 and 3 are the zones where the cable disc elevator is inside the steel fixed tubes, much like in Test Rig 2.

Combining zones 1 and 3 $$T_e^{z1,3} = T_e^{Lz1,3} + T_e^{az1} + T_e^{fz1,3} \qquad (7.24)$$

The working tension in zones 1 and 3 combined is determined by, $T_e^{z1,3}$.which also includes the friction. This allows the tension required to overcome friction to be calculated.

Tensions in zone 1 and 3 for lift and acceleration have already been calculated.

The following table is the combined calculations for lift and acceleration for zones 1 and 3 with the addition of the tensions T_e^{Lz1} , $T_e^{Lz1,3}$, and T_e^{az1} from Tables 123-125.

Table 126. Tensions in zones 1 and 3 for lift and acceleration

Table number Appendix 4	Test run number Appendix 4	Ore type and bin auger speed rpm	Ore weight on 26 discs. measured kg	Ore weight on one disc.kg	Ore weight on 4 discs, combined zone 1 &3 kg	Tension from ore weight for 4 discs, combined for zone 1 &3 $T_e^{Lz1,3}$ N	Tension from acceleration in zone 1 T_e^{az1} N	Tensions $T_e^{Lz1,3}+T_e^{az1}$ Combined for zones 1 & 3 N
404	91	gravel 11	15.21	0.59	2.34	22.96	9.44	32.40
407	88	granite 11	15.58	0.60	2.40	23.55	9.60	33.15
413	94	coal 11	12.57	0.48	1.92	18.84	7.74	26.58
405	92	gravel 17	19.16	0.74	2.95	28.92	11.80	40.72
408	89	granite 17	19.28	0.74	2.97	29.14	11.80	40.94
416	97	coal 17	18.53	0.71	2.85	27.96	11.36	39.32
414	95	coal 17	18.34	0.71	2.82	27.66	11.36	39.02
403	107	gravel 22	22.05	0.85	3.39	33.26	13.60	46.86
410	108	granite 22	22.17	0.85	3.41	33.45	13.60	47.05
415	96	coal 22	24.32	0.94	3.74	36.69	15.04	51.73
401	110	gravel 44	52.36	2.01	8.06	79.07	32.16	110.23
412B	112B	granite 44	52.68	2.03	8.10	79.46	32.48	111.94

7.7.5 Zone 1 and 3 Combined Working Tension Calculated by Experimentation

The effect of friction in this test rig is calculated as the difference between the tension required to lift the cable with ore and the tension of gravity for the mass of the ore. This difference is allocated to the pipe conveyor in zones 1 and 3.

The tension from the ore in zone 2 can be calculated from the weight of ore that has left the ore bin. This represents the ore on 26 discs, after which the weight of ore on the 22 discs in zone 2 can be calculated, and hence the tension required for the ore on 22 discs. Subtracting this from the measured cable tension, gives the total tension $\mathrm{T_e^{z1,3}}$ for zones 1 and 3. Knowing this tension and applying it to equation 7.23, the tension for friction $\mathrm{T_e^{fz1,3}}$ can be calculated:

$$\mathrm{T_e^{fz1,3}} = \mathrm{T_e^{z1,3}} - (\mathrm{T_e^{Lz1,3}} + \mathrm{T_e^{az1}}) \qquad (7.25)$$

This equation is used to calculate the friction in zones 1 and 3. The results are shown below in Table 127.

In Table 128 the elevator has received ore at a constant feed rate, and the elevator speed has operated at 2.0, 2.5, 3.0, and 3.5 m/s. The friction in zones 1 and 3 are in the last column.

The results for the calculation for friction as a percent of the ore weight on 26 discs results are in the last column in Table 129.

Table 127. Calculation of the combined friction in zones 1 and 3. Elevator velocity is 2.0 m/s, variable ore feed rate

Table number Appendix 4	Test run number Appendix 4	Ore type and bin auger speed rpm	Ore weight on 26 discs. measured kg	Ore weight on one disc.kg	Tension from ore weight 26 discs N	Tension from ore weight 22 discs T_e^{z2} N	Cable elevator tension 26 discs. From graphs $T_e^{z1,2.3}$ N	Cable elevator tension $T_e^{z1,.3}$ N	Tensions $T_e^{Lz1,3}+T_e^{az1}$ Combined for zones 1 & 3 from Table 130 N	Tension due to friction. Eqn.7.24 $T_e^{fz1,3}$ N
404	91	gravel 11	15.21	0.59	149.21	126.25	166.87	40.62	32.40	8.22
407	88	granite 11	15.58	0.60	152.84	129.33	168.05	38.72	33.15	5.57
413	94	coal 11	12.57	0.48	123.31	104.34	138.81	34.47	26.58	7.89
405	92	gravel 17	19.16	0.74	197.96	159.04	209.35	50.31	40.72	9.59
408	89	granite 17	19.28	0.74	189.14	160.04	205.52	45.48	40.94	4.54
416	97	coal 17	18.53	0.71	181.78	153.81	198.75	44.94	39.32	5.62
414	95	coal 17	18.34	0.71	179.92	152.25	198.26	46.01	39.02	6.99
403	107	gravel 22	22.05	0.85	216.31	183.03	259.18	76.15	46.86	29.29
410	108	granite 22	22.17	0.85	217.49	184.03	254.36	70.33	47.05	23.28
415	96	coal 22	24.32	0.94	238.58	201.88	260.75	58.87	51.73	7.14
401	110	gravel 44	52.36	2.01	513.65	434.63	585.85	151.22	110.23	40.99
412B	112B	granite 44	52.68	2.03	516.79	437.28	591.84	154.56	111.94	42.62

Table 128. Calculation of the combined tension and tension from friction in zones 1 and 3. Elevator velocity is 2.0-3.5 m/s, with a fixed ore feed rate

Table number Appendix 4	Test run number Appendix 4	Ore type	Cable velocity m/s	Ore bin rpm	Ore weight on 26 discs kg	Ore weight on one disc.kg	Tension from ore weight 26 discs N	Tension from ore weight 22 discs T_e^{z2} N	Cable elevator tension 26 discs $T_e^{z1,2.3}$ N	Cable elevator tension in zone 1&3 $T_e^{z1,.3}$ N	Tension from friction $T_e^{fz1,3}$ N
403	107	gravel	2.0	22	22.05	0.85	216.31	183.03	259.18	76.15	29.29
410	108	granite	2.0	22	22.17	0.85	216.49	184.03	254.36	70.33	23.28
419	109	coal	2.0	22	24.32	0.94	238.58	201.88	260.75	58.87	7.14
403	107	gravel	2.5	22	18.62	0.72	182.66	154.56	201.99	47.43	22.37
410	108	granite	2.5	22	18.81	0.72	184.53	156.14	212.09	55.94	30.88
419	109	coal	2.5	22	18.68	0.72	183.15	154.97	204.15	49.18	23.12
403	107	gravel	3.0	22	15.62	0.60	153.23	129.66	174.03	44.37	16.80
410	108	granite	3.0	22	15.69	0.60	153.92	130.24	176.48	46.24	18.67
419	109	coal	3.0	22	15.56	0.60	152.64	129.64	174.03	44.87	17.30
403	107	gravel	3.5	22	11.61	0.45	113.89	96.37	132.14	35.77	9.17
410	108	granite	3.5	22	11.74	0.45	115.17	97.45	126.45	29.0	2.40
419	109	coal	3.5	22	11.66	0.45	114.38	96.78	131.85	35.07	8.47

Table 129. Calculation of the percentage of friction in the combined test rig

Table number Appendix 4	Test run number Appendix 4	Ore type	Cable velocity m/s	Ore bin rpm	Ore weight on 26 discs kg	Ore weight per disc.kg	Tension from friction T_e^f Eqn. 7.24 N	Tension from friction adjusted to 1.00 kg of ore T_e^f N	T_e^f % of the cable tension of 26 discs
403	107	gravel	2.0	22	22.05	0.85	29.30	34.47	11.30
410	108	granite	2.0	22	22.17	0.85	23.34	27.78	9.18
419	109	coal	2.0	22	24.32	0.94	7.13	7.59	2.73
403	107	gravel	2.5	22	18.62	0.72	7.66	10.63	3.79
410	108	granite	2.5	22	18.81	0.72	16.00	22.22	7.54
419	109	coal	2.5	22	18.68	0.72	9.52	13.22	4.66
403	107	gravel	3.0	22	15.62	0.60	11.06	18.43	6.36
410	108	granite	3.0	22	15.69	0.60	12.93	21.55	7.33
419	109	coal	3.0	22	15.56	0.60	11.84	19.73	6.80
403	107	gravel	3.5	22	11.61	0.45	11.11	24.69	8.41
410	108	granite	3.5	22	11.74	0.45	4.06	9.02	3.21
419	109	coal	3.5	22	11.66	0.45	10.30	22.89	7.81

7.7.6 Lifting Distance for the Cable Disc Elevator inside the Pipe Conveyor

The lifting duty of the cable disc elevator inside the pipe conveyor only has the forces of gravity, acceleration for the length between two discs, and the friction of the ore at the infeed (zone 1) and friction at the elevator drive end (zone 3), plus any miscellaneous frictions from the drive and idle rollers.

The friction measured in this section does not differentiate between the miscellaneous frictions and the ore friction in zones 1 and 3. However, for the purpose of this discussion, all friction measured is taken as the friction between the ore and the steel tube in zones one and three.

For equations 7.11 and 7.12 the tension in zones 1 and 3 changes from T_e^c to $T_e^{z1,,3}$. That means that the equations can be rewritten.

Where T_1^c is the required cable tension for a predetermined lifting distance.

$$T_1^c = LD \; x \; g\,(m \, x \, D^n + BW) + T_e^{z1,,3} \quad N \qquad (7.26)$$

Where LD the lifting distance is calculated for a predetermined cable strength the equation is:

$$LD = \frac{T_1^c - T_e^{z1,,3}}{g\,(m \, x \, D^n + BW)} \quad \text{metres} \qquad (7.27)$$

These calculations are used to project what tensions would be required of the cable when:

- There is 1.0kg of ore on each disc for gravel, granite and coal.
- For 2 kg of gravel or granite on each disc.
- The maximum amount of ore is on the discs. i.e. the volume between the discs is 80% full. This is 3.218 kg for gravel, 4.087kg for granite, and 1.370kg for coal.

Calculations for the following Table 130 use the tension in zones 1 and 3, $T_e^{z1,,3}$, as the maximum tension that was experienced for any of the ores. This was 76.15N for an ore weight of 0.85 kg per disc and was calculated from the gravel sample run number 107 Appendix 4 Table 403. Scaling this to 1 kg then the tension would be 89.59 N.

These zones are a fixed tension dimension that is not considered relevant to expanding the length of zone two. For the calculated lifting distance, only the tension in zone 2 is expanded. Using equations 7.25 and 7.26 and $T_e^{z1,,3}$ at 89.59N the lifting distance can be calculated for a cable of known tension capability. Alternatively, for a selected lifting distance (LD) the required cable tension can be calculated. The cable selected for this example in Table 130 is the Bridon 34LR 40mm diameter cable referred to in Table 9. Table 130 shows examples for the selected cable the distance it could lift, and for a 1000 metre lift, the calculated cable capacity that would be required.

For 2kg of gravel and granite the data is taken from Table 128 for $T_e^{z1,,3}$ and scaled back to 2.0 kg. Gravel and granite achieved an ore fill of 2.01kg and 2.03kg respectively when the ore bin feed was at 44 rpm.

2.01kg of gravel with tension $T_e^{z1,,3}$ of 151.22 N, for 2kg proportions to 150.47 N

2.03 kg of gravel with tension $T_e^{z1,,3}$ of 154.56 N for 2kg proportions to 152.28 N

3kg of gravel is calculated by adding the 1 and 2 kg tensions, then up scaled

For 3.218kg of gravel the tension is (89.59 +150.47) $x\ \frac{3.218}{3.0}$ = 257.50 N

For 4.087kg of granite the tension has been calculated as 2 x 152.28 $x\ \frac{4.087}{4.0}$ =311.12 N

Table 130. Test Rig 3 lifting distance calculations for a selected 40mm cable. Cable tension required for 1000 metre lift

Ore	m. Ore weight per disc Selected from Table 110 kg	Equation number	T_1^C Specified by cable selection kN	LD Lifting distance Specified m	$T_e^{z1,.3}$ Max. tension selected at 89.59/kg ore N	BW 40 mm dia., cable selected from Table 58 at 9.0 kg/m	LD Lifting distance determined by calculation metres	Required cable strength for 1000m lift. T_1^C Determined by calculation kN
Gravel	1.000	7.26	219.0		89.59	9.0	1717	
	2.000	7.26	219.0		150.47	9.0	1312	
	3.218	7.26	219.00		288.30	9.0	1019	
	1.000	7.25		1000	89.95	9.0		127.62
	2.000	7.25		1000	150.47	9.0		166.92
	3.218	7.25		1000	288.30	9.0		214.71
Granite	1.000	7.26	219.0		89.59	9.0	1717	
	2.000	7.26	219.0		152.28	9.0	1312	
	4.087	7.26	219.0		311.12	9.0	887	
	1.000	7..25		1000	284.70	9.0		127.62
	2.000	7.25		1000	152.28	9.0		166.92
	4.087	7.25		1000	311.12	9.0		248.98
Coal	1.000	7.26	219.0		89.59	9.0	1717	
	1.370	7.26	219.0		89.59	9.0	1540	
	1.000	7.25		1000	89.59	9.0		127.62
	1.370	7.25		1000	89.59	9.0		142.13

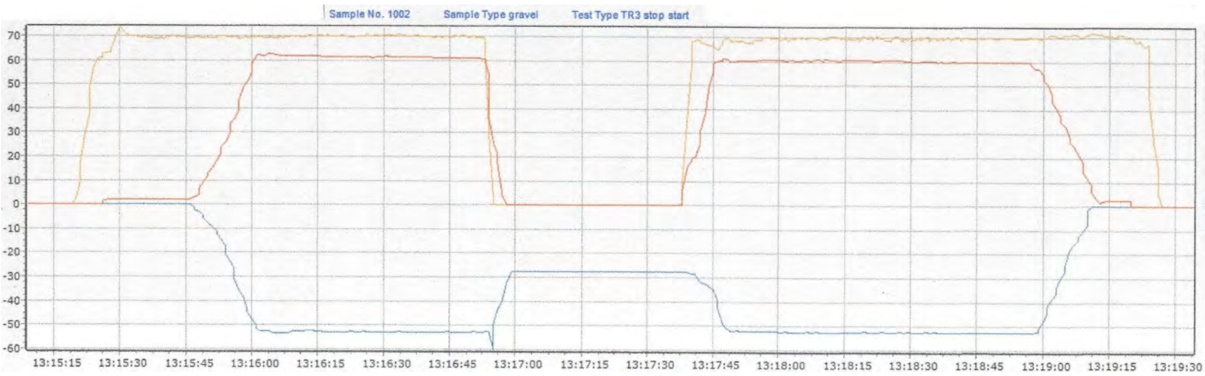
The projected lifting distance (LD) that this size cable disc elevator could lift from when the tube is a pipe conveyor has been calculated and shown in Table 130. Granite when filling the space between the discs at 80% full is the only example where there would need to be a stronger cable to achieve a 1000m lift.

7.8 Elevator Stop and Start Under Load

A stop and restart of the combined elevator was tested when the elevator was loaded with ore. This was to simulate a situation in which is an electrical failure at the mine and the elevator has to be restarted. Test Rig 1 when testing for static friction showed there was a high restart load from static friction and from jamming. Jamming was eliminated in Test Rig 1 by using ore particles smaller in size than the gap between the lifting disc and the ore tube. In Test Rig 2 the elevator was stopped with ore loaded on the discs. The static friction between the ore and the tube was much higher than the dynamic friction, for gravel this is shown in Table 65 and i.e. Graph 25.

Test Rig 3 has a variable gap between the discs and the pipe conveyor as the belt has an over-lap as shown in Figure 44. The steel tube in zones 1 and 3 has a 12.5 mm gap, so ore fall back was not considered, as the distance in these zones is small and in zone 3 the ore already has momentum.

A stop start trial was done for each of the ores with the ore feed. Graphs and Tables are referred to in Appendix 4, for gravel are shown in Graph 402 run 111, for granite they are shown in Graph 411 run 113 (both used 2 kg per disc), and for coal (using 0.7 kg per disc) shown in Graph 418 run 99.



Graph 26. Stop start test for static friction on start up. Appendix 4 Graph 402 run 111.for gravel.

The observations are:

- When the elevator is stopped suddenly as in Graph 402, there is still some momentum in the machinery that allows ore to be returned to the bin. This partially unloads the elevator.
- When the elevator restarts the ore bin also restarts at the same time.
- The final shut down of the elevator is the same for the normal trials where the elevator is allowed to completely empty.

The most important observation is that there is no measurable static friction at the restart that would suggest a stronger cable would be required. This is different to the results from Test Rig 2.

7.9 Test Rig 3 Summary

This test rig is unique in demonstrating the use of a vertical pipe conveyor to help a cable disc elevator to operate without friction between the cable disc with ore and the lifting side tube. The research question that looks at what friction exists has been answered: there is only ore friction within the tube when the ore enters the steel tube of the elevator. The steel tube in this elevator is 750mm long at the top and 250mm long at the bottom of the elevator. These are the only sections that experience ore friction.

Friction in these zones 1 and 3 was measured by two methods. One method was to use the experimental data from Test Rig 2 (over a distance of 1 metre) which included friction, lift and acceleration to calculate the cable lifting tensions.

The second method was to use the data from experiments conducted using Test Rig 3.

Calculation of the lifting distance or the required cable tension for a particular lifting distance was determined using two equations;

$$\mathrm{T}_1^{\mathrm{c}} = \mathrm{LD}\ x \mathrm{g}\,(\,\mathrm{m}\ x\ \mathrm{D}^{\mathrm{n}} + \mathrm{BW}) + \mathrm{T}_{\mathrm{e}}^{\mathrm{z1,.3}} \quad \mathrm{N} \tag{7.26}$$

$$\mathrm{LD} = \frac{\mathrm{T}_1^{\mathrm{c}} - \mathrm{T}_{\mathrm{e}}^{\mathrm{z1,.3}}}{\mathrm{g}\,(\,\mathrm{m}\ x\ \mathrm{D}^{\mathrm{n}} + \mathrm{BW})} \quad \text{metres} \tag{7.27}$$

The pipe conveyor belt was used to hold the ore onto the cable discs. Results showed that this belt was operating separately to the cable disc elevator, and that neither component was influencing one another other.

Stop and restart trials were run with the elevator loaded with ore without any of the adverse static friction effects that were seen with Test Rigs 1 and 2.

8.0 Discussion

The purpose of this thesis was to research a continuous flow elevator to lift ore from 1000metres depth or deeper. The cable disc elevator has a distinct characteristic in that, as a single steel wire cable elevator, any size cable can be selected to match the tension requirements of the lifting duty. There is no requirement of that cable to match or pair with other cables which is a requirement for cables in overland conveyor belts. This elevator is a vertical drag conveyor where the discs mounted on the lifting cable pull the ore up a tube.

This chapter summarises the answers to the research questions of friction, static and dynamic and the significance of the hybrid elevator at removing friction.

The key to understanding the potential of this conveyor is to know the friction that exists between the ore and the tube as the ore is being dragged through.

A cable disc elevator vertical lift has three main force components that make up the working tension:

- The force required to lift the ore against the effect of gravity, T_e^L
- The acceleration force T_e^a required to take the ore from zero speed to elevator velocity.
- The force required to overcome the friction between the ore and the elevator tube. T_e^f
- The extra strength in the cable to carry its own weight. T_2

The additional force that the cable has to carry is that for lifting the weight of the cable T_2 and discs however, for the working tension this is balanced by the return side cable.

The sum of these forces is T_1. which is calculated by the equation 8.01:

$$T_1 .= T_2 + T_e = T_2 + T_e^L + T_e^a + T_e^f \qquad (8.01)$$

The tension capacity of the cable required to overcome friction T_e^f has been determined for the three test rigs by experimentation and deduction.

The force that the elevator cable has to lift against is T_1 and hence, this needs to be the safe lifting capability for the steel wire cable specifications. If the cable strength is sufficient to lift against the required tension T_1, for the depth that ore that is required to be lifted from, then the cable and elevator are viable for the ore lifting duty.

8.1 Ores Selected

The selected ore used for testing with the test rigs and this research were gravel, granite, and coal. These were all collected from local mining operations. Gravel from Kopkees open cut quarry, granite from the local underground gold mine, and coal from the open cut Maddingley coal mine at Bacchus Marsh.

Testing of the ore was for particle size and moisture content. Ore used was ungraded plus various separations of ore size were selected by sieving the ore using Endecott sieves and collecting the sieve fractions. Fractions collected were of the size 9.5mm +, 5.0-9.5mm, 2.0-5.0mm and less than 2.0mm. All the ore was allowed to stand inside the testing building to dry to be free of surface water.

The ore was tested for compaction in a drop test to simulate what the compaction of the ore on the cable disc elevator may be when landing on the elevator traveling at the set velocity. This compaction was only tested from a 2.5 metre drop and measured for the ore height in the tube, then the volume of the ore was calculated and the ore packing density was determined, as shown in Tables 13,14 and 16. This data was used throughout the research to calculate the surface area of ore in the elevator tube.
Test Rig 1 for static friction tests all sizes of the ore were selected. Test Rig 2 only used 2mm ore for testing of the dynamic friction in order to have a small uniform topography of the ore at the tube surface, and test Rig 3 used all sizes up to 9.5mm.
No testing was done of ore for other physical parameters of shear, compressive and tensile strength, and rolling friction, etc.
Visual observations were made of the 2mm ore on the disc travelling up a clear polycarbonate tube for 1.5 metres shown in Pictures 20-28. Figure 28 is a drawing of the ore rotational movement on the disc, ore is seen to travel slower at the surface of the tube. This implies that the ore is not compacting but continues to rotate.

8.2 Static Friction

'*What is the Static Friction between the Ore being Elevated and the Tube of the Cable Disc Elevator and What Different Friction Forces are interacting in the Tube?'*

Experiments using Test Rig 1 does answer this question because static friction was measured. Aditionally other forces relating to jamming and increase in friction as a result of any free water on the ore were also measured.

The static friction is the minimum force required to start movement between the ore on the elevator disc and the steel tube that the ore and disc are inside of. It is necessary to understand the effect of static friction because an elevator may have to restart under load when the discs are loaded with ore as a result of a sudden mine shut down due to power failure. Static friction was measured for different amounts of ore on the elevator disc. Increasing amounts of ore occupied a larger volume above the disc and hence had a greater surface area contact with the steel tube. Data was analysed and friction then calculated as the force per surface area of ore contact with the tube, N/cm^2. Resolving the force per surface area is used for the purpose of extrapolating and predicting the friction for longer elevators of the same diameter with the same ores. Extrapolation was only lineal, and no predictions are made for larger diameters.

For static friction equation, 8.02 (Metlikovic) can be simplified to:

$$T_1 .= T_2 + T_e$$

$$T_1 .= T_2 + T_e^L + T_e^f \qquad (8.01)$$

As there is no acceleration, the static friction is only concerned with the breakfree force and not what velocity the ore reaches.

8.2.1 Static Friction in Test Rig 1

This test rig showed the importance of the topography of the ore at the steel tube surface in the lifting tube and

Test Rig 1 only tested for static friction for one disc. This was also referred to in this research as the breakfree force. Not only did this rig test for the breakfree force, but it gave results that demonstrated for a cable disc elevator where success and failure is placed. This helped to determine testing that guided research in a direction where the cable disc elevator can be used successfully.

The most successful ore lifted in Test Rig 1 was for ore where the particle size was less than the gap between the disc and the steel elevator tube. The gap between the lifting disc and the steel tube was 2.5mm and ore selected had been sieved through a 2mm Endecott sieve than the ore size was smaller than the gap.

8.2.2 Ore with High Friction or Jamming

The effect of jamming and of water addition create an environment for the elevator that would contribute to the cable disc elevator to fail, or the elevator would need to have a much stronger cable than those selected for examples in this research. Ore that had high ‘friction’ were ores larger than 2.5 mm that jammed between the discs and the steel tube, and for 2mm ore when water was added.

8.2.2.1 Ore causing Jamming

Samples of ore were tested with particle sizes ranging from 2-5 mm, 5-9.5mm, and above 9.5mm. The comparison of the breakfree force for different particle size are shown in Table 25 and displayed on Graph 5:

- Most of the gravel and coal samples that jammed between the disc and the tube broke free as the ore sheared and broke, however the break free force was much higher than ore of 2mm or less in size.
- For gravel, ore that was above 2.5mm in size provided a greater number of pieces that can jam between the disc and the tube, meaning that ore between 2.5 and 5.0mm in size could jam more firmly than larger ore.
- Coal sheared much more easily and the rate of jamming of ore larger than 2.0mm in size varied only slightly.
- Granite tested with the large particles jammed and in all tests the operation was stopped to protect the test rig. The maximum shown is just the point where the test was terminated.

In order to measure the effect of jamming, a back-testing method was applied where 1000grams of ungraded ore of full particle size ore (Ungraded ore as measured in Tables 8-11) was placed on top of 500 grams of 2mm coal of known breakfree force. The combined sample was tested for break free force, then the force for the ungraded ore was calculated back by subtracting the break free force of the coal. This method gave the true static friction of the ungraded ore with the steel tube.

The difference between the trues static friction and that of the ungraded ore without the coal is the jamming effect.

These results are shown in Table 24 and summarised in Table 131 below

Table 131. The percentage break free force for jamming using ungraded ore

Ore & tube size inches	Ave. Breakfree Force/surface area kN/ cm^2 On the disc $\mathrm{bF}^{\mathrm{UG}}_{\mathrm{ore}}$ Table 22	Avg. Static Friction N/cm^2 $\mathrm{sf}^{\mathrm{UG}}_{\mathrm{ore}}$ Clear of the disc. On coal. Table 21	Jamming J_{ore} and disc effect DE_{ore} Eqn. (5.11)		Max. Breakfree Force/surface area kN/cm^2 On the disc $\mathrm{bF}^{\mathrm{UG}}_{\mathrm{ore}}$ Table 22	Max. Static Friction N/cm^2 $\mathrm{sf}^{\mathrm{UG}}_{\mathrm{ore}}$ Clear of the disc. On coal Table 21	Jamming J_{ore} and disc effect DE_{ore} Eqn. (5.11)	
			N	%			N	%
Gravel 8	0.361	**0.063**	0.505	71.5	0.896	**0.077**	0.819	91.4
Granite 8	1.460	**0.080**	1.38	94.5	2.496	**0.084**	2.412	96.6
Coal 8	0.054	**0.095**	-0.041		0.084	**0.095**	-0.011	
Gravel 5	0.165	**0.103**	0.062	37.5	0.374	**0.112**	0.262	70.1
Granite 5	0.364	**0.107**	0.257	70.6	0.894	**0.126**	0.658	73.6
Coal 5	0.053	**0.023**	0.030	56.6	0.081	**0.030**	0.051	63.0

In Table 131 the red numbers are the percentage breakfree force for ungraded ore that contributed to jamming.

8.2.2.2 Testing 2mm Particle Size Ore with Added Water

An increase in static friction resulting from water being added to the ore is summarised in Tables 35-40, from which the following can be concluded:

- With gravel with 20 percent water added the static friction increased by 144%
- With granite with 20 percent water added the static friction increased by 117 %
- With coal with 20 percent water added the static friction increased by 300 %

Coal become very viscus and sticky. Adding more than 20% water the ore mix resulted in a runny sloppy slurry.

As a result of the high load duty that would be required for the cable disc elevator when using wet ore, and ore with the large sized particles, the research focused on dry raw materials. As a result, moist ores were not used in Test Rig 2. However, when it comes to the cable disc elevator, this data is important for understanding where the vulnerabilities are.

8.2.3 Ore Tested with a Particle Size smaller than 2mm

The following testing for ores gravel, granite and coal was carried out with ore that had passed through a 2mm Endecott sieve. Ore was tested with different loadings on the disc. The results for the cable disc elevator demonstrate that this type of elevator can be successful, however, the requirement would be that ore has to be crushed and sieved prior to being loaded into the elevator.

To calculate the static friction for the total length of the cable disc elevator the results for one disc are multiplied by the number of discs that was required for the length of the cable. The static friction for ore less than 2mm in size using data from Test Rig 1 was calculated from the determined break-free force ($\mathrm{Bf_{ore}}$) divided by the calculated ore tube surface contact area (S.A.) in N/cm^2. The ore tube surface area was calculated from an ore drop test into a tube of known diameter and the height of the ore for a predetermined weight was measured. (Table 13,14 and 16). This allowed the surface contact area (S.A.) between the ore and the tube to be calculated.

The static friction was defined as:

$$\mathrm{sf_{ore}} = \frac{\mathrm{Bf_{ore}}}{\mathrm{SA}} \qquad (8.03)$$

Table 132. A summary of the static friction for the 5-inch and 8-inch tubes for gravel, granite and coal. (Data from Table 46)

Tube Diameter	Ore tested	Static Friction determined for the selected ores N/cm^2		
		1000 grams per disc	2000 grams per disc	3000 grams per disc
8-inches 203.2mm	Gravel	0.09	0.08	0.08
	Granite	0.10	0.06	0.04
	Coal	0.02	0.02	0.02
5-inches 127mm	Gravel	0.19	0.20	0.21
	Granite	0.18	0.14	0.14
	Coal	0.02	0.07	0.15

8.2.4 Lifting Distance based on Static Friction

The fourth research question concerns the lifting depth that a cable disc elevator could lift.
It asks:

'What is the Maximum Distance that a Cable Disc Elevator can lift from?'

This question is relevant to each of the three test rigs. The relevance of Test Rig 1 is that the static friction is higher than the dynamic friction, (Graphs 1-3) and the choice of elevator cable size may be chosen based on the total tension T_1 requirements for the cable. There is no acceleration calculation for the ore with the static friction tests.
The lifting distance that could be achieved is calculated using equation 8.04

$$\text{LD} = \frac{\text{Cable safe tension N}}{\text{T}_1 \ \text{N/m}} \qquad (8.04)$$

Table 128 is a summary of results for the maximum lifting depth calculated from the test results. All ore tested for this was less than 2mm in size.

Table 133. A summary of lifting distance based on using the friction of static friction for the 5-inch and 8-inch tubes using gravel, granite and coal. (Data repeated from Table 51)

Tube Diameter	Cable size	Ore Tested	Maximum Lifting Depth for the ore weight and cable size as determined in Tables 46 - 48, metres.		
			1000 grams	2000grams	3000 grams
8-inch 203.3mm	40mm	Gravel	1156	794	558
		Granite	1144	899	670
		Coal	1348	909	691
	50mm	Gravel	1512	1490	769
		Granite	1398	1133	974
		Coal	1590	1139	890
	75mm	Gravel	1768	1465	1260
		Granite	1695	1542	1295
		Coal	1895	1487	1244
5-inch 127.0mm	40mm	Gravel	690	379	262
		Granite	817	631	408
		Coal	1257		

8.2.5 Static Friction in Test Rig 2

The friction force in Test Rig 2 was measured in the steel tube on the lifting side of the elevator which was held by four weigh load cells. Test Rig 2 used the same ore that had the least static friction in Test Rig 1 which was ore less than 2mm in particle size and which had no added water. Ore was fed into Test Rig 2 via a horizontal screw conveyor, which pushed ore into the elevator at in right angles to the lifting tube. This gave some control over the amount of ore that was placed on the discs. The static friction effect was measured by a sudden stop of the elevator and the ore feed when in full operation, then after the test rig had a short time to relax the rig was restarted and the breakfree force is shown by a spike in the graph. The peak force measured at the restart on the tube was the static friction force by this method. This static friction or the friction at the elevator restart was higher than the dynamic friction when Test Rig 2 was operational.

For gravel, the results are shown in Graphs 15-16 and data summarised in Table 65, granite in Graphs 17-18 and data summarised in Table 66, and for coal Graphs 21-22 with data in Table 68. There was an increase friction force on the load cells holding the tube when the elevator was restarted, however the restart involved turning the power onto full instantly in order to lift the cable. Hence, the response of friction measured by the load cells is strictly under the circumstances that this test was done. Lower start up tension may have been achieved if the motor driving the cable was started with a soft starter that added powers slowly until power built up to overcome the static friction.

8.2.6 Static Friction in Test Rig 3

The ore tested in Test Rig 3 was the ungraded ore that had a particle size less than 12.5mm. The technique used was the same as the stop start system as for Test Rig 2. There were some differences though; notably, for coal and gravel the ore sheared and in less than one minute was fine and had a particle size of less than 1mm. Hence, for coal and gravel the stop start test for static friction used fine ore. The particle size of granite did not change, and it maintained its shape.

When the elevator was stopped there was a certain amount of momentum of the pipe conveyor and the cable disc elevator meaning it continued to move, which resulted in approximately 50% of the ore in the elevator being unloaded back to the ore bin. The second thing that happened was any excess ore in the feed tube, which was present after the elevator stopped flowed back past the infeed single disc into the bottom of the cable disc. This could have been stopped if there was a smaller gap between the disc and the bottom of the tube in zone 1 if this was longer than the infeed for a few more discs that may have helped in the ore bridge the gap.

However, with all the stop start tests there was no static friction effect detected. The elevator started back up to speed with no detectable change in load above that of the dynamic friction. The graphs are shown in Appendix 4, gravel Graph 419 run 99, granite Graph 411 run 113, and for coal Graph 402 run 111.

8.3 Dynamic Friction

The dynamic friction between the ore and the tube is the force required to keep the ore moving at a constant speed against the resistance of friction between the ore and the steel tube. The dynamic friction is less than the static friction. In order to calculate the required cable tension T_1 for the elevator T_e^f for the dynamic friction needs to be established. The force to accelerate T_e^a the ore is relevant, however, this only accelerates the ore in one lifting cell which is the distance between two consecutive discs of 250mm. For Test Rig 2 equation 8.05. applies:

$$T_1 = T_2 + T_e^L + T_e^a + T_e^f \tag{8.05}$$

Where T_e^f is the tension from the dynamic friction.

8.3.1 Dynamic Friction Test Rig 1.

This test rig did not measure any quantitative aspects of dynamic friction. However, when the break free force was reached, the counterweight bucket accelerated down, and the ore accelerated upward due to the counterweight force. Consequently, the force required to hold the steel tube in place reduced as a result of the fact that the friction between the ore and the tube was now dynamic rather than static. This is clear evidence that the dynamic friction after the breakfree point in Graphs 1-3 is less than the static friction.

8.3.2 Dynamic Friction Test Rig 2

This test rig is specially designed to measure the dynamic friction between the ore and the steel elevator tube. The ore is on the discs and pulled up the tube. This tube is an integral part of the elevator but is physically isolated and supported by four load cells that measure the resistance required to hold the tube in place as the ore is dragged up the tube. The knowledge from this research is required to add to the other forces to determine an elevator cable tension requirement.

Test Rig 2 is designed to answer the following research question;

'What are the Friction Forces that would be acting in a Cable Disc Elevator for Dynamic Friction?'

This test rig had one critical design parameter; that the disc to tube gap was 2.5mm which is a carryover design dimension to ensure continuity between the two test rigs. There were two main data inputs, the load on the weight load cells holding the tube in place, and the load cells measuring the ore bin weight. However, Test Rig 2 was only a 5-inch tube elevator. This test rig was a fully operational elevator to which ore was supplied via a screw auger, before the elevator lifted the ore and discharged it via a chute back to the ore bin. Any ore missing from the bin was ore in the elevator from which the amount of ore per disc can be calculated from the bin weight.

The ore selected was gravel, granite and coal that had passed through a 2.0 mm Endecott sieve. Any wet ore that was used clogged onto the discs and the chute that returned ore to the ore bin, hence the weight of ore that was missing from the bin was not necessarily on the discs and the data was of no use other than to qualitatively acknowledge that this ore was sticky and not measurable. Those tests with water were abandoned.

In this test rig it was not possible to set the weight of the ore exactly (i.e.1 or 2 kg per disc). The ore weight on the discs was calculated, then the friction was calculated based on the surface area that this amount of ore was taking up as shown in Table 14. Using the equations for ore density, volume and surface area, the friction forces were adjusted for the selected weights. The calculations then considered the friction at 1.0, 2.0 and 3.0 kg of ore per disc.

Table 134 shows a comparison between the static friction and the dynamic friction for 1kg of ore on each disc.

Table 134. (From Table 84). Friction comparisons

Cable speed m/s		2.0	2.5	3.0	3.5
	Static Friction T_{sf} N/cm^2 Table 46	Average dynamic friction df N/cm^2 x 10^{-3} Tables 68-79			
Gravel	0.19	10.58	7.76	8.20	5.53
Granite	0.18	6.85	3.65	6.74	6.28
Coal	0.02	2.41	1.70	2.08	2.57

In Table 134 the static friction is much larger than the dynamic friction. Dynamic friction as a percentage of the static friction is:

- Gravel 5.57 – 2.02%

- Granite 3.81-2.02%
- Coal 12.05 – 8.5%

A second set of calculations was undertaken that combined the effect of the cable displacement for a 40mm cable and the volume between the discs being 80% full.

Table 135 below show the calculated data, including that for ore filling 80% of the volume between the discs.

Table 135. (from Table 86) Calculated frictions for 1kg of ore and ore filling 80% of the cell volume

Cable speed m/s			2.0	2.5	3.0	3.5
	Ore weight per disc. grams	Ore contact surface area with tube per disc. cm^2	**Average dynamic friction df N/cm^2 x 10^{-3} From Table 85**			
Gravel Dynamic friction force T_e^f (DF_1) per disc.			**10.58**	**7.76**	**8.20**	**5.53**
	1000	255.48	2.70 N	1.98 N	2.09 N	1.41 N
	3128	798	8.44 N	6.19 N	6.54 N	4.41 N
Granite Dynamic friction force T_e^f (DF_1) per disc.			**6.85**	**3.65**	**6.74**	**6.28**
	1000	195.53	1.34 N	0.71 N	1.32 N	1.23 N
	4087	798	5.47 N	2.91 N	5.38 N	5.01 N
Coal Dynamic friction force T_e^f (DF_1) per disc.			**2.41**	**1.70**	**2.08**	**2.57**
	1000	583.33	1.41 N	0.99 N	1.21 N	1.50 N
	1370	798	1.92 N	1.36 N	1.66 N	2.05 N

8.3.3 Lifting Distance based on Dynamic Friction

To expand the data for Test Rig 2, the data was reduced to that for one disc then multiplied by the number of discs required to the projected length. Two equations were developed, one to determine the cable tension strength required for a particular lifting depth, and the other to determine the lifting length a particular cable could operate with. These equations were developed to add to the answer of the fourth research question:

'What is the Maximum Distance that a Cable Disc Elevator can lift from?'

Equation 6.33 for lifting distance $$LD = \frac{\text{Cable tension spec}(CT_{1000}) - T_e^a\ (\text{One disc})}{T_1}\ \text{metres}$$

Cable tension specification required for a 1000m lift.

$$CT_{1000} = LD \times T_1 - T_e^a \text{ (One disc) N}$$

These equations were developed for this test rig elevator.

8.3.4 Tension for Acceleration of a Full Elevator after an Incidental Stop.

When the elevator has stopped with a fully loaded ore at 80% volume between the discs being filled, then the whole elevator ore load has to be accelerated to the operational speed V_2. Data is shown in Table 93 for the tensions required where the elevator is 1000 metres long and at 4 discs per metre. The data shows that most important operational factor to minimize the cable tension load is the acceleration time. Taking ten minutes to accelerate to V_2 only requires 1/10th of the tension strength compared to a 2-minute long acceleration.

8.3.5 Cable Tensions and Lifting Distance Projections for the 5-inch Elevator when Dynamic Friction is Used

The lifting distance calculated for the 5-inch elevator ore cells when 80% of the volume is full is shown in Table 136 (from Table 91).

Table 136. (from Table 91). Calculation of the cable tension T_1, the lifting distance in metres, and production capacities for the 5-inch elevator, with the cell volume at 80% full

Cable velocity V_2 m/s			2.0	2.5	3.0	3.5
T_e^a (One disc) ore weight Gravel 3.13kg			100.32 N	156.50 N	227.11 N	310.53 N
T_e^a (One disc) ore weight Granite 4.09kg			136.08 N	204.50 N	296.77 N	405.77 N
T_e^a (One disc) ore weight Coal 1.37kg			53.52 N	83.50 N	121.18 N	165.68 N
Cable	9.0 kg/m	T_2 N/m	88.29	88.29	88.29	88.29
Gravel	$T_e + T_2$	T_1 N/m	244.77	235.77	237.17	228.65
Lifting distance m		$\frac{219000 - T_e^a N}{T_1\ N/m}$	**894**	**928**	**922**	**956**
Lifting cable tension required for 1000m lift. N		eqn. (6.33)	**244,669**	**235,614**	**236,943**	**228,339**
Granite	$T_e + T_2$	T_1 N/m	270.56	260.33	270.20	268.72
Lifting distance m		$\frac{219000 - T_e^a N}{T_1\ N/m}$	**809**	**840**	**809**	**813**
Lifting cable tension required for 1000m lift. N		eqn. (6.33)	**270,424**	**260,126**	**269,903**	**268,314**
Coal	$T_e + T_2$	T_1 N/m	149.73	147.49	148.69	150.25
Lifting distance m		$\frac{219000\ N}{T_1\ N/m}$	**1462**	**1484**	**1472**	**1456**
Lifting cable tension required for 1000m lift. N		eqn. (6.33)	**149,676**	**147,407**	**148,569**	**150,084**
Gravel. Production tonnes per 220 days per year at 20 hours per day			369,643	477,259	594,950	694,108
Granite. Production tonnes per 220 days per year at 20 hours per day			518,285	635,026	777,427	906,998
Coal. Production tonnes per 220 days per year at 20 hours per day			173,606	217,008	260,410	303,811

8.3.6. The Lifting Distance Calculated for the 5-inch Elevator Ore Cells when they have 1kg of Ore per Cell

Table 137. (from Table 90). Calculation of the cable tension T_1, the lifting distance in metres, and production capacities for the 5-inch elevator with only 1kg of ore per disc

Cable velocity V_2 m/s			2.0	2.5	3.0	3.5
T_e^a (One disc) ore weight is 1kg. T_e^a			32.5 N	50.00 N	72.56 N	99.21 N
Cable	9.0 kg/m	T_2 N/m	88.29	88.29	88.29	88.29
Gravel 1000g per disc	eqn. (6.09) $T_e + T_2$	T_1 N/m	138.33	135.45	135.89	133.17
Lifting distance m for 40mm cable		$\frac{219000 - T_e^a\ N}{T_1\ N/m}$	**1583**	**1616**	**1611**	**1644**
Lifting cable tension required for 1000m lift. N		eqn. (6.33)	**138,298**	**135,400**	**135,817**	**133,071**
Granite 1000g per disc	eqn. (6.09) $T_e + T_2$	T_1 N/m	132.89	130.37	132.81	132.79
Lifting distance m for 40mm cable		$\frac{219000 - T_e^a N}{T_1\ N/m}$	**1648**	**1679**	**1648**	**1648**
Lifting cable tension required for 1000m lift. N		eqn. (6.33)	**132,858**	**130,320**	**132,802**	**132,691**
Coal 1000g per disc	eqn. (6.09) $T_e + T_2$	T_1 N/m	133.17	131.49	132.37	133.53
Lifting distance m for 40mm cable		$\frac{219000 - T_e^a\ N}{T_1\ N/m}$	**1644**	**1665**	**1654**	**1639**
Lifting cable tension required for 1000m lift. N		eqn. (6.33)	**133,138**	**131,440**	**132,297**	**133,431**
Gravel granite and coal. Production tonnes per hour **(1kg/disc)**			28.8	36.0	43.2	50.4
Production tonnes per 20hr day			576	720	864	1008
Production tonnes per 220 days per year at 20 hours per day			126,720	158,400	190,080	221,760

Comparing the difference between the lifting distance of the static friction model and the dynamic friction model, the shortest distance is from the static friction model.

8.3.7 Lifting Differences associated with Static and Dynamic Friction:

The distances below where calculated for one kilo of ore per disc in the 5-inch tube elevator for 2mm particle size. The data is taken from Table 137 for the dynamic friction model, and Table 133 for the static friction model. The results show that to maintain a factor of safety of 6.67 then the expected maximum lifting distance has to be based on the lessor distance of the static friction model:

• Gravel	dynamic model 1583m	static model 690m
• Granite	dynamic model 1648m	static model 817m
• Coal	dynamic model 1644m	static model 1257m

8.4 Test Rig 3. A Vertical Pipe Conveyor and Cable Disc Elevator Combined

Test Rig 3 was built to answer the following research questions.

They are:

‘What Would be the Impact of the Frictional Forces for a Hybrid Cable Disc Elevator Combined with a Pipe Conveyor when Used to Replace the Lifting Tube?’

‘*What is the Maximum Distance that a Hybrid Combined Pipe Conveyor with a Cable Disc Elevator Can Lift From?*

8.4.1 The Vertical Pipe Conveyor Component

The vertical pipe conveyor was used with the cable disc elevator to replace the steel 5-inch tube of the cable disc elevator. Pipe conveyors are normally used in a horizontal position. The purpose to use the pipe conveyor is to remove friction for the section (zone 2) in which the cable elevator is inside of the pipe conveyor. This hybrid model then has the cable and the pipe conveyor traveling at exactly the same velocity V_2. Friction between the ore and the tube only exists where the ore is in the steel tube, in zone 1prior to it entering the pipe conveyor zone2 and when the ore leaves the pipe conveyor into zone 3. Zone 1 and 3 represent only one metre of ore travel. The length of zone 1and 3 does not change when the pipe conveyor is lengthened, only zone 2 but there is no friction in this section (Figure 39).

The only purpose of the pipe conveyor is to stop the ore falling off the sides of the disc. Both the pipe conveyor and the cable disc elevator were separately powered and can operate independently of each other. Figure 45 showed that increasing or decreasing the amount of ore on the cable disc elevator did not change the load T_1^P for the pipe conveyor. The evidence then shows that there is no friction interaction between the pipe conveyor and the ore that influences the tension requirements for the pipe conveyor.

The only increase in friction on the pipe conveyor resulted from an increase in the operational velocity V_2.(Figure 45).

Frictions in the pipe conveyor that make up the working tension T_e^P are:

- The roller resistance of the centre panels that keeps the pipe conveyor in shape T_e^{Pctr}.
- The pipe forming shape section, the pipe relaxing section back to a flat belt, drive and idle roller resistances T_e^{Ps}.
- Pipe top seal T_e^{pTs}.
- Pipe bottom seal T_e^{pBs}.

$$T_1^P = T_2^P + T_e^{pTs} + T_e^{pBs} + T_e^{Pctr} + T_e^{Ps}$$

For Test Rig 3 equation 7.04 is used to calculate the maximum pipe conveyor belt tension T_1^P that defines the belt specification

$$T_1^P = BW \text{ x } LD \text{ x } 9.81 + T_e^{pTs} + T_e^{pBs} + (T_e^{Pctr} \text{ x } LD \text{ x } D_n^P) + T_e^{Ps}$$

For Test Rig 3 extended to 1000m as calculated in 7.3.9 the belt tension required would be T_1^P 537N/mm of belt width. The test rig belt is 210N/mm. To achieve a distance of 1000m would require a ST 710 steel wire belt as in Table 4 AS1333-1994.

The belt used for Test Rig 3 was required to have short belt forming section in order to fit into the experimental site. Therefore, a textile belt structure was selected. The test rig site was not suitable for long belt forming section as required for a steel wire cable corded belt, needs a lead in pipe forming section of 60 x the pipe outside diameter (Continental, 2012) as discussed in Section 2.5 , which for the test rig would have been 9 metres of pipe shape length at each end.

8.4.2 The Cable Disc Elevator Component

The cable disc elevator in Test Rig 3 had 26 discs lifting ore at any one moment of which 4 discs were in zones 1 and 3 of the steel elevator tube. These zones represent the only part of this test rig where there is friction between the steel tube and the ore. As described in Section 7.4.2,the ore infeed is in zone 1 has ore lift against gravity for 250mm, ore friction between the ore and the tube for 250mm and ore acceleration from V_1 which is zero to the elevator cable velocity V_2 in 250mm.

Zone 2 only has the carry the ore weight against gravity, there is no acceleration or friction.

Zone 3 is where the ore leaves the pipe conveyor and enters the steel pipe tube which is750mm long and has 3 discs.

8.4.3 Modelling for the Cable Disc Elevator using Friction from Test Rig 2

The similarities between Test Rig 2 and 3 is for ore in the steel tube zone 1 and 3 except that the gap between the disc and the tube is larger in test Rig 3. (7.4.2). In this model, calculation of the lifting distance for Test Rig 3 data from Test Rig 2 is used for zones 1 and 3.

The equations developed in 7.4.7 were for:

- Lifting distance (LD) based on a specified cable tension T_1^C.
- Cable tensionT_1^C required for a specified lifting distance. (LD)
- Friction in zones 1 and 3, T_e^f.

Equation 7.12 shows the cable tension required for a selected lifting distance:

$$T_1^c = LD \text{ x } g\,(\,m \text{ x } D^n + CW) + T_e^c \qquad N \qquad (8.06)$$

Equation 7.11 shows the lifting distance where a specific cable tension strength is specified:

$$LD = \frac{T_1^c - T_e^c}{g\,(\,m \text{ x } D^n + CW)} \qquad \text{metres} \qquad (8.07)$$

Table 135 showing the results for a cable of tension strength 219kN, and the cable strength that would be required for a 1000 metre lift

Table 138. Reproduced from Table 114. Test Rig 3 lifting distance calculations for a selected 40mm cable. Cable tension required for 1000m lift

Ore	m. Ore weight per disc Selected from Table 114 kg	Equation number	T_1^C Specified by cable selection kN	LD Lifting distance Specified m	T_e^c for 1m of lift data from Table 110 Equation 7.04 N	CW 40 mm dia., cable selected from Table 62 at 9.0 kg/m	LD Lifting distance determined by calculation metres	Required cable strength for 1000m lift. T_1^C Determined by calculation kN
Gravel	1.000	7.11	219.0	x	285.50	9.0	1715	x
	3.218	7.11	219.0	x	893.10	9.0	1034	x
	1.000	7.12	x	1000	285.50	9.0	x	127.8
	3.218	7.12	x	1000	893.10	9.0	x	211.9
Granite	1.00	7.11	219.0		284.70	9.0	1715	x
	4.087	7.11	219.0		1160.94	9.0	876	x
	1.000	7.12	x	1000	284.70	9.0		127.8
	4.087	7.12	x	1000	1160.94	9.0		248.7
Coal	1.000	7.11	219.0	x	302.58	9.0	1715	x
	1.370	7.11	219.0	x	399.05	9.0	1534	x
	1.000	7.12	x	1000	302.58	9.0	x	127.5
	1.370	7.12	x	1000	399.05	9.0	x	142.4

8.4.4 Modelling for the Cable Disc Elevator using Friction from experiments conducted using Test Rig 3.

The calculations for the working tension in zones 1 and 3 are taken from the cable disc elevator torque load cell readings. The tension is for lifting the ore on 26 discs of which 22 are in the pipe conveyor. The amount of ore on those 26 discs is the amount of ore that is not in the ore bin and is measured from the ore bin load cells. The ore bin weight is accurate for the number of kilograms of ore and when divided by the number of discs (26), the weight per disc can be calculated, the same calculation can be made for the 22 discs in the pipe conveyor. By working out the difference the tensions in zones 1 and 3 are calculated.

It is expected that the working tensions in zone 1 and 3, $T_e^{z1,,3}$,would be slightly different to the theoretical tensions used for Test Rig 2 as Test Rig 3 measures the tension of the cable which would include any tension effect from the sheaves, whereas in Test Rig 2 the tension is directly measured from the load cells holding the steel 5-inch tube.

Equations for both models are the same except for the value of $T_e^{z1,,3}$ and T_e^c. However, whether experimental data or using data from Test Rig 2 for zones 1 and 2 was used, made little difference as can be seen on Tables 135 and 136.

Equation 8.08 for cable tension required for a selected lifting distance.

$$T_1^c = LD \text{ x } g\,(\,m \text{ x } D^n + CW) + T_e^{z1,,3} \quad \text{N} \qquad (8.08)$$

Equation 8.09 for the lifting distance, where a specific cable tension strength is specified.

$$LD = \frac{T_1^c - T_e^{z1,,3}}{g\,(\,m \text{ x } D^n + BW)} \qquad \text{metres} \qquad (8.09)$$

The following is from Table 130 showing the results for a cable of tension strength of 219kN and shows the cable strength that would be required for a 1000 metre lift using experimental data from Test Rig 3.

Comparing the experimental data from Test Rig 3 and using the data from Test Rig2 for zones1 and 3, there is little difference in the outcomes. The explanation as to why the lifting distances and the tensions are so close is that the increase in elevator length is a function of zone 2 only. Zones 1 and 3 have only 4 discs, regardless of elevator lengths.

Table 139. (Reproduced from Table 130.) Test Rig 3 lifting distance calculations for a selected 40mm cable. Cable tension required for 1000m lift

Ore	m. Ore weight per disc Selected from Table 110 kg	Equation number	T_1^C Specified by cable selection kN	LD Lifting distance Specified m	$T_e^{z1,,3}$ Max. tension selected at 89.59/kg ore N	BW 40 mm dia., cable selected from Table 58 at 9.0 kg/m	LD Lifting distance determined by calculation metres	Required cable strength for 1000m lift. T_1^C Determined by calculation kN
Gravel	1.000	7.26	219.0		89.59	9.0	1717	
	2.000	7.26	219.0		150.47	9.0	1312	
	3.218	7.26	219.00		288.30	9.0	1019	
	1.000	7.25		1000	89.95	9.0		127.6
	2.000	7.25		1000	150.47	9.0		166.9
	3.218	7.25		1000	288.30	9.0		214.7
Granite	1.000	7.26	219.0		89.59	9.0	1717	
	2.000	7.26	219.0		152.28	9.0	1312	
	4.087	7.26	219.0		311.12	9.0	887	
	1.000	7..25		1000	284.70	9.0		127.6
	2.000	7.25		1000	152.28	9.0		166.9
	4.087	7.25		1000	311.12	9.0		249.0
Coal	1.000	7.26	219.0		89.59	9.0	1717	
	1.370	7.26	219.0		89.59	9.0	1540	
	1.000	7.25		1000	89.59	9.0		127.6
	1.370	7.25		1000	89.59	9.0		142.1

8.5 Discussion Summary

The aim of this thesis was to research an elevator that could be used to lift ore vertically in a continuous flow from over 1000m. A cable disc elevator was selected because it only uses a single cable that does not require any matching cables and other mediums to hold a belt together all of which add weight and absorbs some of the lifting capacity.

In selecting the cable disc elevator there is a degree of friction as the elevator drags ore up a tube. Measurements for static friction were higher than that for dynamic friction. This means the cable strength choice needs to be based on the static friction. As a result of those higher frictions the projected lifting distances for the cable disc elevator is lower. Static friction has to be considered for restarting the elevator when it is loaded with ore after a sudden stoppage.

Removing the friction with the hybrid combined cable disc elevator and the pipe conveyor for the lifting distance in zone 2 and minimising the length of the steel tube sections of the cable disc elevator zones 1 and 3, allowed the theoretical model for Test Rig 3 to demonstrate that this hybrid elevator can achieve lifting distances greater than 1000m.

9.0 CONCLUSION

The title of this thesis is '*A Continuous Flow Elevator to Lift Ore Vertically for Deep Mine Haulage using a Cable Disc Elevator'*

The motivation for such research is to encourage the mining industry:

- To look for more simplified continuous ore flow methods to haul ore to the surface.
- Find a way to move beyond the current limitations that present haulage methods have regarding diesel emissions, and long haul being a batch operation.
- To develop vertical elevators.

Ores used for testing were gravel, granite and coal.

The most important knowledge required for a cable disc elevator is the tension strength of the lifting cable because the working strength of this cable must overcome the forces of acceleration, lift against gravity, carry its own weight and overcome friction between the steel tube and the ore, in a fixed tube elevator. This research established the data on friction, both static and dynamic for the test rig sizes selected, as well as defines some limitations.

The most important advance in this thesis was to remove friction in the steel tube (Picture 41 and Appendix 7) by replacing it with a pipe conveyor (Figure 38 and 39). To remove this friction a hybrid elevator was developed consisting of a vertical pipe conveyor and a vertical cable disc elevator that was able to carry ore at 12.5mm size without jamming and without friction in the combined section. This research was carried out in a 5-inch tube and of necessity the test rig was limited in height, however, data from this research enables the calculation required for this hybrid test elevator to lift ore vertically beyond 1000m. Neither the cable disc elevator, nor the vertical disc elevator on their own could lift ore of 12.5mm particle size on their own but as a hybrid elevator they can lift from a depth beyond 1000m.

9.1 The Research Steps

The research of this elevator was completed in three major steps using three different test rigs. This testing demonstrated the success of the elevators and the vulnerability of some aspects of the cable disc elevator when the lifting side tube was a fixed steel tube.

9.1.1 Static Friction Testing.

Static friction testing was undertaken using a 5-inch and 8-inch tube test rig with the ore on a disc to be pulled vertically in a tube that was mounted on weigh load cells. Testing for static friction in Test Rig 1 was most successful when the ore was dry, and of particle size less than the gap between the lifting disc and the fixed steel elevator tube. The gap around the disc to the tube was 2.5mm.

Ore particles greater than 2.5 mm caused jamming between the disc and the tube which would lead to elevator cable failure, (Section 5.11.4). Another ore property that resulted in high static friction was 2mm ore that was wet from free moisture, the highest result was for coal with a 300% increase in static friction (Table 35).

Dry ore of particles less than 2mm in size had the least static friction and it was determined that such ore would be practical for the cable disc elevator where the ore is dragged up inside a fixed steel tube. Static friction results are reported as the breakfree force for various weights of 2mm ore on the disc and calculated as the force per surface area N/cm^2.

The static friction data was used for the 5-inch and 8-inch elevator to calculate and project the friction that would be that experienced for 1000m elevator where there was 4 discs per metre. With the friction force T_e^f added to force to overcome gravity T_e^L and the force required to carry the selected cable weight T_2, the total tension T_1required of the lifting cable is calculated for various depths. and for a selection of commercial cables, their lifting distance capability.

$$T_1 = T_2 + T_e^f + T_e^L \qquad (9.01)$$

Table 140. (Data from Table 50) A summary of the static friction for the 5-inch and 8-inch tubes. Gravel, granite and Coal

Tube Diameter	Ore tested	Static Friction determined for the selected ores N/cm^2		
		1000g per disc	2000g per disc	3000g per disc
8-inches 203.2mm	Gravel	0.09	0.08	0.08
	Granite	0.10	0.06	0.04
	Coal	0.02	0.02	0.02
5-inches 127mm	Gravel	0.19	0.20	0.21
	Granite	0.18	0.14	0.14
	Coal	0.02	0.07	0.15

The lifting distance LD that a cable of known safe tension strength can lift from is given by equation 9.02:

$$LD = \frac{\text{Cable safe tension N}}{T_2 + T_e^f + T_e^L \ \text{N/m}} \qquad (9.02)$$

Table 141. (Data from Table 51). A summary of lifting distance based on using the friction of static friction for the 5-inch and 8-inch tubes, for gravel, granite and coal

Tube Diameter	Cable size	Ore Tested	Maximum Lifting Depth for the ore weight and cable size as determined in Tables 45,46 and 47m		
			1000g	2000g	3000g
8-inch 203.3mm	40mm	Gravel	1156	794	558
		Granite	1144	899	670
		Coal	1348	909	691
	50mm	Gravel	1512	1490	769
		Granite	1398	1133	974
		Coal	1590	1139	890
	75mm	Gravel	1768	1465	1260
		Granite	1695	1542	1295
		Coal	1895	1487	1244
5-inch 127.0mm	40mm	Gravel	690	379	262
		Granite	817	631	408
		Coal	1257	xxx	xxx

9.1.2 Dynamic Friction

Dynamic friction testing was undertaken using a 5-inch fully operational elevator that had fixed steel tubes with the lifting side tube mounted on four weigh load cells. The ore used was dry and particle size was 2mm or less. Ore was fed into the elevator from the ore bin that is mounted on weight load cells. The disc to tube gap was the same as for testing static friction at 2.5mm.

Cable tension requirement included the forces to overcome gravity T_e^L, for acceleration T_e^a, dynamic friction T_e^f between the ore and the tube, plus the force required to lift the cable weight T_2. Based on the results for dynamic friction the capability for the 5-inch elevator with a fixed steel tube to lift is calculated for the lifting distance and the cable tension required to lift ore from 1000m when the cable is a 40mm steel wire cable.

$$T_1 = T_2 + T_e^f + T_e^L + T_e^a \qquad (9.03)$$

For the 5-inch elevator using the dynamic friction, as can be seen in Table 137 the data enabled the calculation for tension T_1 ranges between the different ore from 130kN to 138kN required to lift ore from 1000 metres when there is 1kg of ore on each disc. For the proposed 40mm diameter cable that has a safe tension capacity of 219kN the cable could lift ore from 1583-1679metres for 1kg of ore per disc. Whereas for the equivalent 5-inch tube in static friction tests where there is one kg of ore per disc the lifting distance for a 40mm diameter cable was determined as, gravel 690m, granite 817m and coal 1257m.

The shortest lifting distance is determined by the static friction which applies when the elevator needs to restart when loaded with ore. The distances determined by the static friction testing set the limit of the depth that the 5-inch elevator could lift. The dynamic friction results are summarised in Table 142 below.

Table 142. (From Table 84). Dynamic friction for the 5-inch tube elevator with 1000g of ore on the disc

Cable speed	2.0	2.5	3.0	3.5
	Average dynamic friction df N/cm^2 x 10^{-3} Tables 63-75			
Gravel	10.58	7.76	8.20	5.53
Granite	6.85	3.65	6.74	6.28
Coal	2.41	1.70	2.08	2.57

9.1.3 Removing Friction

Test rig 3 was a hybrid elevator combining a pipe conveyor in a vertical position and a cable disc elevator. Friction in Test Rigs 1 and 2 was measured and contributed to the limit of the lifting height for the elevator cable. It was accepted that friction was at every disc and hence proportional to the height of the elevator. The most significant effects of Test Rig 3 are the elimination of static friction, and limiting dynamic friction for a total distance of 1 metre in zones 1 and 3, regardless of how long the elevator is calculated to be.

The synergistic effect of the hybrid elevator is that it overcomes difficulties that cable disc elevator or the pipe conveyor could not achieve on their own:

- The cable disc elevator cannot lift 12.5mm particle size ore as this would jam between the disc and the tube for a small gap disc-tube diameter as shown in Picture 35 and demonstrated in Tables 17-19.
- Plus, if the gap is increased ore will fall off the disc and fall back down the elevator as shown in Pictures 36-40.
- The pipe conveyor does not lift the ore regardless of how much ore was in the elevator as shown in Figure 38, the forces on the pipe conveyor are related to the pipe conveyor and are influenced by the elevator speed.

The main function of the pipe conveyor is to hold ore on the discs. Frictional forces occurred in zone 1 and 3 but were a short-combined distance of 1 metre. Replacing the lifting tube of Test Rig 2 eliminated friction from zone 2 allowing expansion of the elevator length without a friction component when increasing the calculated length of zone 2.

9.1.3.1Test Rig 3 Friction in zones 1 and 3 for 1 kg of Ore per Disc

The tension due to friction in Test Rig 3 is a result of friction in zones 1 and 3 and is a fixed component for this elevator and not a function of elevator zone 2 length, as shown in Figure 39.

Table 143. (from Table 123). Calculation of the combined friction in zones1&3. Elevator velocity is 2.0 m/s, with variable ore feed rate.

Table number from Appendix 4	Test run number	Ore type and bin auger speed rpm	Ore weight on 26 discs. measured kg	Ore weight on one disc.kg	Tension due to friction. Eqn.7.24 $T_e^{fz1,3}$ N
404	91	gravel 11	15.21	0.59	8.22
407	88	granite 11	15.58	0.60	5.57
413	94	coal 11	12.57	0.48	7.89
405	92	gravel 17	19.16	0.74	9.59
408	89	granite 17	19.28	0.74	4.54
416	97	coal 17	18.53	0.71	5.62
414	95	coal 17	18.34	0.71	6.99
403	107	gravel 22	22.05	0.85	29.29
410	108	granite 22	22.17	0.85	23.28
415	96	coal 22	24.32	0.94	7.14
401	110	gravel 44	52.36	2.01	40.99
412B	112B	granite 44	52.68	2.03	42.62

9.1.3.2 Test Rig 3 Lifting Distance

The lifting distance from Section 7.7.6 was calculated in two ways using the following equations:

The cable tension required for a predetermined lifting distance.

$$T_1^c = LD \text{ x } g\,(\,m \text{ x } D^n + BW) + T_e^{z1,.3} \quad N \qquad (9.04)$$

The lifting distance is calculated for a predetermined cable strength the equation is:

$$LD = \frac{T_1^c - T_e^{z1,.3}}{g\,(\,m \text{ x } D^n + BW)} \quad \text{metres} \qquad (9.05)$$

These equations were developed for the 5-inch hybrid elevator where the total tension for zones 1 and 2 is $T_e^{z1,.3}$ which includes the effect of gravity, acceleration, friction, and lift, is for 1 metre.

Unlike the predictions for dynamic friction, this elevator would not be overridden by static friction.

Table 144. (Table 125). Test Rig 3 lifting distance calculations for a selected 40mm cable. Cable tension required for 1000m lift

Ore	m. Ore weight per disc Selected from Table 110 kg	Equation number	T_1^C Specified by cable selection kN	LD Lifting distance Specified m	$T_e^{z1,.3}$ Max. tension selected at 89.59/kg ore N	BW 40 mm dia., cable selected from Table 58 at 9.0 kg/m	LD Lifting distance determined by calculation m	Required cable strength for 1000m lift. T_1^C Determined by calculation kN
Gravel	1.000	7.26	219.0		89.59	9.0	1717	
	2.000	7.26	219.0		150.47	9.0	1312	
	3.218	7.26	219.00		288.30	9.0	1019	
	1.000	7.25		1000	89.95	9.0		127.62
	2.000	7.25		1000	150.47	9.0		166.92
	3.218	7.25		1000	288.30	9.0		214.71
Granite	1.000	7.26	219.0		89.59	9.0	1717	
	2.000	7.26	219.0		152.28	9.0	1312	
	4.087	7.26	219.0		311.12	9.0	887	
	1.000	7..25		1000	284.70	9.0		127.62
	2.000	7.25		1000	152.28	9.0		166.92
	4.087	7.25		1000	311.12	9.0		248.98
Coal	1.000	7.26	219.0		89.59	9.0	1717	
	1.370	7.26	219.0		89.59	9.0	1540	
	1.000	7.25		1000	89.59	9.0		127.62
	1.370	7.25		1000	89.59	9.0		142.13

The results and calculations for the hybrid elevator have shown that this elevator is capable of lifting ore beyond 1000m vertically with only a small friction component.

9.2 Potential Future Hybrid Elevator Development

The testing for the hybrid elevator was done on a pilot plant test rig which can be considered or defined as a 5-inch tube elevator. The potential to build a bigger hybrid elevator is limited by the size of the cable available for the cable disc elevator component and the maximum diameter of the pipe conveyor, pipe conveyor strength, and the pipe conveyor maximum velocity.

The major strengths in this design of elevator established in this research is that the cable disc elevator component can have a cable selection based on the strength of cable required provided there is enough space in the pipe conveyor for this. From Table 6 the 75mm Gold strand cable has a minimum breaking strength of 4160kN which is 2.8 times stronger than the 40mm cable used in calculations for Test Rig 3. The second strength is that because the pipe conveyor only carries its only weight, this allows it to be as long the belt strength can achieve. In Table 4 the strongest steel wire cord belt is the ST 6300 which is 4.5 time stronger than the ST1400 textile belt used in Test Rig 3.

The production design aim of this elevator would be to have this operating at a maximum design velocity and with the elevator 80 %volumetrically full of ore.

9.3 Future Research for the Hybrid Elevator

The hybrid elevator has potential for use in mine haulage, but there needs to be further research to gain knowledge for larger systems, different orientations vertical to steep angle lift, and different speeds, even different speeds between the pipe conveyor and the cable disc elevator.

9.3.1 Some Parameters to Test in a small Production Research Elevator

The next step is to explore the potential of this elevator and develop a more detailed production size data base. Research suggested for a hybrid elevator should include the following parameters:

- A longer elevator, perhaps to 200metres effective ore lift.
- The pipe diameter of a larger size, perhaps up to 200mm.
- Based on the pipe diameter the disc size needs to be set and the sheave size needs to be scaled to match so that there is an exact number of sections for the disc diameter.
- Selecting the cable diameter will determine the minimum sheave diameter to achieve a cable to sheave diameter ratio of 1:100 or better.
- The elevator needs a continuous production supply of ore, rather than the ore recirculating as was the situation for Test Rig 3, which resulted in the ores, coal and gravel reducing in particle size.
- Minimizing the length of zones 1 and 3.
- Rapid unloading of zone 3. Similar to Test Rig 3 where there was a central discharge pipe, taking the dependency away from the elevator for the need to throw the ore needs to be tested.

- The pipe conveyor could have a cord centre made from steel wire cables. This will effectively help hold the pipe conveyor shape between the roller panels but would need longer pipe shape forming sections.
- The ability for the elevator velocity to achieve the maximum velocity of the pipe conveyor belt.
- Zone 1 still having only one disc in the ore section to reduce the effect of ore fall back and jamming.

In future experiments, measurement of ore flow rates, cable tensions and the pipe conveyor tensions are essential to understand the design and protect from overloading. In Test Rig 3 this was done with load cells that the system could also apply to much larger elevators. Additionally, monitoring of the electrical power loads for the pipe conveyor and the cable disc elevator should be added in order to establish limits that can be used to protect equipment.

Further testing should be carried out on the following:

- Testing of materials that the discs are made from. In the Test Rig 3 wear on the discs was not noticeable, however, the test rig only operated for 200 hours in total, the cast nylon material was very successful.
- A method for replacing discs and swages insitu. Disc with slots were easy to replace albeit they were not required as replacements in Test Rig 3.
- It would be unlikely that swages would have to be replaced after the original cable construction. However, designing and testing a swage that could be bolted on and disc sections to match the swage could be beneficial.
- The top ore seal was not very good at holding the ore in at slow elevator speeds below 2m/s. The success of the seal was at higher speeds and it was taken that at the higher speed the ore had enough momentum to enter the cone entrance of zone 3, then got pulled though by the discs, even if the ore was falling off the sides of the disc, at the higher speeds the seal was not challenged.

There are many parts to test, however a great step forward would be to build a production model of longer length and possibly a larger diameter.

9.3.2 Operating the Hybrid Elevator with Differential Speeds between the Pipe conveyor and the Cable Disc Elevator

When testing with Test Rig 3, the two conveyors were travelling at the same speed, this was a deliberate choice in order to remove friction between the pipe and the ore. However, this begs the question ‘is some friction ok?’. If the cable disc elevator is going 2m/s faster than the pipe conveyor, what is the friction force and what increase in production can be achieved? The pipe conveyor belt may be limited to 4.5 m/s, however, if the cable disc elevator can travel at 6.5 m/s or faster, what are the implications for friction forces and tension loads. Based on the data in Figure 45 it would not be unreasonable to expect there may be little effect on the pipe conveyor, only trials will determine what the outcome for the pipe conveyor would be. Any friction between the ore and the pipe conveyor would be expected then to transfer load onto the cable disc elevator.

9.3.3 A Steep Angle Hybrid Elevator

Another potential use for this elevator could be a steep angle elevator for lifting ore from an open cut mine and depositing the ore on a horizontal overland conveyor belt. In this case, the cable disc elevator is longer than the pipe conveyor and there is no centrifugal ore throw. The discharge would need a guide to have the ore stay on the belt in the pipe conveyor belt deforming section and the transfer the ore to the overland belt. Then there is no zone 3 tube of the cable disc elevator. Similarly, the ore feed coming from a primary crushing plant in the mine pit could with guide plate be loaded onto the hybrid elevator with no cable disc elevator tube for zone 1.

Elevator orientation of the cable disc elevator to the pipe conveyor can be at right angles to each other. The elevator can also be orientated on an angle to the mine face and unlike the bucket elevator it does not have to be perpendicular as shown in Figure 47 view AA.

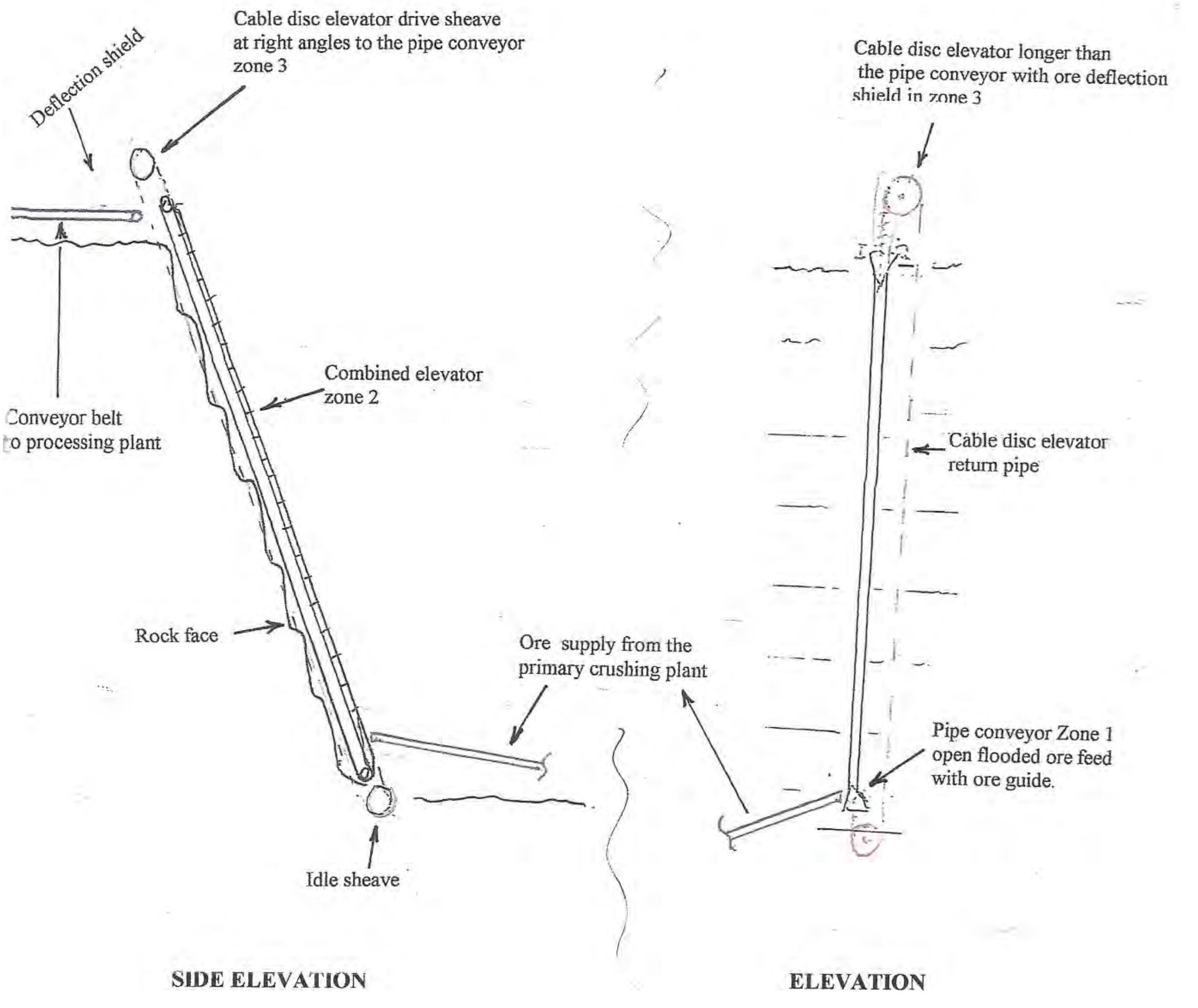


Figure 47. A hybrid cable disc elevator and pipe conveyor in a mine face.

References

ABB. (2019). Mine *hoisting system at Pyhasalmi Mine.* ABB Industries AB Metals and Mining SE-721 67 Vasteras, Sweden. Email: mines.seasy@se.abb.com. Retrieved from www.abb.com/mining

Ake. (2018). Pipe conveyor images, Akecn No.23, Lane 1101, Ninhong Road, Shanghai, China. www.akecn.com. Phn. +86 21 61556225

ARPM, (2011) *Conveyor and elevator belt handbook,* Fourth edition. Association for Rubber Products Manufactures, 7321 Shadeland Station way, Suite 285, Indianapolis IN 46256. www.arpminc.org

Atlas Copco Mine Truck Specifications. (2012*). Atlas Copco Underground trucks, MinetruckMT6020*, Technical specification, 9851 2553 01 H. Retrieved from www.atlascopco.com

AS 1333-1994, *Conveyor belting of elastomeric and steel cord construction*

Bharat B., (2002) *Introduction to tribology,* John Wiley and Sons publication NY. ISBN 0-471-15893-3

BeltCo. (2018). Image. Beltco Conveyor belt Company, Lerchenweg 2, 63762 Grossostheim Germany. Retrieved from www.beltco.com/conveyor-belt-sidewall.php

Berg Van Den G. and Cooke R. (2004). *Hydraulic hoisting technology for platinum mines.* International Platinum Conference 'Platinum Adding Value' The South African Institute of Mining and Metallurgy 2004. pp 15-24.

Beumer. (2015). *Technology in motion, conveyor technology.* Beumer Maschinenfabrick GmbH & Co., KG., Postfach 1254, D-59267 Beckum, Germany. Retrieved from www.beumergroup.com

Bise C.J., *Mining Engineering Analysis.* (2003). 2nd Ed. Society for Mining, Metallurgy, and Exploration Inc (SME). ISBN 10-87335-211-1

Blau P.J. (2013). *Encyclopedia of Tribology.* Materials, Science and Technology Division. Oak Ridge National Laboratory, Oak ridge USA.

Blau P.J., (2008) *Friction Science and Technology- from concepts to applications.* 2nd edition (CRC/Taylor and Francis, Boca Raton, FL)

Bogaert-Transmission, (2018). *D bucket elevator chains and components.* - Bogaert-Transmission, NV Neringstraat 5-7 B-1840 Londerzeel Belgium. Retrieved from www.bogaert-transmission.com

Bhowmick T. and Dutta P., (2015) *A conceptual approach to design a magnetically propelled integrated underground hoisting system.* Published May 2015. 37th International Symposium on Applications of Computers and Operations Research in the Mining Industry.

Bridgestone. (2018). *Conveyor belt design manual.* Bridgestone TPE Co., Ltd 2001. International Industrial products Department 10-1, Kyobashi 1 – chome, Chuo-ku Tokyo 104 Japan. Retrieved from www.bridgestone.com/products/diversified/conveyorbelt/products/index.html

Bridon. (2011). Bridon Steel Rope Technical Manual (2011). Bridon oil and gas www.bridon.com/china/downloads/steel_technical

Britannica. (2018). Retrieved from www.britannica.com/science/friction*ref135523

Cancer Council. (2018). *Occupational cancer risk series diesel engine exhaust. know workplace cancer.* Retrieved from www.cancer.org.au/preventing-cancer/workplace-cancer/dieselengine-exhaust.html

CEMA, (2014). *Belt conveyors for bulk materials.* Conveyor Equipment Manufacture Association, Engineering Conference ISBN 1-891171.44.5 Published by Conveyor Equipment Manufacture Association 5672 Strand Ct., Ste.2 Naples Florida USA 34110. www.cemanet.org

CEMA, (2017). *Bucket elevator book- best practices in design*. First Edition pp 141-150, 64-67, 391-403. Conveyor Equipment Manufacture Association, Engineering Conference ISBN 978-1-891171-89-9 Published by Conveyor Equipment Manufacture Association 5672 Strand Ct., Ste.2 Naples Florida USA 34110. www.cemanet.org

Changwoon Nah, Bong Young Sohn and Soo-jin Park, (2002) *Adhesion of brass/cobalt/copper-plated steel cord to a typical rubber compound.* Journal of Adhesion Science Technical, Vol. 16 No. 6 pp. 653-667

Contitech, (2013), *Conveyor belts and design calculations*, Conveyor Belt Group Contitech, Transportbandsystem GmbH Breslauer Straβe 14, 37154 Northern Germany., 5th edition 2013, pp.54- 63 'Peripheral Force 3.5.' Published by, Continental Aktiengesellschaft, Hanover, Germany. www.contitech.de

Conti Pipe. (2018). Retrieved from https://www.contitech.de/getmedia/7672bdb4-5b4a-4445-9dcc-05595af76ca5/CBG9016-En-Conti-Pipe.pdf

Crosby., (2014). *Wire rope ends terminations user's manual,* The Crosby Group, P.O. Box 3128 Tulsa OH., USA. www.thecrosbygroup.com

De La Vergne, Jack (2003) *Hard Rock Mines Handbook,* M^{c}Intosh Engineering p114-124 ISBN 0-9687006-1-6

Department of Mines and Petroleum, (2013). *Management of diesel emissions in western Australian mining operations-guideline:* Resources Safety. Department of Mines and Petroleum, Western Australia. ISBN 978 1 92 2149 04 6

Dick J.S., (editor) and others, (2009), Alpha Technologies. *Rubber technology compounding and testing for performance.* 2nd Edition, Chapter 3, pp.46-67, Hanser Publications, ISBN 978-3-446-42155-4

DIN 15061-2: (1977). *Cranes, groove profiles for wire rope drums.* DIN handbook 185,342 and DIN VDE HDBK 342/3

REFERENCES

Dunlop. (2011). *Dunlop conveyor belting technical manual* Version 2.3 11-07-2011. Fenner Dunlop. 268 Geelong road West Footscray, Vic., Australia.

DIN 22101(2011-12) *Belt conveyors for loose bulk materials-basis for calculation and dimensioning.*

Electrek, (2018). Retrieved from www.electrek.co

Evans L.R., Waddell W.H., (June 1997), *Cobalt and other moderates stimulate sulfide bonds.* Rubber World June 1997, pp.22-28.

Fenner-Dunlop, (June 2009), Australia *Conveyor handbook.* Fenner Dunlop. 268 Geelong road West Footscray, Vic., Australia

Fenner Dunlop (2013), *Steel cord belt- Siempelkamp. manufacturing capability at the Kwinana, WA plant.* Retrieved from www.siempelkamp.com

Feyrer, K. (2015) p125-129. *Wire Ropes. tension, endurance, reliability.* www.springer.com/978-3-642-54995-3

Fairhurst, C. (2017). *Some Challengers of Deep Mining* Engineering Volume 3, Issue 4, pp 527-537. Elsevier

Farshad F.F., SPE, and H.H. Rieke, (2017). SPE. *Surface Roughness Design Values for Modern Pipes,* University of Louisiana at Lafayette.

Floveyor. (2015). 6 Alice Street, Bayswater, Western Australia 6053. +61(08)93783333. www.floveyor.com.au. (accessed Jan.2015)

Glushko, M.F. (1996). *Steel lifting ropes.* Kiev Technica, p 327

Goldenest. (2015). Shandong Goldenest Machinery Co., Ltd. No. 261, Sancheng Rd. Development Zone, Qingdoa Pingda City Shandong Provence China. Retieved from www.jinchaol1988.com .

Google maps. *Open Cut Coal Mine, Maddingley.* https://www.google.com.au/maps/place/Bacchus+Marsh+VIC+3340/@-37.6957682,144.4317723,5532m/data=!3m1!1e3!4m5!3m4!1s0x6ad6956b81d87165:0x5045675218cd000!8m2!3d-37.6763789!4d144.4463206

Google maps. *Ballarat Gold Mine, and Kopkees Quarry.*https://www.google.com.au/maps/place/Ballarat+VIC/@-37.5860021,143.8206207,9640m/data=!3m1!1e3!4m5!3m4!1s0x6ad1445430931879:0x40579a430a0b720!8m2!3d-37.5621587!4d143.8502556

Gough, V.E. (1968), Rubber Chem. Technol.44, 988

Gwalia Mine. (2019). Retrieved from www.stbarbara.com.au.

Hankus, J. (1993). *Non-typical process of the progressive weakening of the mining hoisting rope.* pp II21-II34 OIPEEC Round Table, Delft.

Hankus, J. (1997). *Consideration of mine hoisting rope contraction.* OIPEEC Bull. 73,9-19 1997).

REFERENCES

Hapman Global. (2017). 5944 East N Arenlde, Kalamazoo, Miehigan 4908 Phn 1(877)7048358 Retrieved from www.hapman.com

Harrison A. (2009). *A comparison of friction models for conveyor design.* Bulk Solids and Powder. Science and Technology. Vol. 4 (2009) No. 1

Holcim, (2011), *Aumund India Rebuilds the World's Highest Bucket Elevator,* Swiss Holcim Group, Lafarge Holcim, Lafarge India Aumund Plant, Equinox Business Park Tower 3 East Wing,4th Floor Off Bandra-Kula Complex, Marg, Kula west, Mumbai 400070, Retrieved from www.aumund.com

IARC. (2015), *Diesel Engine Exhaust Carcinogenic,* Press release No. 213 International Agency for Research on Cancer, 150 Cours Albert Thomas, 69372 Lyon CEDEX 08 France. Retrieved from www.iarc.fr

Jordan D. and Dittmann F W. (1980). *The hydraulic hoisting from dry coal from a depth of 850metres.* Journal of the South African Institute of Mining and Metallurgy. May 1980. pp.177-182.

Kevlar. (2013), *Kevlar helps extend the life of and creates long term solutions for conveyor belts in the mining industry.* Retrieved from www.kevlar.com

Kevlar. (2014), *Dare Bigger When extreme is not a sport it's your job.* DuPont K-27929 (09/14) *Properties and processing of Dupont Kevlar Brand Yarn for Mechanical Rubber Goods* Retrieved from www.kevlar.com

Kinder. (2015). *Kinder Bulk Materials Handling Solutions Made Better,* Kinder Bulk Materials Handling. Table Maxi Tuff Industrial Duty AA Buckets, 18 x 10-inch size selection. Retrieved from www.kinder.com

Lodewijks G., (2012), Zamiralova M. E., *Energy consumption of pipe belt conveyors: indentation rolling resistance.* Faculty of Mechanical Engineering, Belgrade. FME Transaction (2012) Vol 40, No. 4, 171-176 (Accessed April.2015).

Lowrie R.L., P.E, (2002) *Mining reference handbook,* pp238, Society for Mining, Metallurgy, and Exploration Inc (SME). ISBN 0-87335-175-4.

Manning. (2018). *Mannings's roughness coefficients for some commonly used surface materials.* The Engineering Toolbox. Retrieved from www.engineeringtoolbox.com/mannings-roughness-d_799.html .

Mark James E., Erman Burak, Roland C. Michael. (2013), *The Science and Technology of Rubber.* 4Th Edition, chapter 9, Brendon Rogers, and Walter Waddell, EXXON MOBIL Chemical Company Houston, TX, USA pp 417 – 471, Academic Press. ISBN 978-0-12-394584-6

Metlikovic P. M., (2006), *Mechanics of Rubber Covered Conveyor Rollers.* A Dissertation, Presented to The Graduate Faculty of The University of Akron, in Partial Fulfillment of the Requirements for the degree –Doctor of Philosophy. UMI Microform 9623201 UMI 300 North Zeeb Road Ann Arbor, MI 48103.

Metso. (2019). MRC Cable belt conveyor. Metso Minerals Industries Inc. 4000 Town Centre Blvd., Ste 400, Canonsburg P.A. 15317 USA. www.metso.com

Mining Technology. (2013). *The Top Ten Deepest Mines in the World,* Retrieved from www.miningtechnology.com.

NMA. (1998). *The Future Begins with Mining.* A vision of the mining industry of the future Conference September 1998. National Mining Association. Washington D.C.

NSW Department of Industry, (2007) Resources and Energy, *Balmain's Own Coal Mine,* Prime fact number 556. First edition,.

Nylacast. (2016). Nylacast Limited Company no. 5949301 *Nylube Engineering Plastics Solutions. Materials Brochure.* Vol.01.05.16 Nylube pp.16,17. 480 Thurmaston Boulevard, Leicester UK LE4 9LN. United Kingdom. www.nylacast.com

Overland. (2017). Overland conveyor belt company. 1536 Cole Blvd, Suite 150 Lakewood CO 80401 USA . Retrieved from www.overlandconveyor.com

Parekh B K. (2009). *Dewatering of fine coal and refuse slurries-problems and possibilities.* 6th International Conference on Mining Science and Technology. Science Direct. Proceia Earth and Planetary Science 1 (2009) 621-626.

Pathagama G. RanjithJianZhaoMingheJuRadhika V.S. De SilvaTharaka D. RathnaweeraAdheesha K.M.S .Bandara**. (**2017) *Opportunities and Challenges in Deep Mining: A Brief Review*Engineering Volume 3, Issue 4, , Pages 546-551.

Peterson Alex, (2009) *Compounding for Brass Wire Adhesion, Rubber Technology Compounding and Testing for Performance* Chapter 20, pp.464-475. 2nd Edition Hanser Publications, ISBN 978-3-446-42155-4

Phoenix, (2004). *Phoenix Conveyor Belts- Design Fundamentals, Hamburg 2004,* Design compliant to DIN22101, Phoenix Conveyor Belt Systems GMBH, Hannoversche Strasse 88, D-21079 Hamburg, Germany. Document 513-102-0804 Retrieved from www.phoenix-ag.com

Pheonix. (2007). *Worlds Strongest Conveyor Belt.* Press release retrieved from www.pheonix-conveyor-belts.com/pages/press-theme/press/2007-01_strongest_conveyorbelt_en.html

Pratt A.G.L.\(2005) *Application of Conveyors for Underground Haulage*. Proc 9th Underground Operators Conference, Perth, WA, 7-9 March 2005, pp 273-283 AusIMM, Melbourne , Vic Australia.

Probelt. (2018). Probelt Global Limited. No. 12, Industrial North Rd., Nantou City 54066, Taiwan, R.O.C. Retrieved from www.pgl.com.tw

QGN21 (2014), *Guidance note for the management of diesel engine exhaust in metalliferous mines.* Mine and Quarrying Safety and Health Act 1999., Version 1 Queensland Department of Natural Resources, Mines and Energy

REFERENCES

Ramakrishna S., (2018*). Competent Engineering.* Plot No.-84, Sector -21C. Fairbad 121003, Haryana India. Info@competentengineering.com Retrieved from www.competentengineering.com.

Ramani R.V. (2012). *Surface Mining Technology: Progress and Prospects*, 2011. 1st International Symposium on Innovation and Technology in the phosphate Industry. SciVerse ScienceDirect Procedia Engineering 46(2012)9-21

Regan Robert, (2007) Chief Inspector for Underground and Coal Mine Health and Safety. *'Requirements for the Design, Registration of Powered Winding Systems'*. NSW Department of Primary Industries.

Renold (2018). *Conveyor chain installation, maintenance and designer guide.* Renold Australia P/L., 508 Wellington Rd., Mulgrave 3170 Victoria Australia. Retrieved from www.renold.com.au.

Rio Tinto. (2008). *Resolution Copper Mine completes deepest single mine shaft in America,* Retrieved from www.riotinto.com

Robertsons Lifting Ropes, (2014) Wire Rope manual, 4 Burchill St., Loganholme, Qld. Australia 4129. www.lifting.com.au

Rosengren N. (1986). *Sites of geological and geomorphological significance in the Western Region of Melbourne*. Prepared by the Department of Geography, University of Melbourne for Department of Conservation, Forests and Lands, Arthur Rylah Institute, Ecological Inventory and Evaluation Section. Available from The Secretary, Western Region Commission, 254 Ballarat Road, Braybrook, Vic. 3019.

SME. *Mining reference handbook.* Society for Mining Metallurgy and Exploration Inc. 8307 Shaffer Parkway Littleton, Colorado, USA 80127. www.smenet.org . ISBN 0-87335-175-4

South West Ropes. (2015). *Wire Rope Gold Strand,* South West Wire Rope a Division of Houston Wire and Cable Company (HWC), 1902 Federal Road, Houston , Texas 77015. Retrieved from www.swwrinc.com

Spreadborough J.C. and Pratt, A.G.L. (2008) *Inclined troughed Belt Conveyor Systems for Underground mass Mining Operations*. Proc 10th Underground Operators Conference, Launceston, Tas. 14-18 April 2008 pp 71-76 AusIMM Melbourne, Vic. Australia.

Staples, P. (2002), *The history of pipe conveyors,* Bulk Solids Handling 22(3). 2002

Thiess. www.thiess.com/project/leinster-underground/detail. Retrieved 2018.

Thomson I.M., (2002). *The cable belt conveyor at selby mine.* Cable Belt Conveyors Pty. Ltd. www.saimh.co.za/beltcon/beltcon2/paper213.html

UC Rusal. (2015). *U C Rusal opens Russia's deepest mine.* Retrieved from www.rusal.ru

VDA. (2018). Verband der Automobilindustries. Adblue specifications. Retrieved from www.vda.de

Vladic J., Jovanovic M., Dokic R., Kljajin M., Karakasic M., (2015), Theoretical *and experimental analysis of mine elevator dynamic characteristics.* ISSN 1330-3651(print) ISSN 1848-6339 (online) DOI: 10.17559/TV-20150107175453. Technical Gazelle 22,4, pp1011-1020

Walker, S.C., (1988) *Mine winding and transport* Advances in Mining Science and Technology 4. Elsevier Amsterdam, New York, p546 .

Wallace. S. J. (2007). *Diesel Engine energy balance study operating on diesel and biodiesel fuels.* Russ College of Engineering and Technology of Ohio University. www.researchgate.net

Wang Q.J., Chung YW.(eds), *Encyclopedia of Tribology.* Springer Boston MA. ISBN 978-0-387-92896-5

Webb S.R. (1968) *Performance and vibration study of the 'floveyor' grain elevator.* Master of Engineering thesis, School of Mechanical Engineering, University of Wollongong. http://ro.uow.edu.au/thesis/2408

Wirelock. (2018). Wirelock Millfield Enterprises (Manufacturing) Limited. Shelley Rd., Newburn Industrial Estate, Newcastle upon Tyne. NE 15 9RT. Retrieved from www.wirelock.com

Woan Graham, (2014). *The Cambridge Handbook of physics formula's [online],* pp.68 Cambridge: Cambridge University Press. Available from Cambridge Books online. (http: dx.doi.org/10.1017/CB09780511755828).

Yates H. (1953) M Sc Geology, *The basalts and granites rocks of the Ballarat districts.* Read 9 July 1953. Ballarat School of Mines. Retrieved from www.victoriancollections.net.au

Zang Y. (2012). Conveyor Dynamics Inc. Bellingham WA, Stevens R. Veyance Tech, Inc. Marysville, OH. *Pipe conveyor and belt: belt construction, low rolling resistance and dynamic analysis.* SME Annual Meeting Feb. 19-22, 2012 Seattle, WA.

Bibliography

Alspaugh M.A. (2003). *The evolution of intermediate driven belt conveyor technology,* (Accessed Nov.2015)

Artisan. (2018). www.artisanvehicals.com/z40/

Association for Rubber Products Manufactures *Conveyor and elevator belt handbook.* Fourth Edition (2011). 7321Shadeland Station Way, Suite 285, Indianapolis, IN 46256. www.arpminc.org (Accessed August 2015)

Australian Government Department of Resources, Energy and Tourism. *Energy efficiency opportunities* case study. *analysis of diesel use for mine haul and transport operations.* Fortescue Metals Group Ltd., Downer EDI Mining Pty. Ltd., and Leighton Contractors Pty., Limited. Retrieved from www.energyefficiencyopportunities.gov.au

Barsukov V.G., Krupicz B., and Barsukov V.V., (2012) *Tribomechanical analysis of interlayer shear and surface crack nucleation process in compacted disperse materials.* Published June 14, 2012. Ya. Kupala State University ul. Oheshko 22 Godono 230023 Belarus. Email: barsukov2002@mail.ruTranslation, L. Pushkina

Beder S., (1996) *The nature of sustainable development*, 2nd ed. Scribe, Newham, ch 4.

Belt Design Program *Viscoelastic calculation.* (2011).Helix Delta T. Retrieved from www.helixconveyor.com/helixprog/sect6helixviscocalcs.pdf

Beumer Conveyor Technology, High *Capacity belt bucket elevators,* Beumer Maschinenfabrick GmbH & Co., KG., Postfach 1254, D-59267 Beckum, Germany. www.BEUMER.com (Accessed Feb.2015).

Brandis U., Klose R., and Simons P., (1986), *Investigations into the transport behavior of highly concentrated fine ground coal slurries using a 470*m^3*hr triplex piston pump.* Hydro transport 10, pp.31-28 (1986) (Accessed Feb. 2016).

Bridgestone, (2001)*, The history of pipe conveyors* – Conveyors Information of Bridgestone TPE Co., Ltd. (Accessed Dec.2014)

Bulk Solids Handling Vol.23 (2003), No.3. Mark Alspaugh- Principle Systems Engineer, Overland Conveying Company, Inc., Ontario Place, Littleton, CO 80127, USA. (Accessed Oct.2015)

Bullivants, Rope and Strand Handbook, 4th Edition. www.bullivants.com (Accessed Sept. 2015).

Canudas de Wit, C., H. Olsson, K.J. Astrom, P. Lischinsky (1995), *A New model for control of systems with friction,* IEEE Transactions on Automatic Control 40(30). (Accessed Feb. 2016),

Chain-Vey Tube Conveyors, 3125 South Kolin Avenue Chicago IL 60623 www.mpechicago.com Accessed April 2016

Continental, *Conti pipe- high-speed pipe conveyor belts.* http://www.contitech.de/pages/produkte/transportbaender/cdgindustry/rollgurtfoerderer_en.html (Accessed September 2016).

Conveyor Dynamics, (Dec 2014). Conveyor Dynamics corporation, Riverside Industrial Centre, 7000 West Geneva Drive, Saint peters, MO 63376 USA. www.conveyordynamicscorp.com (Accessed August. 2015).

Carlos III University, (2008,) *Bucket elevator transportation,* Mechanical Engineering Department Carlos III University, Av.de la Universidad, 30,28911 Leganes, Madrid, Spain. (Accessed Dec.2014)

Crowther Bryan editor, (Reprinted 2003), *Handbook of rubber bonding Rapra* Technology D. Wootton. Limited, Shawbury, Shrewsbury, Shropshire, SY4 4NR, UK. 2003. ISBN 1-85957-394-0

De la Vergne Jack (2003) *Hardrock miners handbook.* McIntosh Engineering pp114-124,64-65, 125-134. ISBN 0 9687006-1--6

Dick J.S. (editor) and others. (September 2013), *How to improve rubber compounds, 1800 experimental ideas for problem solving,* 2nd Edition. 'Decreasing Air Permeability 'Hanser Publications, ISBN 978-1-156990-533-3

Donkin T., and Pulvermacher B., (15 March 2015), *Developments and trends in conveyor belts reinforced with Kevlar aramid fibre,* Du Pont de Nemours International S.A. Industrial Fibres Division, Geneva, Switzerland, South African Branch Office, Sandton, Transvaal. www.saimh.co.za (Accessed May 2015).

DuPont, Technical Information - *Property and processing of du Pont Kevlar brand yarn for mechanical rubber goods.* DuPont reference H89934 Rev 2/01. DuPont Australia 254 Canterbury Road Bayswater, Victoria 3153. www.dupont.co.uk , www.kevlar.com (Accessed March 2015).

Engineering Tool Box, *Wire rope –strength- wire rope 6-strand x 19 wire (6x19) –* weight minimum breaking strength and safe load, www.engineeringtoolbox.com (Accessed Nov. 2014).

Feed Forward, (2001) *Bucket elevator design notes.* Feed forward Publications P.O. Box 578 Bentley Western Australia 6102. (Accessed Feb. 2015)

Fenner Dunlop, (2014), *Conveyor belting Australia – steel cord belt. steel cord splicing methods.* 268 Geelong road West Footscray, Vic., Australia. (Accessed Sept. 2015)

Forbo, (2013), Calculation *Methods –Conveyor belts.* Siegling Transition, Conveyor and Processing Belts. Forbo Movement Systems, Lilienthalstrasse 6/8, D-30179 Hanover. www.forbo-segling.com, www.forbo.com Company Ref. No. 404-2, 01/2013(Accessed March 2015).

Frank G. (2005), *Conveyor belt tension calculations-full motor method.* Fenner Dunlop USA. Accessed, August 2005

Goodyear Engineered Products, (2007), *Heavy weight conveyor belt guide*. Worldwide Conveyor Belt Technology Centre, Marysville, Ohio, USA. www.goodyearep.com/conveyorbelts. (Accessed 14 June 2015)

Gabriel Fedorko, Vladimir Ivanco, Vieroslav Molnar, Nikoleta Husakova. (2012), *Simulation of interaction of a pipe conveyor belt with moulding rolls.* Faculty of Mechanical Engineering, Technical University of Kosice, Letna 9, 04200 Kosice, Slovak Republic. Procedia Engineering 48, pp129-134. (Accessed April 2015).

Gabriel Fedorko, Vladimir Ivanco. *Analysis of force ratios in conveyor belt of classic belt conveyor.* Faculty of Mechanical Engineering, Technical University of Kosice, Letna 9, 04200 Kosice, Slovak Republic. Procedia Engineering 48 (2012) 123-128. (Accessed June 2015).

Gerard van den Hondel, (2010), *Aramids for low weight and low rolling resistance of conveyor belts.* Bulk Solids Europe 2010- Glasgow. Teijin Aramid B.V. (Accessed July 2015).

GE, General Electric, www.enewables.gepower.com (Accessed June 2015).

Goldsack D.E., (1998), *Elements of paste fill rheology,* Centre in Mining and Mineral Exploration Research, Laurentian University, Sudbury. (Accessed August 2015).

Grant I.S., Phillips W.R., (1991), *Electromagnetism 2E,* Wiley 2nd Edn. January 1991, ISBN 978 0471927129

Hardygora M Prof., & others. (2012), *Method of predicting the fatigue strength in multiplies splices of belt conveyors*. Maintenance and Reliability Vol. 14, No.2, Institute of Mining Eng. Wroclaw University of Technology. (Accessed April 2015).

Harman Howard L. (1992)”17” SME Mining Engineering Handbook. ISBN 0-87335-100-2 (Accessed August 2015).

Hazewinkel Michiel, (2001), *Euler formulas, encyclopedia of mathematics,* Springer, 2001 ISBN 978-1-55608-010-4

Helmich Tony, *The true value of magnetic separators and metal detector in bulk handling.* Eriez Magnetics Europe Ltd, UK. Tony.helmich@eriezeurope.co.uk (Accessed July 2015)

Hetezel F. V., (1922), *Belt conveyors and belt elevators.* John Wiley & Sons Inc., 1922 ISBN 9 781142 679088

Honeywell Sensing and Control, www.measurementsencors.honeywell.com www.sensing.honeywell.com (Accessed 14 May 2015),

ICSDP, Kola *Superdeep borehole (KSDB) – IGCP 408 rocks and minerals at great depths and on the surface.* International Continental Scientific Drilling Program, ICDP internal ID: IGCP408 http://www-icdp.icdp-online.org (Accessed 14 July 2015), Intersystems, *Bucket Elevator Manual- safety, installation, operation and maintenance.* Intersystems 9575 No.109th Ave. Omaha, NE 68142 PC 522142-C4. (Accessed June 2015)

Imai, A. (2001) *Pipe conveyor development, benchmark and future trend'* Bulk Solids India 2001, India. (Accessed April 2015).

Iyengar Y., (March 1978) (published online 9 March 2003) *Adhesion of Kevlar aramid cords to rubber.* Du Pont de Nemours & Company, Inc., Textile fibers Department, Willington, Delaware 19898, Journal of Applied Polymer Science, Volume 22, Issue 3 Pages 801-812 March 1978. (Accessed April 2015).

Jonkers C.O. (1980), The *Indentation rolling resistance of belt conveyors- a theoretical approach.* Fordern and Heben Vol 30, No. 4, pp.312-317, 1980 (Accessed July 2015).

Koné, *KONE Ultrarope elevator hoisting technology,* KONE Corporation Finland, Kone Oyi, Keilasatama, P.O. Box 7, Espoo, 02150 Finland, www.kone.com (Accessed 22 Feb. 2015).

Kruse D.J., and Lemmon R., *A comparison of various belt tension calculation methodologies including CEMA 6th Edition.* Advanced Conveyor technologies Inc. (AC-TEK) 19415 594th Avenue Mankato Minnesota 56001 USA. (507) 345-5748 www.actek.com

Kessler Franz, (2002), *Pipe conveyor with a completely new belt guidance.* Department of Conveying Technology and Design Methods, University of Leoben Franz-Josef-StraBe 18, A-8700 Leo ben, Austria. E-mail: Kessler@unileoben.ac.at (Accessed March 2015).

Ko Arts, Case *Study: Aramid reinforced conveyor belt in Maritsa Istook 2 power plant.* Teijin Aramid Velperweg 76, P.O. Box 5153, 6802 ED Arnhem, Netherlands. www.teijinaramid.com (Accessed April 2015).

Kolesnikov V.I., (Dec 2011) Bulgarevich S.B., M.V. Boiko, V.A. Freizo, *Mechanoactivation in friction and the laws of sliding and rolling friction.* Journal of Friction and Wear Volume 32, Issue 6, pp.413-418. 01/12/2011. ISSN 1068-3666 (Accessed June 2015).

LI Shengtian, Dong Jianhua, YU Fusheng. (1986), *A Study on the yield strength of sbr raw rubber.* Changchun Institute of Applied Chemistry, Academia Sinics, Changchun. Chinese Journal of Polymer Science 1986. (Accessed April 2015).

Lawrence M.A., de Almeida J., (2001) Maximize *Steel cord adhesion with resorcinol formaldehyde resins',* Tire Technology International , pp. 58-61. (Accessed Feb. 2015).

Lodewijks G. *Applied belt design delft* University of Technology. Department of Marine and Transport Technology. Mekelweg 2 2628 CD Delft the Netherlands. (Accessed Jan. 2015).

Lodewijks Gabriel, *Determination of rolling resistance of belt conveyors using rubber data: fact or fiction?* Faculty of Mechanical Engineering and Marine Technology, Delft University of Technology, the Netherlands. (Accessed May 2015).

Ludema K.C., (1975), P*hysical factors in tyre traction.* Physics in Technology January 1975. Department of Mechanical Engineering, University of Michigan, Ann Arbor, Michigan USA. (Accessed May 2015).

Magnetix. Commercial magnets. www.magnetix.com.pl (Accessed July 2015)

May W.D., Morris E.L, and Atack D., (March 1959), *Rolling friction of a hard cylinder over a viscoelastic material.* Pulp and Paper research institute of Canada, Montreal, Canada. Journal of Applied Physics, Volume 30, Number 11, (Accessed May 2015).

MEP-Oblo, Mehler – Engineered Products, Edelzeller, Straβe 44, Fulda 3604, Hessen Germany. www.mehler.com (Accessed August 2015).

Mitchell J.J., and Anderson D.W, *High angle conveyor offers mine haulage savings,* continental Conveyor & Equipment Co. Inc., Winfield, Alabama USA. & Spencer (Melksham) S.A Pty. Ltd., Johannesburg, South Africa. www.saimh.co.za/beltcon/beltcon3/paper37 (Accessed June 2015).

Michio O. (2013) & Hiroshi Matsukawa, *Systematic breakdown of Amontons' law of friction for an elastic object locally obeying Amontons law.* Article Number 1586 (2013) Scientific Reports 3 doi:10.1038/srep01586. (Accessed June 2015).

Nordell L.K. (November 1993) *Steel cord belt and splice construction- modernizing their specifications, improving their economics.* Bulk Solids Vol 13 No.4 November 1993.

Nuttall Ashley, (Dec. 2007), *Design aspects of multiple driven belt systems.* TRAIL Thesis Series No. T2007/12, the Netherlands TRAIL, Research School. ISBN 978-90-5584-092-2.

Rainer Alles. Ing Dr. (1994) *Conveyor belt system design., conti conveyor belt service manual.* Published by ContiTech Transportbandsysteme GmbH D-30001 Hannover, Germany.

Orlov E.K., Nedostup A.A., (2011) *Results of verification of the formula for calculation of friction coefficient of threads, cords, and ropes on a traction drum of the frictional mechanism.* 10th International Workshop. University of Split DEMaT'.

Patrick M. McGuire P.E., (2009) *Conveyors application, selection, and integration.* CRC Press. August 5, 2009. ISBN 978 1 4398 0388-2

Pitcher D.M., *Joining conveyor belting,* Dunlop Industrial Products, 25 Lincoln Rd., Benoni, 1500 South Africa, www.dunlopindustrial.co.za ww.saimh.co.za/beltcon/beltcon12/paper1214a.htm (Accessed 19th April 2015), Rebel G., Verreet R., Briem U., (5-7 September 2005). *Composite steel wire ropes for mine hoisting applications.* Hoist and Haul Conference Perth Western Australia (Accessed August 2016).

Reicks A.V., (Dec.2012), Overland Conveyor Company. T.J. Rudolphi , Department of Aerospace Engineering Iowa State University. C.A. Wheeler. University of Newcastle Callagan NSW Australia. *A comparison of calculated and measured indentation losses in rubber belt conveyors.* (Dec 2012). White paper for Bulk Solids Handling (Accessed April 2015).

Rema, *Pulley laggings and belt idler sleeves.* Rema Tip Top / north A (Accessed June 2015).

Rema Tip Top America Inc. Industrial division. 1500 Industrial Blvd. Madison GA. www.rematiptop.com (Accessed May 2015),

Roylance David, (23 August 2001), *Stress- strain curves,* Department of Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139. (Accessed May 2016).

Schicker Rainer, Wegener Dr.Georg, *Measuring torque correctly.* www.hbm.com/torque Electronic edition (Accessed 29 May 2017} HBM Australia 61(0)893806933

SME, (Feb. 27th- March 02, 2011), Annual Meeting, Denver CO., *Haul truck fuel consumption and* CO_2 *emissions under various engine load conditions.* Kecojevic V., West Virginia University Morgan Town NY., Komljenovic D., University of Quebec Montreal QC Canada,

Spiroflow Systems Inc. 1609 Airport Rd., Monroe, North Carolina 28110 USA. www.spoiroflow.com (Accessed May 2017),

Spirolflow. www.spirolflow.com accessed (Accessed July 2018).

Stojanovic B., Babic M., Marjanovic N., Ivanovic L., Ilic A., (March 2012) *Tribomechanical systems in mechanical power transmitters.* Faculty of Engineering, University of Kragujevac, 6 Sestre Janjic Street 34000 Kraguievac, Serbia. Journal of the Balkan Tribological Association. 03/2012; 18:497-506 Email: blaza@kg.ac.rs (Accessed Feb. 2016).

Sundstrom T., *A hoist application in the mining industry.* Research and Development, SPM instrument AB. Box 504 SE-645 25 Strangnas, Sweden. SPM 2014-01. www.spminstrument.com (Accessed April 2015)

Validakis V., Australian Mining, *Newcrest's Cadia East underground gold mine.* from www.miningaustrlia.com.au (Downloaded, 22May 2014).

Vieroslav Molnar, Gabriel Fedorko, Beata Stehlikova, Lubos Kudelas, Nikoleta Husakova. (June 2013) *Statistical approach for evaluation of pipe conveyors belt contact forces on guide rollers.* Faculty of Mining, Ecology, Process Control and Geotechnology, Technical University of Kosice, Park Komenskeho 14,04200, Kosice, Slovak Republic. 24 June 2013 (Accessed May 2016).

Wang Tony, Normanton Geoff, (April 2007) Version 2. *Comparison of worldwide safety test standards.* Fenner Dunlop USA

White James L., Kim Kwang-Jea, (2008) Thermoplastic *and rubber compounds, technology and physical chemistry,* Hanser Gardiner Publications Inc. 2008. ISBN 978-3-446-40980-4

Wilkinson S., Cawley T., Pero L., Browning R., Parminter G., McDonald S*Analysis of diesel use for mine haul and transport operations.*energyefficiencyopportunities@ret.gov.au 51 Allara st, Canberra ACT 2600 ,Australian Government, Department of Resources Energy and Tourism, in Cooperation with Fortescue Metals Group Ltd., Downer EDI Mining Pty. Ltd., and Leighton. (Accessed June 2015).
Wire Rope Industries *Underground mining products-product selector manuals*.pp.1-48, 5501 Trans-Canada Highway, Pointe-Claire, Quebec H9R 1B7 Canada www.wirerope.com (Accessed March 2015).

Wootton D., (2001), Chapter 9, *Rubber to fabric bonding*.

Yam Kok Peng. (September 2007), *The effects of carbon black and silica fillers on cure characteristics and mechanical properties of breaker compounds.* University of Malaysia. Thesis submitted in fulfillment of the requirements for the degree of Master of Science. (Accessed Feb. 2016).

Veyance Technologies Inc. (2015), 703 S Cleveland Massillon Rd. Fairlawn, OH 44333 (Feb 215 taken over by Contitech)

Bibliography List of Standards

AS 1332-2000, Conveyor *Belting- Textile Reinforced ISBN* 0 72625107 0

AS 1141.11.1-2009, *Methods for sampling and testing aggregates. Method 11.1: Particle size distribution-Sieving method.* ISBN 0 7337 9162 X

AS 1334.9-1982, *Determination of Electrical Resistance of Conveyor Belting*

AS1403—2004.*Design of rotating steel shafts.* Fourth Edition 2004, ISBN 0 7337 5893 2

AS2758.0-7 *Aggregates and Rock for Engineering*

AS2758.0-2009 *Aggregates and Rock for Engineering Purposes. Part 0: Definitions and Classification.* ISBN 0 7337 9227 8

AS 2759-2004, *Steel wire rope. Use, operation and maintenance* ISBN 0 7337 6246 8

AS 3552-1988, *Conveyor belting- Guide to splicing steel cord belting.* ISBN 0 72625107 0

AS3569-2010, *Steel wire ropes-Product specification* ISBN 978 0 7337 9427 8.

AS 3570-1998, *Automotive Diesel Fuel.*

AS3552. *Conveyor belting-Guide to splicing steel cord belting*. ISBN 0 7262 5107 0

ASTM Designation: A 1007-07. *Standard Specification for Carbon Steel Wire for Wire Ropes.* Published 2007.

ASTM Designation E2428-15a, *Standard Practice for Calibration and Verification of Torque Transducers.* Published May 2015

ASTM Designation E2624-09, *Standard Practice for Torque Calibration of Testing machines and Devices.*

ASTM Designation E276-13, *Standard Test Method for Particle Size or Screen Analysis at No.4(4.75mm) Sieve and Finer for Metal Bearing Ores and Related Materials.* Current addition approved Oct. 1 2013. Published November 2013.

ASTM Designation E389-13, *Standard Test Method for Particle Size or Screen Analysis at No.4(4.75mm) Sieve and Coarser for Metal Bearing Ores and Related Materials.* Current addition approved Oct. 1 2013. Published November 2013.

ATSM D448-12. *Standard Classification for Sizes of Aggregate for Roads and Bridge Construction.* Published December 2012

ASTM D6683-19*, Standard Test Method for Measuring Bulk Density Values of Powders and Other Bulk Solids as Function of Compressive Stress,* ASTM International, West Conshohocken, PA, 2019, www.astm.org

BS ISO 48:2010 Rubber, Vulcanized or Thermoplastic, *Determination of Hardness (hardness between 10 IRHD and 100 IRHD).**

BS ISO 812:2011, Rubber, Vulcanized or Thermoplastic, *Determination of Low Temperature Brittleness,*

BS ISO 1432:2013, Rubber, Vulcanized or Thermoplastic, *Determination of Low Temperature Stiffness, Gehman Test. **

BS ISO 2285-2013, Rubber, vulcanized or thermoplastic- *Determination of tension set under constant elongation, and of tension set, elongation and creep under constant load. **

BS ISO 2781:2008 + AI: 2010, Rubber, Vulcanized or Thermoplastic, *Determination of Density**

BS ISO 4664-1:2011 + AI: 2010, Rubber, Vulcanized or Thermoplastic, *Determination of Dynamic Properties, General Guidance* *

BS ISO 8013:2012, Rubber Vulcanized, *Determination of Creep in Compression or Shear, **

DIN 22110-3 (2015) *Testing methods for conveyor belt joints-Part 3: Determination of times strength for conveyor belt joints (Dynamic testing method).* German institute of Standardization (Deutsches Institut fur Normung).

ISO 34-1:2015, *Rubber, vulcanized or thermoplastic- Determination of tear strength-Part 1: trouser, angle and crescent test pieces, -Part 2: Small (Delft) test.*

ISO 37, Fifth edition. 2011-12-*15 Rubber, vulcanized or thermoplastic-Determination of tensile stress-strain properties.*

ISO 1817:2015, *Rubber, vulcanized or thermoplastic- Determination of the effect of liquids*

ISO 1827, Fourth edition 2011-11-01, *Rubber, vulcanized or thermoplastic-Determination of shear modulus and adhesion to rigid plates- Quadruple-shear methods.*

ISO 2408, Third edition 2004-02-01, *Steel wire ropes for general purposes-Minimum requirements.*

ISO 3384-*1:* 2011(E) *Rubber, vulcanized or thermoplastic- Determination of stress relaxation in compression- Part 1 Testing at constant temperature.*

ISO 3384-2 *Rubber, vulcanized or thermoplastic- Determination of stress relaxation in Compression – Part 2 Testing with temperature cycling*

ISO 4664-1, Second edition 2011-11-15, *Rubber, vulcanized or thermoplastic-Determination of dynamic properties. Part 1: general guidance.*

ISO 5051:1981, BS 6318-3:1982, Bucket Elevators-Part 3: *Specification for dimensions of deep elevator bucket with flat rear wall.*

BIBLIOGRAPHY

ISO 7623, Second edition 1996-05-15, *Steel cord conveyor belts-Cord-to-coating bond test- Initial test an after thermal treatment*

ISO 7743, Fourth edition 2011-11-15, *Rubber, vulcanized or thermoplastic-Determination of compression stress-strain properties*

ISO 15236-1, First edition 2005-10-01, Steel cord conveyor belts- Part 1: *Design, dimensions and mechanical requirements for conveyor belts for general use.*

ISO 17893, First edition 2004-02-15, *Steel wire ropes- Vocabulary, designation and classification.*

APPENDIX 1
8-inch (203.2 ID mm) Tube, Tables 100 to 159

Table 100. Test Rig 1 Break free force $\mathrm{BF}^{2}_{8\mathrm{Gv}}$ for 500 grams of gravel on the disc. Gravel less than 2mm.The average $\mathrm{BF}^{2}_{8\mathrm{Gv}}$ per kilogram of ore was 30.1 N.

Run Number	Sample Number	Sample wt. g.	Release wt. lbs.	$\mathrm{BF}^{2}_{8\mathrm{Gv}}$Newtons
67	36A	500	7.1	31.6
68	36B	500	2.6	11.6
69	36C	500	5.1	22.7
70	36D	500	4.4	19.6
71	36E	500	1.0	4.4
72	36F	500	3.4	15.1
73	35G	500	0.7	3.1
74	35H	500	1.8	8.0
75	35I	500	4.3	19.3
76	35J	500	3.4	15.1
				Max. min. Av. 31.6 3.1 15.1

Table 101. Test Rig 1 Break free force $\mathrm{BF}^{2}_{8\mathrm{Gv}}$ for 1000 grams of gravel on the disc. Gravel less than 2mm. The average $\mathrm{BF}^{2}_{8\mathrm{Gv}}$ per kilogram of ore is 14.7 N

Run Number	Sample Number	Sample wt. g.	Release wt. lbs.	$\mathrm{BF}^{2}_{8\mathrm{Gv}}$ Newtons
14	6GF	1000	1.9	8.5
15	5GF	1000	5.6	24.9
16	4GF	1000	4.0	17.8
57	35A	1000	3.3	14.7
58	35B	1000	0.8	3.6
59	35C	1000	4.3	19.2
60	35D	1000	3.3	14.7
61	35E	1000	4.2	18.7
62	35F	1000	1.0	4.4
63	35G	1000	2.5	11.1
64	35H	1000	4.0	17.8
65	35I	1000	4.7	20.9
66	35J	1000	4.6	20.5
				Max. Min. Avg 20.9 3.6 14.7

Table 102. Test Rig 1 Break free force BF^{2}_{8Gv} for 1500 grams of gravel on the disc. Gravel less than 2mm. The average BF^{2}_{8Gv} per kilogram of ore is 15.7 N.

Run Number	Sample Number	Sample wt. g.	Release wt. lbs.	BF^{2}_{8Gv} Newtons
47	34A	1500	5.8	25.8
48	34B	1500	4.5	20.0
49	34C	1500	3.0	13.3
50	34D	1500	4.5	20.0
51	34E	1500	5.0	22.2
52	34F	1500	4.7	20.9
53	34G	1500	7.0	31.1
54	34H	1500	6.2	27.6
55	34I	1500	5.6	24.9
56	34J	1500	6.6	29.4
				Max. Min. Avg. 31.1 13.3 23.5

Table 103. Test Rig 1 Break free force BF^{2}_{8Gv} for 2000grams of gravel on the disc. Gravel less than 2mm. The average BF^{2}_{8Gv} per kilogram of ore.

Run Number	Sample Number	Sample wt. g.	Release wt. lbs.	BF^{2}_{8Gv}Newtons
37	33A	2000	7.6	33.8
38	33B	2000	6.8	30.2
39	33C	2000	5.9	26.2
40	33D	2000	Error	
41	33E	2000	4.5	20.0
42	33F	2000	Error	
43	33G	2000	7.2	32.0
44	33H	2000	4.7	20.9
45	33I	2000	4.4	19.6
46	33J	2000	4.5	20.0
				Max . Min . Avg. 32.0 19.6 25.3

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Table 104. Test Rig 1 Break free force BF^{2}_{8Gv} for 2500grams of gravel on the disc. Gravel less than 2mm. The average BF^{2}_{8Gv} per kilogram of ore is 11.4 N.

Run Number	Sample Number	Sample wt. g.	Release wt. lbs.	BF^{2}_{8Gv} Newtons
27	32A	2500	5.9	26.2
28	32B	2500	Error	
29	32C	2500	5.9	26.2
30	32D	2500	7.5	33.4
31	32E	2500	7.4	32.9
32	32F	2500	Error	
33	32G	2500	5.2	23.1
34	32H	2500	7.2	32.0
35	32I	2500	4.9	21.8
36	32J	2500	7.5	33.4
				Max. Min. Avg. 35.1 21.7 28.5

Table 105. Test Rig 1 Break free force BF^{2}_{8Gv} for 3000grams of gravel on the disc. Gravel less than 2mm. The average BF^{2}_{8Gv} per kilogram of ore is 13.5 N.

Run Number	Sample Number	Sample wt. g.	Release wt. lbs.	BF^{2}_{8Gv} Newtons
18	31A	3000	10.7	47.6
19	31B	3000	12.8	56.9
17	31C	3000	9.1	40.5
20	31D	3000	6.0	26.7
21	31E	3000	7.6	33.8
22	31F	3000	Error	
23	31G	3000	8.3	36.9
24	31h	3000	10.6	47.1
25	31I	3000	Error	
26	31J	3000	8.0	35.6
				Max . Min. Avg. 56.9 26.7 40.5

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Table 106. Break free force $\mathrm{BF}_{8\mathrm{Gv}}^{2-5}$ 1000gram samples of gravel, sieve size retained on a 2.0mm sieve and through 5.0mm sieve. The average $\mathrm{BF}_{8\mathrm{Gv}}^{2-5}$ per kilogram of ore is.125.9N.

Run Number	Sample Number	Sample wt. g	Release wt. lb	. $\mathrm{BF}_{8\mathrm{Gv}}^{2-5}$ Newtons
77	37A	1000	24.7	109.9
78	37B	1000	24.7	109.9
79	37C	1000	14.7	65.4
80	37D	1000	26.1	116.1
81	37E	1000	46.1	205.1
82	37F	1000	25.8	114.8
83	37G	1000	7.4	32.9
84	37H	1000	56.4	250.8
85	37I	1000	27.7	123.2
86	37J	1000	37.0	165.8
87	37D2	1000	21.3	94.7
				Max . Min. Avg 250.8 32.9 125.9

Table 107. Break free force $\mathrm{BF}_{8\mathrm{Gv}}^{5-9.5}$ 1000gram samples of gravel, sieve size retained on a 5mm sieve and through a 9.5mm sieve. The average $\mathrm{BF}_{8\mathrm{Gv}}^{5-9.5}$ per kilogram of ore is 95.2 N.

Run Number	Sample Number	Sample wt. g	Release wt. lb	$\mathrm{BF}_{8\mathrm{Gv}}^{5-9.5}$ Newtons
88	38A	1000	12.6	56.0
89	38B	1000	7.8	34.7
90	38C	1000	35.0	155.7
91	38D	1000	29.0	129.3
92	38E	1000	13.3	59.2
93	38F	1000	21.1	93.9
94	38G	1000	32.1	142.8
95	38H	1000	30.7	136.9
96	38I	1000	21.6	96.1
97	38J	1000	10.3	45.8
				Max. Min . Avg. 155.7 34.7. .95.2

Table 108. Break free force $BF_{8Gv}^{9.5+}$ 1000gram samples of gravel retained on a 9.5mm sieve. The average $BF_{8Gv}^{9.5+}$ per kilogram of ore is 79.2 N.

Run Number	Sample Number	Sample Wt. g	Release wt.lb	$BF_{8Gv}^{9.5+}$ Newtons
98	39A	1000	35.8	159.2
99	39B	1000	21.8	97.0
100	39C	1000	8.3	36.9
101	39D	1000	15.8	70.3
102	39E	1000	16.1	71.6
103	39G	1000	19.7	87.6
104	39H	1000	11.5	51.2
105	39I	1000	18.5	82.5
106	39J	1000	12.8	56.9
				Max. Min. Avg. 159.2 36.9 79.2

Table 109. Break free force WBF_{8Gv}^{2} 1000 grams below 2mm of gravel with 100 grams of added water. The average WBF_{8Gv}^{2} per kilogram of ore is 22.1 N and 20.1 N for wet ore weight.

Run Number	Sample Number	Sample Wt. g	Release Wt.lb	WBF_{8Gv}^{2} Newton
166	47A	1000 + 100	5.01	22.3
167	47B	1000 + 100	error	
168	47C	1000 + 100	4.40	19.6
169	47D	1000 + 100	3.47	15.4
170	47E	1000 + 100	4.22	18.8
171	47F	1000 + 100	6.54	29.2
173	47G	1000 + 100	7.51	33.4
174	47H	1000 + 100	4.80	21.4
175	47I	1000 + 100	4.74	21.1
176	47J	1000 + 100	3.98	17.7
				Max. Min. Av. 33.4 15.6 22.1

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Table 110. Break free force WBF_{8Gv}^{2} 2000grams of below 2mm gravel with 200 grams of water added. The average WBF_{8Gv}^{2} per kilogram of ore is 17.2 N and 15.7 N for the wet ore weight.

Run Number	Sample Number	Sample Wt. g	Release Wt.lb	WBF_{8Gv}^{2} Newton
177	48A	2000 + 200	7.02	31.2
178	48B	2000 + 200	8.79	39.1
179	48C	2000 + 200	7.07	31.4
180	48D	2000 + 200	7.17	31.9
181	48E	2000 + 200	11.00	48.9
182	48F	2000 + 200	10.5	46.7
183	48G	2000 + 200	7.16	31.8
184	48H	2000 + 200	6.34	28.2
185	48I	2000 + 200	4.81	21.4
186	48J	2000 + 200	7.65	34.1
			.	Max. Min. Av. 48.9 21.4 34.5

Table 111. Break free force WBF_{8Gv}^{2}3000 grams of below 2mm gravel with 300 grams of water added. The average WBF_{8Gv}^{2} per kilogram of ore is 13.6 N and 12.4 N for the wet ore weight

Run Number	Sample Number	Sample Wt. g	Release Wt.lb	WBF_{8Gv}^{2} Newton
187	49A	3000 + 300	8.45	37.6
188	49B	3000 + 300	11.80	52.5
189	49C	3000 + 300	7.94	35.1
190	49D	3000 + 300	8.29	36.9
191	49E	3000 + 300	7.97	35.5
192	49F	3000 + 300	10.50	46.7
193	49G	3000 + 300	11.60	51.2
194	49H	3000 + 300	8.67	38.6
195	49I	3000 + 300	7.74	34.4
196	49J	3000 + 300	8.74	38.9
				Max. Min. Av. 52.5 34.3 40.9

Table 112. Break free force WBF$^{2}_{8Gv}$4000 grams of below 2mm gravel with 400 grams of water added. The average WBF$^{2}_{8Gv}$ per kilogram of ore is13.2 N and 12.0 N for the wet ore weight

Run Number	Sample Number	Sample Wt. g	Release Wt.lb	WBF$^{2}_{8Gv}$ Newton
197	50A	4000 + 400	8.55	38.0
198	50B	4000 + 400	12.0	53.4
199	50C	4000 + 400	11.2	49.8
200	50D	4000 + 400	11.3	50.3
201	50E	4000 + 400	15.8	70.3
202	50F	4000 + 400	11.6	51.6
203	50G	4000 + 400	12.9	57.4
				Max. Min. Av. 70.3 49.8 52.9

Table 113. Break free force WBF$^{2}_{8Gv}$5000 grams of below 2mm gravel with 500 grams of water added. The average WBF$^{2}_{8Gv}$ per kilogram of ore is13.5 N and 12.3 N for the wet ore weight. The effect of water run off makes the test difficult to asses as much of the water had drained away before the test started.

Run Number	Sample Number	Sample Wt. g	Release Wt.lb	WBF$^{2}_{8Gv}$ Newton
204	51C	5000 + 500	14.9	66.3
205	51D	5000 + 500	17.2	76.5
206	51E	5000 + 500	13.5	60.1
				Max. Min. Av. 76.5 60.1 67.6

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Table 114. Break free force $\mathrm{WBF}_{8\mathrm{Gv}}^{2}$ 1000 grams of below 2mm gravel with 200 grams of water added. The average $\mathrm{WBF}_{8\mathrm{Gv}}^{2}$ per kilogram of ore is 26.1 N and 21.8 N for the wet ore weight.

Run Number	Sample Number	Sample Wt. g	Release Wt.lb	$\mathrm{WBF}_{8\mathrm{Gv}}^{2}$Newton
207	52A	1000 + 200	6.15	27.4
208	52B	1000 + 200	error	
209	52C	1000 + 200	7.21	32.1
210	52D	1000 + 200	4.64	20.6
211	52E	1000 + 200	3.38	15.0
212	52F	1000 + 200	7.33	32.6
213	52G	1000 + 200	6.15	27.4
214	52H	1000 + 200	5.99	26.6
215	52I	1000 + 200	3.86	17.2
216	52J	1000 + 200	8.00	35.6
				Max. Min. Av. 35.6 15.1 26.1

Table 115. Break free force $\mathrm{WBF}_{8\mathrm{Gv}}^{2}$ 2000grams of below 2mm gravel with 400grams of added water. The average $\mathrm{WBF}_{8\mathrm{Gv}}^{2}$ per kilogram of ore is 19.6 N and 16.3 N for the wet ore weight.

Run Number	Sample Number	Sample Wt. g	Release Wt.lb	$\mathrm{WBF}_{8\mathrm{Gv}}^{2}$ Newton
217	53A	2000 + 400	7.16	31.8
218	53B	2000 + 400	7.83	34.8
219	53C	2000 + 400	8.13	36.2
220	53D	2000 + 400	9.16	40.7
221	53E	2000 + 400	8.65	38.5
222	53F	2000 + 400	10.1	44.9
223	53G	2000 + 400	7.10	31.6
224	53H	2000 + 400	8.36	37.2
225	53I	2000 + 400	13.2	58.7
226	53J	2000 + 400	8.51	37.9
				Max. Min. Av. 58.7 32.0 39.2

Table 116. Break free force WBF^{2}_{8Gv}3000 grams of below 2mm gravel with 600grams of added water. The average WBF^{2}_{8Gv} per kilogram of ore is 22.1 N and 18.4 N for the wet ore weight

Run Number	Sample Number	Sample Wt. g	Release Wt.lb	WBF^{2}_{8Gv} Newton
227	54A	3000 + 600	16.7	74.3
228	54B	3000 + 600	14.9	66.3
229	54C	3000 + 600	13.8	61.4
230	54D	3000 + 600	14.3	63.6
231	54E	3000 + 600	14.8	65.8
232	54F	3000 + 600	18.7	83.2
233	54G	3000 + 600	13.9	61.8
234	54H	3000 + 600	15.5	68.9
235	54I	3000 + 600	12.6	56.0
236	54J	3000 + 600	13.9	61.8
				Max. Min. Av. 83.2 56.0 66.3

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Table 117. Break free force WBF^{2}_{8Gv} 4000grams of below 2mm gravel with 800grams of added water. The average WBF^{2}_{8Gv} per kilogram of ore is 20.4 N and 17.0 N for the wet ore weight.

Run Number	Sample Number	Sample Wt. g	Release Wt.lb	WBF^{2}_{8Gv} Newton
237	55A	4000 + 800	13.4	59.6
238	55B	4000 + 800	14.3	63.6
239	55C	4000 + 800	17.3	77.0
240	55D	4000 + 800	19.9	88.5
241	55E	4000 + 800	23.0	102.3
242	55F	4000 + 800	15.0	66.7
243	55G	4000 + 800	22.8	101.4
244	55H	4000 + 800	16.7	74.3
245	55I	4000 + 800	17.7	78.7
246	55J	4000 + 800	23.4	104.1
				Max. Min. Av. 104.1 59.6 81.6

Table 118. Break free force $\mathrm{WBF}_{8\mathrm{Gv}}^{2}$ 5000grams of below 2mm gravel with 1000grams of added water. The average $\mathrm{WBF}_{8\mathrm{Gv}}^{2}$ per kilogram of ore is 20.1 N and 19.7 N for the wet ore weight

Run Number	Sample Number	Sample Wt. g	Release Wt.lb	$\mathrm{WBF}_{8\mathrm{Gv}}^{2}$ Newton
248	56A	5000 + 1000	27.4	121.9
249	56B	5000 + 1000	25.4	113.0
250	56C	5000 + 1000	30.5	135.7
251	56D	5000 + 1000	23.7	105.4
252	56E	5000 + 1000	19.1	85.0
253	56F	5000 + 1000	16.2	72.1
254	56G	5000 + 1000	17.9	79.6
255	56H	5000 + 1000	19.6	87.2
256	56I	5000 + 1000	20.4	90.7
257	56J	5000 + 1000	25.7	114.3
				Max. Min. Av. 135.6 72.1 100.5

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Table 119. Break free force $\mathrm{WBF}_{8\mathrm{Gv}}^{2}$ 1000grams of below 2mm gravel with 300grams of added water The average $\mathrm{WBF}_{8\mathrm{Gv}}^{2}$ per kilogram of ore is 24.2 N and 18.6 N for the wet ore weight.

	Sample Number	Sample Wt. g	Release Wt.lb	$\mathrm{WBF}_{8\mathrm{Gv}}^{2}$ Newton
258	57A	1000 + 300	4.49	20.0
259	57B	1000 + 300	6.68	29.7
260	57C	1000 + 300	10.7	47.6
261	57D	1000 + 300	3.86	17.17
262	57E	1000 + 300	3.35	14.9
263	57F	1000 + 300	5.00	22.2
264	57G	1000 + 300	5.75	25.6
265	57H	1000 + 300	4.45	19.8
266	57I	1000 + 300	6.00	26.7
267	57J	1000 + 300	4.01	17.9
				Max. Min. Avg. 47.9 14.9 24.2

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Table 120. Test Rig 1 Break free force BF^2_{8Gn} for 500 grams of granite below 2mm on the disc. The average BF^2_{8Gn} per kilogram is16.0 N.

Run Number	Sample Number	Sample Wt. g	Release Wt.lb	BF^2_{8Gn} Newton
107	40A	500	0.95	4.2
108	40B	500	2.14	9.5
109	40C	500	0.59	2.6
110	40D	500	2.05	9.1
111	40E	500	1.01	4.5
112	40F	500	2.31	9.8
113	40G	500	2.51	11.2
114	40H	500	1.66	7.4
115	40I	500	3.04	13.5
116	40J	500	error	
				Max. Min. Avg. .13.5 8.0 8.0

Table 121. Break free force BF^2_{8Gn} for 1000 grams of granite below 2mm on the disc. The average BF^2_{8Gn} per kilogram is 6.4 N

Run Number	Sample Number	Sample Wt. g	Release Wt.lb	BF^2_{8Gn}Newton
146	44A	2500	4.19	18.6
147	44B	1000	1.75	7.8
148	44C	1000	4.23	18.8
149	44D	1000	3.56	15.8
150	44E	1000	3.74	16.6
151	44F	1000	4.09	18.2
152	44G	1000	3.28	14.6
153	44H	1000	3.21	14.3
154	44I	1000	3.38	15.0
155	44J	1000	4.66	20.7
				Max. Min. Av. 20.8 8.0 16.0

Table 122. Break free force BF^2_{8Gn} for 1500 grams of granite below 2mm on the disc. The average BF^2_{8Gn} per kilogram is16.4 N

Run Number	Sample Number	Sample Wt. g	Release Wt.lb	BF^2_{8Gn} Newton
117	41A	1500	error	
118	41B	1500	4.24	18.9
119	41C	1500	3.93	17.5
120	41D	1500	4.70	20.9
121	41E	1500	3.99	17.7
122	41F	1500	4.21	18.7
123	41G	1500	3.33	14.8
124	41H	1500	3.35	14.9
125	41I	1500	2.45	10.9
126	41J	1500	3.08	13.7
				Max. Min. Av. 20.9 13.7 16.4

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Table 123. Break free force BF^2_{8Gn} for 2000 grams of granite below 2mm on the disc. The average BF^2_{8Gn} per kilogram is 9.4 N

Run Number	Sample Number	Sample Wt. g	Release Wt.lb	BF^2_{8Gn} Newton
137	43A	2000	3.75	16.7
138	43B	2000	4.35	19.3
139	43C	2000	5.27	23.4
140	43D	2000	4.91	21.8
141	43E	2000	3.78	16.8
142	43F	2000	error	
143	43G	2000	error	
144	43I	2000	2.92	11.7
145	43J	2000	4.51	20.1
				Max. Min. Avg. 23.6 12.9 18.7

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Table 124 Break free force $\mathrm{BF}_{8\mathrm{Gn}}^{2}$ for 2500 grams of granite below 2mm on the disc. The average $\mathrm{BF}_{8\mathrm{Gn}}^{2}$ per kilogram is13.9 N.

Run Number	Sample Number	Sample Wt. g	Release Wt.lb	$\mathrm{BF}_{8\mathrm{Gn}}^{2}$ Newton
127	42A	2500	3.85	17.1
128	42B	2500	7.23	32.2
129	42C	2500	5.04	22.4
130	42D	2500	4.34	19.3
131	42E	2500	4.73	21.0
132	42F	2500	3.99	17.7
133	42G	2500	4.39	19.5
134	42H	2500	4.38	19.5
135	42I	2500	5.27	23.4
136	42J	2500	4.05	18.0
				Max. Min. Av. 32.0 17.3 20.9

Table 125. Break free force $\mathrm{BF}_{8\mathrm{Gn}}^{2}$ for 3000 grams of granite below 2mm on the disc. The average $\mathrm{BF}_{8\mathrm{Gn}}^{2}$ per kilogram is 7.3 N.

Run Number	Sample Number	Sample Wt. g	Release Wt.lb	$\mathrm{BF}_{8\mathrm{Gn}}^{2}$ Newton
156	45A	3000	4.17	18.5
157	46B	3000	6.50	28.9
158	46C	3000	5.38	23.9
159	46D	3000	4.68	20.8
160	46E	3000	5.72	25.4
161	46F	3000	4.01	17.8
162	46G	3000	4.66	20.7
163	46H	3000	4.44	19.8
164	46I	3000	4.11	18.3
165	46J	3000	4.23	18.8
				Max. Min. Av. 25.4 18.2 21.8

Table 126. Breakfree force BF^{2}_{8coal} for 500 grams of coal below 2mm on the disc. The average BF^{2}_{8coal} per kilogram is 14.8 N

Run Number	Sample Number	Sample wt. g	Release wt. lb.	BF^{2}_{8coal}Newtons
815	114A	500	2.3	10.2
816	114B	500	2.1	9.3
818	114C	500	1.6	7.1
817				
819	114D	500	1.6	7.1
820	114E	500	1.5	6.7
821	114F	500	1.5	6.7
822	114G	500	1.5	6.7
823	114H	500	1.5	6.7
824	114I	500	1.4	6.2
825	114J	500	1.6	7.1
				Max. Min. Avg. 10.4 6.2 7.4

Table 127. The Breakfree force BF^{2}_{8coal} for 1000 grams of coal below 2mm on the disc. The average BF^{2}_{8coal} per kilogram is 9.3 N

Run Number	Sample Number	Sample wt. g	Release wt. lb.	BF^{2}_{8coal}Newtons
268	58A	1000	1.77	7.9
269	58B	1000	2.05	9.1
270	58C	1000	2.28	10.1
271	58D	1000	2.56	11.4
272	58E	1000	1.93	8.6
273	58F	1000	2.20	9.8
274	58G	1000	2.35	10.5
275	58H	1000	2.09	9.3
276	58I	1000	1.49 error	
277	58J	1000	1.95	8.7
278	58K	1000	2.04	9.1
				Max. Min. Avg. 11.7 8.0 9.3

Table 128. Breakfree force BF^{2}_{8coal} for 1500 grams of coal below 2mm on the disc. The average BF^{2}_{8coal} per kilogram is 8.53 N.

Run Number	Sample Number	Sample wt. g	Release wt. lb.	BF^{2}_{8coal}Newtons
826	115A	1500	2.8	12.5
827	115B	1500	2.2	9.8
828	115C	1500	2.5	11.1
829	115D	1500	2.9	12.9
830	115E	1500	2.8	12.5
831	115F	1500	3.1	13.8
832				
833	115G	1500	2.8	12.5
834	115H	1500	2.9	12.9
835	115I	1500	2.7	12.0
836	115J	1500	3.1	13.8
				Max. Min. Avg. 13.8 9.8 12.8

Table 129. Breakfree force BF^{2}_{8coal} for 2000 grams of coal below 2mm on the disc. The average BF^{2}_{8coal} per kilogram is 8.0 N.

Run Number	Sample Number	Sample wt. g	Release wt. lb.	BF^{2}_{8coal}Newtons
279	59A	2000	4.25	18.9
280	59B	2000	3.13	13.9
281	59C	2000	3.52	15.7
282	59D	2000	3.36	14.9
283	59E	2000	3.88	17.3
284	59F	2000	3.64	16.2
285	59G	2000	3.51	15.6
286	59H	2000	3.03	13.5
287	59I	2000	3.40	15.1
288	59J	2000	4.51	20.1
				Max. Min. Av. 20.0 13.3 16.0

Table 130. Breakfree force BF^2_{8coal} for 3000 grams of coal below 2mm on the disc. The average BF^2_{8coal} per kilogram is 8.6 N

Run Number	Sample Number	Sample wt. g	Release wt. lb.	BF^2_{8coal}Newtons
289	60A	3000	5.29	23.5
290	60B	3000	5.51	24.5
291	60C	3000	5.96	26.5
292	60D	3000	5.94	26.5
293	60E	3000	6.03	26.8
294	60F	3000	5.54	24.6
295	60G	3000	5.08	22.6
296	60H	3000	5.81	25.8
297	60I	3000	5.94	26.4
298	60J	3000	6.41	28.6
				Max. Min. Av. 28.5 22.7 25.8

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Table 131. Breakfree force BF^2_{8coal} for 4000 grams of coal below 2mm on the disc. The average BF^2_{8coal} per kilogram is 10.2 N

Run Number	Sample Number	Sample wt. g	Release wt. lb.	BF^2_{8coal}Newtons
299	61A	4000	8.59	38.2
300	61B	4000	9.19	40.9
301	61C	4000	9.29	41.3
302	61D	4000	9.93	44.2
303	61E	4000	8.91	39.6
304	61F	4000	9.49	42.2
305	61G	4000	6.84	30.4
306	61H	4000	10.00	44.5
307	61I	4000	9.47	42.1
308	61J	4000	10.3	45.8
				Max. Min. Av. 45.8 30.2 40.9

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Table 132. Breakfree force $\mathrm{BF}_{8\mathrm{coal}}^{2}$ for 5000 grams of coal below 2mm on the disc. The average $\mathrm{BF}_{8\mathrm{coal}}^{2}$ per kilogram is 13.6 N.

Run Number	Sample Number	Sample wt. g	Release wt. lb.	$\mathrm{BF}_{8\mathrm{coal}}^{2}$Newtons
309	62A	5000	15.6	69.4
310	62B	5000	12.6	56.0
311	62C	5000	15.8	70.3
312	62D	5000	15.4	68.5
313	62E	5000	15.6	69.4
314	62F	5000	16.3	72.5
315	62G	5000	14.8	65.8
316	62H	5000	17.4	77.4
317	62I	5000	14.3	63.6
318	62J	5000	13.9	61.8
				Max. Min. Av. 77.4 56.0 67.8

Table 133. Breakfree force $\mathrm{BF}_{8\mathrm{coal}}^{2}$ for 6000 grams of coal below 2mm on the disc. The average $\mathrm{BF}_{8\mathrm{coal}}^{2}$ per kilogram is 18.4 N

Run Number	Sample Number	Sample wt. g	Release wt. lb.	$\mathrm{BF}_{8\mathrm{coal}}^{2}$Newtons
770	109A	6000	24.4	108.5
771	109B	6000	26.5	117.9
772	109C	6000	27.0	120.1
773	109D	6000	26.8	119.2
	109E	6000		
774	109F	6000	23.7	105.4
775	109G	6000	22.7	101.2
776	109H	6000	24.8	110.3
777	109I	6000	23.8	106.1
778	109J	6000	23.9	106.5
				Max. Min. Avg. 120.1 101.2 110.6

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Table134. Breakfree force $\mathrm{BF}^{2}_{8\mathrm{coal}}$ for 7000 grams of coal below 2mm on the disc. The average $\mathrm{BF}^{2}_{8\mathrm{coal}}$ per kilogram is 18.5 N.

Run Number	Sample Number	Sample wt. g	Release wt. lb.	$\mathrm{BF}^{2}_{8\mathrm{coal}}$Newton
779	110A	7000	32.8	145.9
780	110B	7000	32.7	145.4
781	110C	7000	34.4	153.0
782	110D	7000	31.2	138.8
783	110E	7000	35.2	156.6
784	110F	7000	36.4	161.9
785	110G	7000	32.8	145.8
786	110H	7000	30.4	135.2
787	110I	7000	33.7	149.9
788	110J	7000	34.1	151.7
				Max. Min. Avg .153.0 135.2..148.4

Table 135. Breakfree force $\mathrm{BF}^{2/\mathrm{UG}}_{8\mathrm{Gv/coal}}$ 500 grams of 2mm coal under 1000 grams of gravel ungraded

Run Number	Sample Number	Sample wt. g	Release wt. lb.	$\mathrm{BF}^{2/\mathrm{UG}}_{8\mathrm{Gn/coal}}$Newton
793	111A	500/1000	5.4	24.0
794	111B	500/1000	3.8	16.9
795	111C	500/1000	3.8	16.9
796	111D	500/1000	4.4data selected	19.6
797	111E	500/1000	3.9data selected	17.3
798	111F	500/1000	4.1data selected	18.2
799	111G	500/1000	4.8data selected	21.6
800	111H	500/1000	4.3	19.1
801	111I	500/1000	3.8	16.9
802	111J	500/1000	1.3 discarded	5.8
817	111J repeat	500/1000	3.4	15.1
				Max. Min. Avg. 24.0 15.1 18.6

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Table 136. Breakfree force $\mathrm{BF}^{2/\mathrm{UG}}_{8\mathrm{Gn/coal}}$ 500 grams of 2mm coal under 1000 grams of granite ungraded

Run Number	Sample Number	Sample wt. g	Release wt. lb.	$\mathrm{BF}^{2/\mathrm{UG}}_{8\mathrm{Gn/coal}}$ Newton
803	112A	500/1000	3.8	16.9
804	112B	500/1000	6.9data selected	30.7
805	113A	500/1000	4.4	19.6
806	113B	500/1000	4.9	21.8
807	113C	500/1000	4.4	19.6
808	113D ©	500/1000	4.6	20.5
809	113E	500/1000	4.1	18.2
810	113F	500/1000	4.7	20.9
811	113G	500/1000	4.3	19.1
812	113H	500/1000	4.7	20.9
813	113I	500/1000	5.3	23.6
814	113J	500/1000	4.8	21.4
				Max. Min. Avg. 23.6 16.9 20.2

Table 137. Breakfree force $\mathrm{BF}^{2/\mathrm{UG}}_{8\mathrm{Coal/coal}}$ 500 grams of 2mm coal under 1000 grams of ungraded Coal

Run Number	Sample Number	Sample wt. g	Release wt. lb.	$\mathrm{BF}^{2/\mathrm{UG}}_{8\mathrm{Coal/coal}}$ Newtons
879	117A	1000	3.5	15.6
883	117B	1000	3.7	16.5
884	117C	1000	3.6	16.0
885	117D	1000	3.7	16.5
886	117E	1000	2.2	9.8
887	117F	1000	3.1	13.8
888	117G	1000	3.3	14.7
889	117H	1000	3.7	16.5
890	117I	1000	3.5	15.6
891	117J	1000	2.6	11.6
				Max. Min. Avg. 16.5 9.8 14.7

Table 138. Breakfree force $BF_{8coal}^{5-2}$for 1000 grams of coal 2-5mm size on the disc.

Run Number	Sample Number	Sample wt. g	Release wt. lb.	$Bf_{8Gn}^{9.5+}$ Newtons
319	63A	1000	5.31	23.6
320	63B	1000	5.22	23.1
321	63C	1000	5.29	23.5
322	63D	1000	6.21	27.6
323	63E	1000	6.87	30.6
324	63F	1000	5.80	25.8
325	63G	1000	5.93	26.4
326	63H	1000	8.30	36.9
327	63I	1000	6.91	30.7
328	63J	1000	5.57	24.8
				Max. Min.. Avg. 36.9 23.1 27.6

Table 139. Breakfree force $BF_{8coal}^{5-9.5}$ for 1000 grams of coal 5.0-9.5mm size on the disc.

Run Number	Sample Number	Sample wt. g	Release wt. lb.	Newtons
329	64A	1000	8.8	39.1
330	64B	1000	5.4	24.0
331	64C	1000	3.7	16.5
332	64D	1000	3.4	15.1
333	64E	1000	7.6	33.8
334	64F	1000	4.8	21.4
335	64G	1000	13.1	58.3
336	64H	1000	11.6	51.6
337	64I	1000	4.3	19.1
338	64J	1000	5.7	25.4
				Max. Min Avg 58.3 16.5 30.4

Table 140. Breakfree force $\mathrm{BF}_{8\mathrm{Gn}}^{9.5+}$ 9.5mm size, 1000grams of granite. * Samples 341,342, and 343 exceeded the measuring 100lb maximum of the test rig

Run Number	Sample Number	Sample wt. g	Release wt. lb.	$\mathrm{Bf}_{8\mathrm{Gn}}^{9.5+}$ Newtons
339	65A	1000	18.2	81.0
340	65B	1000	30.0	133.4
341	65C	1000	>100*	>444.8*
342	65D	1000	>100*	>444.8*
343	65E	1000	>100*	>444.8*
344	65F	1000	32.6	145.0
345	65G	1000	37.4	166.4
346	65H	1000	25.2	112.1
347	65I	1000	7.8	34.7
348	65J	1000	10.9	48.4
				Max. Min. Avg. >444.8 34.7 205.5

Table 141. Breakfree force $\mathrm{Bf}_{8\mathrm{Coal}}^{9.5+}$ 9.5mm size, 1000grams of coal.

Run Number	Sample Number	Sample wt. g	Release wt. lb.	$\mathrm{Bf}_{8\mathrm{Coal}}^{9.5+}$ Newtons
892	117A	1000	4.0	17.8
893	117B	1000	2.4	10.7
894	117C	1000	6.3	28.0
895	117D	1000	3.9	17.3
896	117E	1000	7.2	31.1
897	117F	1000	9.6	42.7
898	117G	1000	3.1	13.8
899	117H	1000	8.6	38.3
900	117I	1000	8.5	37.8
901	117J	1000	10.1	44.9
				Max. Min. Avg. 44.9 10.7 28.2

Table 142. Breakfree force $\mathrm{WBF}^2_{8\mathrm{coal}}$ for 500 grams of coal 2mm size with 50 grams of water added. The average $\mathrm{WBF}^2_{8\mathrm{coal}}$ per kilogram of ore is 13.6 N and 12.3 N for the wet ore weight

Run Number	Sample Number	Sample wt. g	Release wt. lb.	$\mathrm{WBF}^2_{8\mathrm{coal}}$Newtons
359	67A	500 +50	2.1	9.3
360	67B	500+50	1.2	5.3
361	67C	500+50	1.6	8.5
363	67D	500+50	1.5	6.7
364	67E	500+50	1.6	8.5
365	67F	500+50	1.3	5.8
366	67G	500+50	1.6	8.5
367	67H	500+50	1.3	5.8
368	67I	500+50	0.8	3.6
369	67J	500+50	1.3	5.8
				Max. Min. Av. 9.3 3.6 6.8

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Table 143. Breakfree force $\mathrm{WBF}^2_{8\mathrm{coal}}$ for 1000 grams of coal 2mm size with 100 grams of water added. The average $\mathrm{WBF}^2_{8\mathrm{coal}}$ per kilogram of ore is 14.6 N and 13.3 N for the wet ore weight

Run Number	Sample Number	Sample wt. g	Release wt. lb.	$\mathrm{WBF}^2_{8\mathrm{coal}}$Newtons
370	68A	1000 +100	2.6	11.6
371	68B	1000 +100	2.9	12.9
372	68C	1000 +100	2.9	12.9
373	68E	1000 +100	2.6	11.6
374	68G	1000 +100	3.0	13.4
375	68H	1000 +100	3.2	14.2
376	68I	1000 +100	3.2	14.2
377	68J	1000 +100	3.6	16.0
				Max. Min. Av. 16.0 11.6 14.6

Table 144. Breakfree force $\mathrm{WBF}^{2}_{8\mathrm{coal}}$ for 2000 grams of coal 2mm size with 200 grams of water added. The average $\mathrm{WBF}^{2}_{8\mathrm{coal}}$ per kilogram of ore is 17.2 N and 15.6 N for the wet ore weight

Run Number	Sample Number	Sample wt. g	Release wt. lb.	$\mathrm{WBF}^{2}_{8\mathrm{coal}}$Newtons
378	69A	2000 +200	5.6	24.9
379	69B	2000+200	7.6	33.8
380	69C	2000+200	9.5	42.3
381	69D	2000+200	8.0	35.6
382	69E	2000+200	7.1	31.6
383	69F	2000+200	6.8	30.3
384	69G	2000+200	7.0	31.2
385	69H	2000+200	8.1	36.0
386	69I	2000+200	7.3	32.5
387	69J	2000+200	10.3	45.8
				Max. Min. Av. 45.8 24.9 34.4

Table 145. Breakfree force $\mathrm{WBF}^{2}_{8\mathrm{coal}}$ for 3000 grams of coal 2mm size with 300 grams of water added. The average $\mathrm{WBF}^{2}_{8\mathrm{coal}}$ per kilogram of ore is 12.8 N and 11.6 N for the wet ore weight

Run Number	Sample Number	Sample wt. g	Release wt. lb.	Newtons
388	70A	3000 +300	8.8	39.2
389	70B	3000 +300	8.6	38.3
390	70C	3000 +300	9.1	41.4
391	70D	3000 +300	10.6	47.2
392	70E	3000 +300	9.8	43.6
393	70F	3000 +300	8.8	39.2
394	70G	3000 +300	9.5	42.3
395	70H	3000 +300	8.0	35.6
396	70I	3000 +300	7.2	32.8
397	70J	3000 +300	5.3	23.6
				Max. Min. Av. 47.2 23.6 38.3

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Table 146. Breakfree force WBF^{2}_{8coal} for 4000 grams of coal 2mm size with 400 grams of water added. The average WBF^{2}_{8coal} per kilogram of ore is 18.6 N and 16.9 N for the wet ore weight.

Run Number	Sample Number	Sample wt. g	Release wt. lb.	WBF^{2}_{8coal}Newtons
398	71A	4000 + 400	15.0	66.8
399	71B	4000+ 400	13.8	61.4
400	71C	4000+ 400	14.7	66.9
401	71D	4000+ 400	16.5	73.4
402	71E	4000+ 400	15.7	69.9
403	71F	4000+ 400	22.2	98.8
404	71G	4000+ 400	17.6	78.3
405	71H	4000+ 400	15.2	67.6
406	71I	4000+ 400	18.6	82.8
407	71J	4000+ 400	17.6	78.3
				Max. Min. Av. 98.8 61.4 74.4

Table 147. Breakfree force WBF^{2}_{8coal} for 1000 grams of coal 2mm size with 200 grams of water added. The average WBF^{2}_{8coal} per kilogram of ore is 24.7 N and 20.5 N for the wet ore weight

Run Number	Sample Number	Sample wt. g	Release wt. lb.	WBF^{2}_{8coal}Newtons
408	72A	1000 +200g	4.4	19.6
409	72B	1000 +200g	3.1	13.8
410	72C	1000 +200g	3.0	13.3
411	72D	1000 +200g	3.9	17.3
412	72E	1000 +200g	4.2	18.7
413	72F	1000 +200g	15.4	68.5
414	72G	1000 +200g	3.3	15.1
415	72H	1000 +200g	3.6	16.0
416	72I	1000 +200g	7.3	32.5
417	72J	1000 +200g	3.1	13.8
419	72F repeat	1000 +200g	4.0	17.8
				Max. Min. Avg 68.5, 13.3 24.7

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Table 148. Breakfree force $\mathrm{WBF}_{8\mathrm{coal}}^{2}$ for 2000 grams of coal 2mm size with 400 grams of water added The average $\mathrm{WBF}_{8\mathrm{coal}}^{2}$ per kilogram of ore is 19.6 N and 16.4 N for the wet ore weight.

Run Number	Sample Number	Sample wt. g	Release wt. lb.	$\mathrm{WBF}_{8\mathrm{coal}}^{2}$ Newtons
418	abandoned	2000 + 400g		
420	73A	2000 + 400g	9.3	41.4
421	73B	2000 + 400g	6.6	29.4
422	73C	2000 + 400g	7.7	34.3
423	73D	2000 + 400g	9.5	42.3
424	73E	2000 + 400g	8.4	37.4
425	73F	2000 + 400g	6.0	26.7
426	73G	2000 + 400g	7.5	33.4
427	73H	2000 + 400g	7.1	31.6
428	73I	2000 + 400g	7.6	33.8
429	73J	2000 + 400g	9.7	43.1
				Max . Min. Avg. 43.1…26.7 35.3

Table 149. Breakfree force $\mathrm{WBF}_{8\mathrm{coal}}^{2}$ for 3000 grams of coal 2mm size with 600 grams of water added. The average $\mathrm{WBF}_{8\mathrm{coal}}^{2}$ per kilogram of ore is 18.2 N and 15.2 N for the wet ore weight.

Run Number	Sample Number	Sample wt. g	Release wt. lb.	$\mathrm{WBF}_{8\mathrm{coal}}^{2}$ Newtons
430	74A	3000 +600g	8.1	36.0
431	74B	3000 +600g	8.9	39.6
432	74C	3000 +600g	11.7	52.0
433	74D	3000 +600g	10.0	44.5
434	74E	3000 +600g	13.3	56.2
435	74F	3000 +600g	13.6	60.5
436	74G	3000 +600g	13.7	60.9
437	74H	3000 +600g	16.3	72.5
438	74I	3000 +600g	18.1	80.5
439	74J	3000 +600g	10.0	44.5
				Max. Min. Avg. 80.5 36.0 54.7

Table 150. Breakfree force $\mathrm{WBF}^{2}_{8\mathrm{coal}}$ for 4000 grams of coal 2mm size with 800 grams of water added. The average $\mathrm{WBF}^{2}_{8\mathrm{coal}}$ per kilogram of ore is 11.4 N and 9.4 N for the wet ore weight.

Run Number	Sample Number	Sample wt. g	Release wt. lb.	$\mathrm{WBF}^{2}_{8\mathrm{coal}}$Newtons
440	75A	4000 +800g	3.5	15.6
441	75A repeat	4000 +800g	8.8	39.1
442	75B	4000 +800g	22.7	101.0
443	75C	4000 +800g	10.9	48.5
444	75D	4000 +800g	9.6	42.7
445	75E	4000 +800g	6.0	26.7
446	75F	4000 +800g	13.1	58.3
447	75G	4000 +800g	11.9	52.9
448	75H	4000 +800g	9.6	42.7
449	75I	4000 +800g	10.1	44.9
450	75J	4000 +800g	6.1	27.1
				Max Min. Avg 101.0 15.6 .45.4

Table 151. Breakfree force $\mathrm{WBF}^{2}_{8\mathrm{coal}}$ for 1000 grams of coal 2mm size with 500 grams of water. The effect of water run off makes the test difficult to assess as much of the water had drained away before the test started.

Run Number	Sample Number	Sample wt. g	Release wt. lb.	Newtons
451	76A	1000 +500g	12.6	56.0
452	76B	1000 +500g	9.5	42.3

Table 152. Breakfree force WBF^2_{8Gn} for 1000 grams of granite 2mm size with 100 grams of water. The average BF^2_{8coal} per kilogram of ore is 29.7 N and 26.9 N for the wet ore weight.

Run Number	Sample Number	Sample wt. g	Release wt. lb.	WBF^2_{8Gn} Newtons
453	77A	1000+100g	5.7	25.4
454	77B	1000+100g	3.8	16.9
455	77C	1000+100g	8.2	36.5
456	77D	1000+100g	9.9	44.0
457	77E	1000+100g	4.6	20.5
458	77F	1000+100g	3.2	14.2
459	77G	1000+100g	8.2	36.5
460	77H	1000+100g	3.6	16.0
461	77I	1000+100g	11.4	50.1
462	77J	1000+100g	8.2	36.5
				Max. Min. Avg. 50.1 14.2 29.7

Table 153. Breakfree force WBF^2_{8Gn} for 2000 grams of granite 2mm size with 200 grams of water. The average BF^2_{8coal} per kilogram of ore is 19.4 N and 17.6 N for the wet ore weight

Run Number	Sample Number	Sample wt. g	Release wt. lb.	WBF^2_{8Gn} Newtons
463	78A	2000 + 200g	9.7	43.1
464	78B	2000 + 200g	5.7	25.4
465	78C	2000 + 200g	4.8	21.4
466	78D	2000 + 200g	6.3	28.0
467	78E	2000 + 200g	9.8	43.6
468	78F	2000 + 200g	11.5	51.2
469	78G	2000 + 200g	4.8	21.4
470	78H	2000 + 200g	8.7	38.7
471	78I	2000 + 200g	16.2	72.1
472	78J	2000 + 200g	7.3	32.5
				Max. Min Avg 72.1 21.4 38.7

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Table 154. Breakfree force WBF^2_{8Gn} for 3000 grams of granite 2mm size with 300 grams of water The average WBF^2_{8Gn} per kilogram of ore is 16.0 N and 14.5 N for the wet ore weight.

Run Number	Sample Number	Sample wt. g	Release wt. lb.	WBF^2_{8Gn} Newtons
492	79A	3000+300g	10.0	44.5
473	79B	3000+300g	9.7	43.1
474	79C	3000+300g	10.0	44.5
#'475	79D	3000+300g	11.6	51.6
476	79E	3000+300g	10.0	44.5
477	79F	3000+300g	10.5	46.7
478	79G	3000+300g	10.4	46.3
479	79H	3000+300g	13.4	59.6
480	79I	3000+300g	11.1	49.4
481	79J	3000+300g	11.0	48.9
				Max Min. Avg. 59.6 43.1 47.9

Table 155. Breakfree force WBF^2_{8Gn} for 4000 grams of granite 2mm size with 400 grams of water. The average BF^2_{8coal} per kilogram of ore is 15.0 N and 13.6 N for the wet ore weight

Run Number	Sample Number	Sample wt. g	Release wt. lb.	WBF^2_{8Gn}Newtons
482	80A	4000+400g	13.0	57.8
483	80B	4000+400g	14.7	65.4
484	80C	4000+400g	13.3	59.2
485	80D	4000+400g	15.4	68.5
486	80E	4000+400g	15.0	66.7
487	80F	4000+400g	11.0	48.9
488	80G	4000+400g	12.3	54.7
489	80H	4000+400g	13.2	58.7
490	80I	4000+400g	13.7	60.9
491	80J	4000+400g	13.4	59.6
				Max Min. Avg 68.5 48.9 60.0

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Table 156. Breakfree force $\mathrm{WBF}_{8\mathrm{Gn}}^{2}$ for 1000 grams of granite 2mm size with 200 grams of water. The average $\mathrm{BF}_{8\mathrm{Gnl}}^{2}$ per kilogram of ore is 33.9 N and 28.3 N for the wet ore weight

Run Number	Sample Number	Sample wt. g	Release wt. lb.	$\mathrm{WBF}_{8\mathrm{Gn}}^{2}$Newtons
493	81A	1000+200G	5.6	24.9
494	81B	1000+200G	9.7	43.1
495	81C	1000+200G	8.3	36.9
496	81D	1000+200G	12.5	55.6
497	81E	1000+200G	10.4	46.3
498	81F	1000+200G	7.4	32.9
499	81G	1000+200G	4.0	17.8
500	81H	1000+200G	6.6	29.4
501	81I	1000+200G	5.9	26.2
502	81J	1000+200G	5.7	25.4
				Max Min Avg. 55.6 17.8 33.9

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Table 157. Breakfree force $\mathrm{BF}_{8\mathrm{Gv}}^{\mathrm{ug}}$ for 1000grams of ungraded gravel.

Run Number	Sample Number	Sample wt. g	Release wt. lb.	$\mathrm{BF}_{8\mathrm{Gv}}^{\mathrm{ug}}$ Newtons
848	106A	1000	36.0	160.1
849	106B	1000	10.4	46.3
850	106C	1000	9.7	43.1
851	106C	1000	ABANDON	
852	106D	1000	10.6	47.1
853	106E	1000	15.4	68.5
854	106F	1000	11.7	49.4
	106G	1000	ABANDON	
855	106H	1000	8.6	38.3
856	106I	1000	20.9	93.0
857	106J	1000	8.1	36.0
				Max. Min. Avg. 160.1 36.0 64.6

Table 158. Breakfree force BF_{8Gn}^{ug} for 1000grams of ungraded granite

Run Number	Sample Number	Sample wt. g	Release wt. lb.	BF_{8Gn}^{ug} Newtons
868	107A	1000	66.3	294.9
869	107B	1000	46.0	204.6
870	107C	1000	53.7	238.9
871	107D	1000	34.5	153.5
872	107E	1000	43.3	192.6
873	107F	1000	56.3	250.4
874	107G	1000	30.1	133.9
875	107H	1000	64.1	258.1
876	107I	1000	45.3	201.5
877	107J	1000	89.5	398.1
				Max. Min. Avg. 398.1 133.9 232.7

Table 159. Breakfree force BF_{8coal}^{ug} for 1000grams of ungraded coal.

Run Number	Sample Number	Sample wt. g	Release wt. lb.	BF_{8coal}^{ug} Newtons
868	108A	1000	13.2	58.7
869	108B	1000	6.3	28.8
870	108C	1000	7.1	31.6
871	108D	1000	4.6	20.5
872	108E	1000	6.6	29.4
873	108F	1000	11.6	51.6
874	108G	1000	11.3	50.3
875	108H	1000	9.4	41.8
876	108I	1000	6.7	29.8
877	108J	1000	7.5	33.4
				Max. Min Avg 58.7 20.5 37.6

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5 inch (127mm) ID tube Test Rig 1. Tables 160- 187

Table 160. Breakfree force $\mathrm{BF}^{2}_{5\mathrm{Gv}}$ for 1000 grams of gravel 2mm size.

Run Number	Sample Number	Sample wt. g	Release wt. lb.	$\mathrm{BF}^{2}_{5\mathrm{Gv}}$Newtons
503	S82A	1000	8.9	39.6
504	S82B	1000	11.9	52.9
505	S82C	1000	10.0	44.5
506	S82D	1000	8.8	39.1
507	S82E	1000	9.2	40.9
508	S82F	1000	10.1	44.9
509	S82G	1000	8.7	38.7
510	S82H	1000	7.0	31.1
511	S82I	1000	11.9	52.9
512	S82J	1000	10.4	46.3
				Max Min Avg. 52.9 31.1 43.1

Table 161. Breakfree force $\mathrm{BF}^{2}_{5\mathrm{Gv}}$ for 2000 grams of gravel 2mm size

Run Number	Sample Number	Sample wt. g	Release wt. lb.	$\mathrm{BF}^{2}_{5\mathrm{Gv}}$Newtons
513	S83A	2000	19.9	88.5
514	S83B	2000	23.4	104.0
515	S83C	2000	20.9	93.0
516	S83D	2000	14.9	66.3
517	S83E	2000	21.1	93.9
518	S83F	2000	22.9	101.9
519	S83G	2000	19.8	88.2
520	S83H	2000	20.2	89.8
521	S83I	2000	20.4	90.7
522	S83J	2000	18.0	80.1
				Max Min Avg. 104.0 66.3 89.6

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Table 162. Breakfree force BF^{2}_{5Gv} for 3000 grams of gravel 2mm size

Run Number	Sample Number	Sample wt. g	Release wt. lb.	BF^{2}_{5Gv}Newtons
523	S84A	3000	38.3	170.4
524	S84B	3000	24.7	109.9
525	S84C	3000	26.9	119.7
526	S84D	3000	33.5	149.0
527	S84E	3000	31.7	141.0
528	S84F	3000	29.1	129.4
529	S84G	3000	31.6	140.6
530	S84H	3000	29.3	131.3
531	S84I	3000	29.6	131.7
532	S84J	3000	32.7	145.4
				Max. Min Avg 170.4 109.9 136.8

Table 163. Breakfree force BF^{2}_{5Gv} for 500 grams of gravel 2mm size.

Run Number	Sample Number	Sample wt. g	Release wt. lb.	BF^{2}_{5Gv}Newtons
533	S85A	500	6.5	28.9
534	S85B	500	3.4	15.1
535	S85C	500	2.7	12.0
536	S85D	500	5.9	26.2
537	S85E	500	3.3	14.7
538	S852F	500	4.1	18.2
539	S85G	500	8.0	35.6
540	S85H	500	2.9	12.9
541	S85I	500	7.3	32.5
542	S85J	500	9.4	41.8
				Max Min Avg 41.8 12.0 18.0

Table 164. Breakfree force BF^{2}_{5Gv} for 1500 grams of gravel 2mm size.

Run Number	Sample Number	Sample wt. g	Release wt. lb.	BF^{2}_{5Gv}Newtons
543	S86A	1500	10.7	47.6
544	S86B	1500	12.6	56.0
545	S86C	1500	15.5	68.9
546	S86D	1500	11.8	52.5
547	S86E	1500	10.7	47.6
548	S86F	1500	11.9	52.9
549	S86G	1500	14.1	62.7
550	S86H	1500	13.4	59.6
551	S86I	1500	6.8	30.2
552	S86J	1500	8.2	36.5
				Max Min Avg 62.7 30.2 51.4

Table 165. Breakfree force BF^{2}_{5Gv} for 2500 grams of gravel 2mm size.

Run Number	Sample Number	Sample wt. g	Release wt. lb.	BF^{2}_{5Gv}Newtons
553	S87A	2500	26.5	117.9
554	S87B	2500	18.1	80.5
555	S87C	2500	17.9	79.6
556	S87D	2500	21.7	96.5
557	S87E	2500	19.3	85.8
558	S87F	2500	23.7	105.4
559	S87G	2500	26.3	117.0
560	S87H	2500	18.5	82.3
561	S87I	2500	19.2	85.3
562	S87J	2500	20.2	89.8
				Max Min Avg 117.9 79.6 94.0

Table 166. Breakfree force BF^{2}_{5Gn} for 500 grams of granite 2mm size

Run Number	Sample Number	Sample wt. g	Release wt. lb.	BF^{2}_{5Gn} Newtons
563	S88A	500	5.1	22.7
564	S88A	500	2.4	10.7
565	S88B	500	3.1	13.8
566	S88C	500	5.0	22.2
567	S88D	500	2.2	9.8
568	S88E	500	2.9	12.9
569	S88F	500	5.8	25.8
570	S88G	500	2.4	11.1
571	S88H	500	3.5	15.6
572	S88I	500	2.1	9.3
573	S88J	500	3.3	14.7
				Max. Min Avg 25.8 9.3 16.9

Table 167. Breakfree force BF^{2}_{5Gn} for 1000 grams of granite 2mm size.

Run Number	Sample Number	Sample wt. g	Release wt. lb.	BF^{2}_{5Gn} Newtons
574	S89A	1000	13.1	58.3
575	S89B	1000	4.2	18.6
576	S89C	1000	3.8	16.9
577	S89D	1000	5.7	25.4
578	S89E	1000	4.3	19.1
579	S89F	1000	5.9	26.2
580	S89G	1000	5.7	25.4
581	S89H	1000	10.2	45.4
582	S89I	1000	3.2	14.2
583	S89J	1000	7.6	33.8
				Max. Min Avg. 58.3.. .14.2 28.3

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Table 168. Breakfree force BF^2_{5Gn} for 1500 grams of granite 2mm size.

Run Number	Sample Number	Sample wt. g	Release wt. lb.	BF^2_{5Gn} Newtons
584	S90A	1500	4.5	20.0
585	S90B	1500	25.1	111.6
586	S90C	1500	12.6	56.0
587	S90D	1500	5.2	23.1
588	S90E	1500	8.2	36.4
589	S90F	1500	9.6	42.7
590	S90G	1500	11.9	52.9
591	S90H	1500	5.6	24.9
592	S90I	1500	5.7	25.4
593	S90J	1500	8.4	37.4
				Max. Min Avg 111.6 20.0 44.0

Table 169. Breakfree force BF^2_{5Gn} for 2000 grams of granite 2mm size.

Run Number	Sample Number	Sample wt. g	Release wt. lb.	BF^2_{5Gn} Newtons
594	S91A	2000	7.2	32.0
595	S91B	2000	9.8	43.6
596	S91C	2000	12.9	57.4
597	S91D	2000	10.1	44.9
598	S91E	2000	14.0	62.3
599	S91F	2000	12.0	53.4
600	S91G	2000	12.5	55.6
601	S91H	2000	7.8	34.7
602	S91I	2000	11.6	51.6
603	S91J	2000	15.5	68.9
				Max. Min. Avg. 68.9 32.0 50.4

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Table 170. Breakfree force $\mathrm{BF}_{5\mathrm{Gn}}^{2}$ for 2500 grams of granite 2mm size. Sample run number 604 if removed from the average calculation the average would be 54.9 N

Run Number	Sample Number	Sample wt. g	Release wt. lb.	$\mathrm{BF}_{5\mathrm{Gn}}^{2}$ Newtons
604	S92A	2500	1.1	4.9
605	S92B	2500	14.8	65.8
606	S92C	2500	18.2	81.0
607	S92D	2500	15.0	66.7
608	S92E	2500	10.5	46.7
609	S92F	2500	10.5	46.7
610	S92G	2500	9.6	42.7
611	S92H	2500	9.5	42.3
612	S92I	2500	9.6	42.7
613	S92J	2500	13.3	59.2
				Max. Min Avg 81.0 4.9 49.8

Table 171 Breakfree force $\mathrm{BF}_{5\mathrm{Gn}}^{2}$ for 3000 grams of granite 2mm size.

Run Number	Sample Number	Sample wt. g	Release wt. lb.	$\mathrm{BF}_{5\mathrm{Gn}}^{2}$ Newtons
614	S93A	3000	15.2	67.6
615	S93B	3000	13.3	59.2
616	S93C	3000	11.6	51.6
617	S93D	3000	15.9	70.7
618	S93E	3000	14.5	64.5
619	S93F	3000	19.6	87.2
620	S93G	3000	15.0	66.7
621	S93H	3000	18.6	82.7
622	S93I	3000	18.5	82.3
623	S93J	3000	17.3	77.0
				Max. Min. Avg. 87.2 51.6 71.0

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Table 172. Breakfree force $\mathrm{BF}^{2}_{5\mathrm{coal}}$ for 500 grams of coal 2mm

Run Number	Sample Number	Sample wt. g	Release wt. lb.		$\mathrm{BF}^{2}_{5\mathrm{coal}}$ Newtons
624	S94A	500	0.9		4.0
625	S94B	500	0.9		4.0
626	S94C	500	1.0		4.4
663	S94D	500	1.2		5.3
627	S94E	500	1.1		4.9
628	S94F	500	1.1		4.9
629	S94G	500	1.1		4.9
630	S94H	500	1.3		5.8
631	S94I	500	1.0		4.4
632	S94J	500	1.2		5.3
					Max . Min. Avg. 5.8 4.0 4.8

Table 173. Breakfree force $\mathrm{BF}^{2}_{5\mathrm{coal}}$ for 1000 grams of coal 2mm.

Run Number	Sample Number	Sample wt. g	Release wt. lb.	$\mathrm{BF}^{2}_{5\mathrm{coal}}$ Newtons
633	S95A	1000	2.5	11.1
634	S95B	1000	2.6	11.6
635	S95C	1000	2.1	9.4
636	S95D	1000	2.4	10.7
637	S95E	1000	1.9	8.5
638	S95F	1000	2.7	12.0
639	S95G	1000	1.9	8.5
640	S95H	1000	2.3	10.2
641	S95I	1000	2.8	12.5
642	S95J	1000	3.0	13.3
				Max. Min. Avg. 13.3 8.5 10.8

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Table 174. Breakfree force BF^{2}_{5coal} for 1500 grams of coal 2mm.

Run Number	Sample Number	Sample wt. g	Release wt. lb.	BF^{2}_{5coal} Newtons
643	S96A	1500	6.1	27.1
644	S96B	1500	5.6	24.9
645	S96C	1500	5.4	24.0
646	S96D	1500	5.3	23.6
647	S96E	1500	5.9	26.2
648	S96F	1500	7.1	31.6
649	S96G	1500	5.6	24.9
650	S96H	1500	6.0	26.7
651	S96I	1500	9.0	40.0
652	S96J	1500	5.0	22.2
				Max. Min. Avg. 40.0 24.0 27.1

Table 175. Breakfree force BF^{2}_{5coal} for 2000 grams of coal 2mm

Run Number	Sample Number	Sample wt. g	Release wt. lb.	BF^{2}_{5coal} Newtons
653	S97A	2000	10.5	46.7
654	S97B	2000	12.9	57.4
655	S97C	2000	12.4	55.2
656	S97D	2000	11.9	52.9
657	S97E	2000	14.7	65.4
658	S97F	2000	13.6	60.5
659	S97G	2000	16.0	71.2
660	S97H	2000	14.1	64.1
661	S97I	2000	23.1	102.7
662	S97J	2000	33.0	146.8
				Max. Min. Avg 146.8 46.7 72.3

Table 176. Breakfree force BF_{5coal}^{2} for 2500 grams of coal 2mm.

Run Number	Sample Number	Sample wt. g	Release wt. lb.	BF_{5coal}^{2} Newtons
664	S98A	2500	23.7	105.4
665	S98B	2500	aborted	
683	S98B	2500	20.1	89.4
666	S98C	2500	24.7	109.9
667	S98D	2500	24.3	108.1
668	S98E	2500	25.9	115.2
669	S98F	2500	25.2	112.1
670	S98G	2500	25.7	114.3
671	S98H	2500	24.8	110.3
672	S98I	2500	32.2	143.2
673	S98J	2500	27.5	122.3
				Max. Min. Avg. 143.2 89.4 113.0

Table 177. Breakfree force BF_{5coal}^{2} for 3000 grams of coal 2mm

Run Number	Sample Number	Sample wt. g	Release wt. lb.	BF_{5coal}^{2} Newtons
674	S99A	3000	56.0	249.1
675	S99A	3000	70.0	311.4
676	S99A	3000	48.2	214.4
677	S99A	3000	54.0	240.2
678	S99A	3000	52.3	232.6
679	S99A	3000	55.9	248.6
680	S99A	3000	46.6	207.3
681	S99A	3000	58.3	259.3
682	S99A	3000	55.0	244.6
684	S99A	3000		
				Max. Min. Avg 311.4 214.4 245.3

Table 178. Breakfree force BF_{5Gn}^{ug} for 1000 grams of granite ungraded

Run Number	Sample Number	Sample wt. g	Release wt. lb.	BF_{5Gn}^{ug} Newtons
685	S100A	1000	42.9	190.8
686	S100B	1000	12.3	54.7
687	S100C	1000	27.1	120.5
688	S100D	1000	14.1	62.7
689	S100E	1000	6.3	28.0
690	S100F	1000	50.6	225.1
691	S100H	1000	21.2	94.3
692	S100J	1000	21.0	93.4
693	S100F	1000	ABORTED	
694	S100F	1000	19.5	86.7
695	S100H	1000	12.0	53.4
				Max. Min. Avg. 225.1 28.0 91.6

Table 179. Breakfree force $BF_{5Gn/coal}^{ug/2}$ for 500 grams of 2mm coal under 1000 grams of granite ungraded

Run Number	Sample Number	Sample wt. g Coal/Granite	Release wt. lb.	$BF_{5Gn/coal}^{ug/2}$ Newtons
	S101A	500/1000		
	S101B	500/1000		
	S101C	500/1000		
697	S101D	500/1000	7.0	31.1
698	S101E	500/1000	7.3	32.5
699	S101F	500/1000	7.8	34.7
700	S101G	500/1000	6.0	26.7
701	S101H	500/1000	6.7	29.8
702	S101I	500/1000	6.4	28.5
703	S101J	500/1000	8.4	37.4
				Max. Min. Avg. 37.4 26.7 31.7

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Table 180. Breakfree force BF_{5Gv}^{UG} 1000 grams of ungraded gravel.

Run Number	Sample Number	Sample wt. g	Release wt. lb.	BF_{5Gv}^{UG} Newtons
726	S102A	1000	20.5	91.2
705	S102B	1000	5.9	26.2
706	S102C	1000	9.6	42.7
707	S102D	1000	6.8	30.2
708	S102E	1000	3.7	16.5
709	S102F	1000	7.5	33.4
710	S102G	1000	23.8	105.9
711	S102H	1000	9.6	42.7
712	S102I	1000	6.7	29.8
713	S102J	1000	12.4	55.2
				Max. Min. Avg. 105.9 16.5 46.8

Table 181. Breakfree force $BF_{5Gv/coal}^{UG/2}$ 500 grams of 2mm coal under 1000 gravel ungraded

Run Number	Sample Number	Sample wt. g Coal/Gravel	Release wt. lb.	$BF_{5Gv/coal}^{UG/2}$ Newtons
715	S103A	500/1000	8.0	35.6
716	S103B	500/1000	8.1	36.0
717	S103C	500/1000	6.9	30.7
718	S103D	500/1000	7.8	34.7
719	S103E	500/1000	6.7	29.8
720	S103F	500/1000	8.0	35.6
721	S103G	500/1000	8.4(graph?)	37.4
722	S103G repeat	500/1000	8.1	36.0
723	S103H	500/1000	7.3	32.5
724	S103I	500/1000	7.7	34.2
725	S103J	500/1000	7.1	32.9
				Max. Min. Avg. 37.4 29.8 33.9

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Table 182. Breakfree force BF_{5coal}^{UG} 1000 grams of coal ungraded

Run Number	Sample Number	Sample wt. g Coal	Release wt. lb.	BF_{5coal}^{UG} Newtons
727	S104A	1000	11.9	52.9
728	S104B	1000	11.2	49.8
729	S104C	1000	19.8	88.1
730	S104D	1000	10.6	47.1
731	S104E	1000	14.5	64.5
732	S104F	1000	10.6	47.1
	S104G	1000		
733	S104H	1000	17.5	77.8
734	S104I	1000	15.5	68.9
735	S104J	1000	17.9	79.6
				Max. Min. Avg. 88.1 47.1 57.6

Table 183. Breakfree force $BF_{5coal/coal}^{UG/2}$ 500 grams of 2m coal under 1000 grams of ungraded coal.

Run Number	Sample Number	Sample wt. g Coal/Coal ungraded	Release wt. lb.	$BF_{5coal/coal}^{UG/2}$ Newtons
736	S105A	500/1000	33.8	150.3
737	S105A	500/1000	35.5	157.9
738	S105B	500/1000	49.4 Assisted	219.7
739	S105C	500/1000	36.5	162.4
741	S105D	500/1000	29.3	130.3
742	S105E	500/1000	45.8	203.7
743	S105F	500/1000	39.6	176.1
744	S105G	500/1000	48.9	217.5
745	S105G	500/1000	22.5	100.1
746	S105I	500/1000	33.7	149.9
747	S105J	500/1000	23.1	102.7
				Max. Min. Avg 219.7 100.1 177.1

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Table184. Breakfree force $\mathrm{BF}_{5\mathrm{coal}}^{\mathrm{UG}}$ 1000 grams of ungraded coal. Revalidating data on Table 182

Run Number	Sample Number	Sample wt. g Coal	Release wt. lb.	$\mathrm{BF}_{5\mathrm{coal}}^{\mathrm{UG}}$ Newtons
748	S106A	1000	16.5	73.4
750	S106B	1000	17.5	77.8
751	S106C	1000	15.0	66.7
752	S106D	1000	16.4	72.9
753	S106E	1000	17.6	78.3
754	S106F	1000	20.2	89.8
755	S106G	1000	20.0	89.0
756	S106H	1000	20.2	89.8
757	S106I	1000	17.8	79.2
758	S106J	1000	17.5	77.8
				Max. Min. Avg. 89.8 72.9 29.5

Table185. Breakfree force $\mathrm{BF}_{5\mathrm{coal}}^{2}$ 500 grams of 2mm coal revalidating data on Table 172

Run Number	Sample Number	Sample wt. g Coal	Release wt. lb.	BF_{5coal}^{2} Newtons
749	S107A	500	1.5	6.7

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Table186. Breakfree force $\mathrm{BF}^{\mathrm{UG/2}}_{\mathrm{5coal/coal}}$500 grams of 2mm coal under 1000grams of ungraded coal. The release point was taken when the sample broke free rapidly. There were smaller movements at much lower breakfree forces, but they were very weak to identify. This creates some confusion as to where the real break free point is for the analysis that is required here. This was confusing and the results are not included in the calculations.

Run Number	Sample Number	Sample wt. g Coal	Release wt. lb.	$\mathrm{BF}^{\mathrm{UG/2}}_{\mathrm{5coal/coal}}$ Newtons
759	S108A	500/1000	26.6	118.3
761	S108B	500/1000	37.9	168.6
762	S108C	500/1000	24.3	108.1
763	S108D	500/1000	26.8	119.2
764	S108E	500/1000	30.4	135.2
765	S108F	500/1000	55.6 assisted	247.3
766	S108G	500/1000	41.4	184.1
767	S108H	500/1000	30.0	133.4
768	S108I	500/1000	27.3	121.4
769	S108J	500/1000	34.8	154.8
				Max. Min. Avg. 247.3 108.1 148.7

Table 187. Breakfree force $\mathrm{BF}^{\mathrm{UG/2}}_{\mathrm{5coal/coal}}$ for 500grams of 2mm coal under 1000grams of ungraded coal. The release point was taken when the sample first started to move

Run Number	Sample Number	Sample wt. g	Release wt. lb.	$BF^{UG/2}_{5coal/coal}$ Newtons
837	S105AR	500/1000	7.3	32.5
838	S105BR	500/1000	6.4	28.5
839	S105CR	500/1000	7.2	32.0
840	S105DR	500/1000	6.7	29.8
841	S105ER	500/1000	6.3	28.0
842	S105FR	500/1000	6.8	30.2
844	S105GR	500/1000	6.5	28.9
845	S105HR	500/1000	6.5	28.9
846	S105IR	500/1000	7.0	31.1
847	S105JR	500/1000	6.7	29.8
				Max. Min. Avg 32.5 28.0 29.6

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APPENDIX 3
5 inch (127mm) id tube Test Rig 2. Tables 188-211

Table 188 Test Rig 2. Coal 2mm, Ore bin auger speed 11 rpm. Variable elevator cable speed of 1.5, 2.0, 2.5, and 3.0 m/s.

Coal 2mm	Run number 9 Sample number 2							
	Ore bin speed fixed at 11 RPM							
Results observation time period 24hour	10:42:00 to 10:42:10		10:43:15 to 10:43:25		10:45:00 to 10:45:10		10:46:15 to 10:46:25	
Elevator speed	60rpm 1.50m/s		80rpm 2.0m/s		100rpm. 2.5m/s		120rpm. 3.0 m/s	
	Ore on 19 discs kg	Ore on 1 disc g	Ore on 19 discs kg	Ore on 1 disc g	Ore on 19discs kg	Ore on 1 disc g	Ore on 19discs kg	Ore on 1 disc g
Average	8.49	446.84	4.64	244.21	3.92	206.32	3.12	164.21
Maximum	8.79	462.63	5.02	264.21	4.08	214.74	3.33	175.26
Minimum	8.20	431.58	4.35	228.95	3.69	194.21	2.09	152.63
	Dynamic force on 16 discs kg	Dynamic force on 1 disc g	Dynamic force on 16 discs kg	Dynamic force on 1 disc g	Dynamic force on 16 discs kg	Dynamic force on 1 disc g	Dynamic force on 16 discs kg	Dynamic force on 1 disc g
Average	3.06	191.25	0.82	51.25	0.57	35.63	0.57	35.63
Maximum	3.92	245.00	1.05	65.63	0.85	53.13	0.96	60.00
Minimum	2.22	138.75	0.64	40.00	0.15	9.38	0.33	20.30

Table 189. Test Rig 2. Coal 2mm. Fixed elevator cable speed at 2.0 m/s. Ore bin auger speed 11, 22, 33, and 44 rpm

Coal 2mm	Run number 10 Sample number 3R3							
Elevator speed	80 rpm 2m/s							
Results observation time period 24hour	11:28:30 to 11:28:40		11:31:15 to 11:31:25		11:33:00 to 11:33:10		11:34:35 to 11:34:45	
Ore bin speed	11		22		33		44	
	Ore on 19 discs kg	Ore on 1 disc g	Ore on 19 discs kg	Ore on 1 disc g	Ore on 19discs kg	Ore on 1 disc g	Ore on 19discs kg	Ore on 1 disc g
Average	3.12	169.47	6.83	359.47	9.52	501.05	12.26	645.26
Maximum	3.34	175.79	7.00	368.42	9.98	525.26	12.59	662.63
Minimum	2.86	150.53	6.61	347.89	9.10	478.95	11.80	621.05
	Dynamic force on 16 discs kg	Dynamic force on 1 disc g	Dynamic force on 16 discs kg	Dynamic force on 1 disc g	Dynamic force on 16 discs kg	Dynamic force on 1 disc g	Dynamic force on 16 discs kg	Dynamic force on 1 disc g
Average	0.34	21.25	1.07	66.88	1.88	117.50	2.16	135.00
Maximum	0.56	29.47	1.42	88.75	2.31	144.38	2.37	148.13
Minimum	0.09	5.63	0.76	47.50	1.46	91.25	1.89	118.13

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Table 190. Coal 2mm. Ore bin auger speed 44 rpm. Variable elevator cable speed of 2.0, 2.5, and 3.0 m/s

Coal 2mm	Run number 11 Sample number 4					
Bin speed	Ore bin speed fixed at 44 RPM					
Results observation time period 24hour	11:46:20 to 11:46:30		11:47:10 to 11:46:20		11:48:30 to 11:48:40	
Elevator Speed	80rpm 2.0m/s		100rpm. 2.5m/s		120rpm. 3.0 m/s	
	Ore on 19 discs kg	Ore on 1 disc g	Ore on 19 discs kg	Ore on 1 disc g	Ore on 19 discs kg	Ore on 1 disc g
Average	12.26	645.26	11.14	586.32	10.11	532.11
Maximum	12.62	664.21	11.49	604.37	10.91	574.21
Minimum	11.82	622.11	10.66	561.05	9.73	512.11
	Dynamic force on 16 discs kg	Dynamic force on 1 disc g	Dynamic force on 16 discs kg	Dynamic force on 1 disc g	Dynamic force on 16 discs kg	Dynamic force on 1 disc g
Average	2.12	132.50	1.16	72.50	0.76	47.50
Maximum	2.47	151.38	1.86	116.25	1.24	77.50
Minimum	1.85	115.63	0.88	55.00	0.50	31.25

Table 191. Coal 2mm. Fixed elevator cable speed at 2.0 m/s. Ore bin auger speed 11, 22, 33, and 44 rpm

Coal 2mm	Run number 19 Sample number 9							
Elevator Speed	80RPM 2.0m/s							
Results observation time period 24hour	10:27:20 to 10:27:30		10:29:55 to 10:30:05		10:32:00 to 10:32:10		10:34:00 to 10:34:10	
Ore Bin Speed	11RPM		22RPM		33RPM		44RPM	
	Ore on 19 discs kg	Ore on 1 disc g	Ore on 19 discs kg	Ore on 1 disc g	Ore on 19 discs kg	Ore on 1 disc g	Ore on 19 discs kg	Ore on 1 disc g
Average	3.69	194.21	7.99	420.53	11.97	630.00	16.01	842.63
Maximum	4.09	215.26	8.14	428.42	12.37	651.05	16.56	871.57
Minimum	3.24	170.53	7.66	403.16	11.66	613.68	15.45	813.16
	Dynamic force on 16 discs kg	Dynamic force on 1 disc g	Dynamic force on 16 discs kg	Dynamic force on 1 disc g	Dynamic force on 16 discs kg	Dynamic force on 1 disc g	Dynamic force on 16 discs kg	Dynamic force on 1 disc g
Average	0.39	24.38	0.89	55.63	1.63	101.88	2.74	171.25
Maximum	0.61	38.13	1.16	72.50	2.08	130.00	3.48	217.50
Minimum	0.17	10.63	0.58	36.25	1.09	68.13	1.90	118.75

Table 192. Coal 2mm. Fixed elevator cable speed at 3.0 m/s. Ore bin auger speed 11, 22, 33, and 44 rpm

Coal 2mm	Run number 21 Sample number 11							
Elevator Speed	120RPM 3.0 m/s							
Results observation time period 24hour	14:41:30 to 14:31:40		14:44:29 to 14:44:39		14:47:00 to 14:47:10		14:50:20 to 14:50:30	
Ore Bin Speed	11RPM		22RPM		33RPM		44RPM	
	Ore on 19 discs kg	Ore on 1 disc g	Ore on 19 discs kg	Ore on 1 disc g	Ore on 19 discs kg	Ore on 1 disc g	Ore on 19 discs kg	Ore on 1 disc g
Average	2.56	134.73	5.74	302.11	8.35	439.47	10.60	557.89
Maximum	3.13	164.74	6.05	319.42	8.82	464.21	11.44	602.11
Minimum	2.11	111.05	5.37	282.63	7.95	418.42	10.09	531.05
	Dynamic force on 16 discs kg	Dynamic force on 1 discs g	Dynamic force on 16 discs kg	Dynamic force on 1 discs g	Dynamic force on 16 discs kg	Dynamic force on 1 discs g	Dynamic force on 16 discs kg	Dynamic force on 1 discs g
Average	0.33	20.63	0.54	33.75	1.03	64.38	1.12	70.00
Maximum	0.56	35.00	0.71	44.38	1.38	86.25	1.53	95.63
Minimum	0.12	7.50	0.42	26.25	0.81	50.63	0.86	53.75

Table 193. Coal 2mm. Fixed elevator cable speed at 3.5 m/s. Ore bin auger speed 11, 22, 33, and 44 rpm

Coal 2mm	Run number 22 Sample number 12							
Elevator Speed	140 RPM 3.5m/s							
Results observation time period 24hour	15:00:00 to 15:00:10		15:03:00 to 15:03:10		15:05:00 to 15:05:10		15:09:00 to 15:09:10	
Ore Bin Speed	11 RPM		22RPM		33RPM		44RPM	
	Ore on 19discs kg	Ore on 1 disc g	Ore on 19discs kg	Ore on 1 disc g	Ore on 19discs kg	Ore on 1 disc g	Ore on 19discs kg	Ore on 1 disc g
Average	3.13	164.74	4.37	230.00	6.90	363.16	9.19	483.68
Maximum	3.89	204.74	5.02	264.21	7.32	385.26	9.64	507.37
Minimum	2.69	141.58	4.22	222.11	6.68	351.58	8.24	433.68
	Dynamic force on 16 discs kg	Dynamic force on 1 disc g	Dynamic force on 16 discs kg	Dynamic force on 1 disc g	Dynamic force on 16 discs kg	Dynamic force on 1 disc g	Dynamic force on 16 discs kg	Dynamic force on 1 disc g
Average	0.39	24.38	0.50	31.25	0.80	50.00	1.04	65.00
Maximum	0.62	38.75	0.71	44.38	0.92	57.50	1.35	84.38
Minimum	0.18	11.25	0.26	16.25	0.67	41.88	0.81	50.63

Sample number 13 continued:

Table 194.Coal 2mm. fixed ore flow rate auger speed 11 rpm, and variable elevator cable speed of 1.5, 1.75, 2.0, 2.5, 3.0, and 3.5 m/s.

Coal 2mm	Run number 23 Sample number 13							
Ore Bin Speed	11 RPM							
Results observation time period 24hour	9:24:30 to 9:24:40		9:26:30 to 9:26:40		9:29:00 to 9:29:10		9:31:00 to 9:31:10	
Elevator Speed	60 RPM 1.5m/s		80 RPM 2.0 m/s		100 RPM 2.5 m/s		120 RPM 3.0 m/s	
	Ore on 19 discs kg	Ore on 1 disc g	Ore on 19 discs kg	Ore on 1 disc g	Ore on 19 discs kg	Ore on 1 disc g	Ore on 19 discs kg	Ore on 1 disc g
Average	16.76	882.11	5.72	301.05	5.01	263.68	3.32	174.74
Maximum	17.62	927.37	6.29	331.05	5.61	295.26	3.71	195.26
Minimum	16.14	849.47	5.00	263.16	4.05	213.16	2.68	141.05
	Dynamic force on 16 discs kg	Dynamic force on 1 disc g	Dynamic force on 16 discs kg	Dynamic force on 1 disc g	Dynamic force on 16 discs kg	Dynamic force on 1 disc g	Dynamic force on 16 discs kg	Dynamic force on 1 disc g
Average	1.79	111.88	0.32	20.00	0.47	29.38	0.59	36.88
Maximum	2.35	146.88	0.60	37.50	0.83	51.88	0.81	50.63
Minimum	1.30	81.25	0.01	0.63	0.36	22.50	0.36	22.50

Sample number 13 continued: Table 194. Continued.

Coal 2mm	Run number 23 Sample number 13					
Ore Bin Speed	11 RPM					
Results observation time period 24hour	9:33:01 to 9:33:11		9:36:00 to 9:36:10		9:39:00 to 9:39:10	
Elevator Speed	140 RPM 3.5m/s		70 RPM 1.75 m/s		60 RPM 1.5 m/s	
	Ore on 19 discs kg	Ore on 1 disc g	Ore on 19 discs kg	Ore on 1 disc g	Ore on 19 discs kg	Ore on 1 disc g
Average	3.79	199.47	6.17	324.74	19.46	1024.21
Maximum	4.35	228.95	6.40	336.84	19.81	1042.63
Minimum	3.14	165.26	5.84	307.37	18.92	995.79
	Dynamic force on 16 discs kg	Dynamic force on 1 disc g	Dynamic force on 16 discs kg	Dynamic force on 1 disc g	Dynamic force on 16 discs kg	Dynamic force on 1 disc g
Average	0.82	51.25	0.48	30.00	2.07	129.38
Maximum	1.08	67.50	1.13	70.63	2.90	181.25
Minimum	0.55	34.38	0.15	9.38	1.47	91.88

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Table 195. Coal 2mm. Fixed ore flow rate auger speed 22 rpm, and variable elevator speed of 1.75, 2.0, 2.5, 3.0, and 3.5 m/s

Coal 2mm	Run number 24 Sample number 14									
	Ore bin speed fixed at 22 RPM									
Results observation time period 24hour	9:49:40 to 9:49:50		9:51:20 to 9:51:30		9:53:10 to 9:53:20		9:55:50 to 9:55:60		9:58:20 to 9:58:30	
Elevator speed	70rpm 1.75m/s		80rpm 2.0m/s		100rpm. 2.5m/s		120rpm. 3.0 m/s		140 rpm. 3.5 m/s	
	Ore on 19 discs kg	Ore on 1 disc g	Ore on 19 discs kg	Ore on 1 disc g	Ore on 19discs kg	Ore on 1 disc g	Ore on 19discs kg	Ore on 1 disc g	Ore on 19discs kg	Ore on 1 disc g
Average	15.68	825.26	10.30	542.11	8.45	444.74	7.06	371.68	5.49	288.95
Maximum	16.26	855.79	10.58	556.84	8.99	473.15	7.66	403.16	6.23	327.89
Minimum	15.24	802.11	9.99	525.79	8.03	422.63	6.53	343.68	4.91	258.42
	Dynamic force on 16 discs kg	Dynamic force on 1 discs g	Dynamic force on 16 discs kg	Dynamic force on 1 discs g	Dynamic force on 16 discs kg	Dynamic force on 1 discs g	Dynamic force on 16 discs kg	Dynamic force on 1 discs g	Dynamic force on 16 discs kg	Dynamic force on 1 discs g
Average	1.67	104.38	0.67	41.88	0.80	50.00	0.66	41.25	0.85	53.13
Maximum	2.08	130.00	1.47	91.88	1.77	110.63	1.31	81.88	1.30	81.25
Minimum	0.79	49.38	0.25	15.63	0.35	21.88	0.35	21.88	0.63	39.38

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Table 196. Coal 2mm. fixed ore flow rate auger speed 33 rpm. Variable elevator cable speed of 1.75, 2.0, 2.5, 3.0, and 3.5 m/s

Coal 2mm	Run number 25 Sample number 15									
	Ore bin speed fixed at 33 RPM									
Results observation time period 24hour	10:08:30 to 10:08:40		10:10:00 to 10:10:10		10:11:30 to 10:11: 40`		10:13:20 to 10:13:30		10:15:30 to 10:15:40	
Elevator speed	70rpm 1.75m/s		80rpm 2.0m/s		100rpm. 2.5m/s		120rpm. 3.0 m/s		140 rpm. 3.5 m/s	
	Ore on 19 discs kg	Ore on 1 disc g	Ore on 19 discs kg	Ore on 1 disc g	Ore on 19discs kg	Ore on 1 disc g	Ore on 19discs kg	Ore on 1 disc g	Ore on 19 discs kg	Ore on 1 disc g
Average	21.80	1147.30	14.81	779.47	9.49	499.47	9.45	497.37	7.24	381.05
Maximum	23.03	1212.11	15.49	815.26	10.25	539.47	9.98	525.26	7.88	414.74
Minimum	20.84	1096.84	14.25	750.00	8.87	466.84	8.62	453.68	6.49	341.58
	Dynamic force on 16 discs kg	Dynamic force on 1 disc g	Dynamic force on 16 discs kg	Dynamic force on 1 disc g	Dynamic force on 16 discs kg	Dynamic force on 1 disc g	Dynamic force on 16 discs kg	Dynamic force on 1 disc g	Dynamic force on 16 discs kg	Dynamic force on 1 disc g
Average	1.99	124.38	1.32	82.50	0.44	27.50	0.53	33.13	0.41	25.63
Maximum	2.58	161.25	2.10	131.25	0.71	44.38	0.84	52.50	0.71	44.38
Minimum	1.74	108.75	1.03	64.38	0.18	11.25	0.30	18.75	0.12	7.50

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Table 197. Coal 2mm. fixed ore flow rate auger speed 44 rpm. Variable elevator cable speed of 2.0, 2.5, 3.0, and 3.5 m/s.

Coal 2mm	Run number 26 Sample number 16							
	Ore bin speed fixed at 44 RPM							
Results observation time period 24hour	10:25:00 to 10:25:10		10:27.00 to 10:27:10		10:29:30 to 10:29:40		10:31:00 to 10:31:10	
Elevator speed	80rpm 2.0m/s		100rpm. 2.5m/s		120rpm. 3.0 m/s		140 rpm. 3.5 m/s	
	Ore on 19discs kg	Ore on 1 disc g	Ore on 19discs kg	Ore on 1 disc g	Ore on 19discs kg	Ore on 1 disc g	Ore on 19discs kg	Ore on 1 disc g
Average	18.59	978.42	12.88	677.89	12.41	653.16	9.41	495.26
Maximum	19.93	1048.95	13.23	696.32	13.54	712.63	11.22	590.52
Minimum	17.50	921.50	12.19	641.58	12.05	634.21	9.42	495.79
	Dynamic force on 16 discs kg	Dynamic force on 1 disc g	Dynamic force on 16 discs kg	Dynamic force on 1 disc g	Dynamic force on 16 discs kg	Dynamic force on 1 disc g	Dynamic force on 16 discs kg	Dynamic force on 1 disc g
Average	1.47	91.88	0.92	57.50	1.02	63.75	0.65	40.63
Maximum	1.87	116.88	1.40	87.50	1.54	96.25	0.98	61.25
Minimum	1.04	65.00	0.62	38.75	0.71	44.38	0.41	25.63

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Table 198. Gravel 2mm. Fixed ore flow rate auger speed 11 rpm. Variable elevator cable speed of 2.0, 2.5, and 3.0 m/s.

Gravel 2mm	Run number 27 Sample number 17					
Elevator Speed	80 rpm 2.0 m/		100 rpm 2.5 m/		120 rpm 3.0 m/	
Ore bin speed	11 rpm		11 rpm		11 rpm	
Results observation time period 24hour	14:21:20 to 14:21:30		14:23:00 to 14:23:10		14:24:15 to 14:24:25	
	Ore on 19 discs kg	Ore on 1 disc g	Ore on 19 discs kg	Ore on 1 disc g	Ore on 19 discs kg	Ore on 1 disc g
Average	34.08	1793.68	10.17	535.26	8.26	434.74
Maximum	35.02	1843.16	11.17	587.89	9.37	439.16
Minimum	33.11	1742.63	9.96	524.21	7.00	369.42
	Dynamic force on 16 discs kg	Dynamic force on 1 disc g	Dynamic force on 16 discs kg	Dynamic force on 1 disc g	Dynamic force on 16 discs kg	Dynamic force on 1 disc g
Average	8.78	462.11	1.41	88.13	1.12	70.00
Maximum	11.04	690.00	2.37	148.13	1.83	114.38
Minimum	7.15	446.88	0.45	28.13	0.67	41.88

Table 199. Gravel 2mm. Elevator cable speed at 2.0m/s and ore bin auger speed at 11rpm.
Elevator cable speed at 2.5 m/s with ore bin auger speed at 22 and 33 rpm.

Gravel 2mm	Run number 28 Sample number 18					
Elevator Speed	80 rpm 2.0 m/		100 rpm 2.5 m/		100 rpm 2.5 m/	
Ore bin speed	11 rpm		22 rpm		33 rpm	
Results observation time period 24hour	11:42:30 to 11:42:40		11:44:30 to 11:44:40		11:45:35 to 11:45:45	
	Ore on 19 discs kg	Ore on 1 disc g	Ore on 19 discs kg	Ore on 1 disc g	Ore on 19 discs kg	Ore on 1 disc g
Average	7.32	385.26	15.74	828.42	21.42	1127.37
Maximum	7.98	420.00	16.51	868.95	22.38	1177.89
Minimum	6.49	341.58	15.24	802.11	19.91	1047.89
	Dynamic force on 16 discs kg	Dynamic force on 1 disc g	Dynamic force on 16 discs kg	Dynamic force on 1 disc g	Dynamic force on 16 discs kg	Dynamic force on 1 disc g
Average	1.23	76.88	2.34	146.25	3.49	218.13
Maximum	1.78	111.25	2.89	180.63	4.17	260.63
Minimum	0.24	15.00	1.98	123.75	3.06	191.25

Table 200. Gravel 2mm. Fixed elevator cable speed at 3.0 m/s. Ore bin auger speed 11, 22, 33, and 44 rpm

Gravel 2mm	Run number 29 Sample number 19							
Elevator Speed	120 rpm 3.0 m/s		120 rpm 3.0 m/s		120 rpm 3.0 m/s		120 rpm 3.0 m/s	
Ore bin speed	11 rpm		22 rpm		33 rpm		44 rpm	
Results observation time period 24hour	13:24:30 to 13:24:40		13:27:30 to 13:27:40		13:28:30 to 13:28:40		13;30::00 to 13:30:10	
	Ore on 19 discs kg	Ore on 1 disc g	Ore on 19 discs kg	Ore on 1 disc g	Ore on 19 discs kg	Ore on 1 disc g	Ore on 19 discs kg	Ore on 1 disc g
Average	4.06	213.68	10.47	551.05	15.21	800.53	21.62	1127.89
Maximum	5.80	305.26	11.06	582.11	16.55	871.05	23.80	1252.63
Minimum	2.56	134.74	9.45	497.37	13.79	725.79	19.85	1044.74
	Dynamic force on 16 discs kg	Dynamic force on 1 disc g	Dynamic force on 16 discs kg	Dynamic force on 1 disc g	Dynamic force on 16 discs kg	Dynamic force on 1 disc g	Dynamic force on 16 discs kg	Dynamic force on 1 disc g
Average	1.71	106.88	2.09	130.63	2.65	165.63	3.92	245.00
Maximum	2.22	138.75	2.70	168.75	3.08	192.50	4.95	309.38
Minimum	0.07	4.38	1.41	88.13	1.39	86.88	3.51	219.38

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Table 201. Gravel 2mm. Fixed elevator cable speed at 3.5 m/s. Ore bin auger speed 11, 22, 33, and 44 RPM.

Gravel 2mm	Run number 31 Sample number 21							
Elevator Speed	140 rpm 3.5 m/s		140 rpm 3.5 m/s		140 rpm 3.5 m/s		140 rpm 3.5 m/s	
Ore bin speed	11 rpm		22 rpm		33 rpm		44 rpm	
Results observation time period 24hour	14:37:00 to 14:37:10		14:38:40 to 14:38:50		14:39:40 to 14:39:50		14:40:40 to 14:40:50	
	Ore on 19 discs kg	Ore on 1 disc g	Ore on 19 discs kg	Ore on 1 disc g	Ore on 19 discs kg	Ore on 1 disc g	Ore on 19 discs kg	Ore on 1 disc g
Average	6.96	366.32	12.08	635.79	16.09	846.84	21.01	1105.79
Maximum	8.12	427.37	12.94	681.05	17.27	908.95	22.27	1172.11
Minimum	5.98	314.74	11.22	590.52	14.83	780.53	18.87	993.16
	Dynamic force on 16 discs kg	Dynamic force on 1 disc g	Dynamic force on 16 discs kg	Dynamic force on 1 disc g	Dynamic force on 16 discs kg	Dynamic force on 1 disc g	Dynamic force on 16 discs kg	Dynamic force on 1 disc g
Average	1.26	78.75	1.30	81.25	1.66	103.75	2.46	153.75
Maximum	1.67	104.38	2.08	130.00	2.32	145.00	3.17	198.13
Minimum	0.57	35.63	0.59	36.88	0.85	53.13	0.97	60.63

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Table 202. Gravel 2mm. Ore flow rate, auger speed 33 RPM, with elevator cable speed of 2.5 metres per second.
Ore flow rate, auger speed 44 RPM, and elevator cable speed of 3.0 and 3.5 m/s.

Gravel 2mm	Run number 32 Sample number 22							
Elevator Speed	100 rpm 2.5 m/s		100 rpm 2.5 m/s		120 rpm 3.0 m/s		140 rpm 3.5 m/s	
Ore bin speed	33 rpm		44 rpm		44 rpm		44 rpm	
Results observation time period 24hour	13:59:10 to 13:59:20		14:00:10 to 14:00:20		14:01:15 to 14:00:25		14:02:10 to 14:02:20	
	Ore on 19discs kg	Ore on 1 disc g	Ore on 19discs kg	Ore on 1 disc g	Ore on 19discs kg	Ore on 1 disc g	Ore on 19discs kg	Ore on 1 disc g
Average	22.03	1159.47	28.51	1500.53	21.54	1133.68	18.69	983.68
Maximum	22.77	1198.42	29.47	1551.05	23.15	1218.42	20.54	1081.05
Minimum	21.21	1116.32	27.73	1459.47	20.58	1083.58	17.46	918.95
	Dynamic force on 16 discs kg	Dynamic force on 1 disc g	Dynamic force on 16 discs kg	Dynamic force on 1 disc g	Dynamic force on 16 discs kg	Dynamic force on 1 disc g	Dynamic force on 16 discs kg	Dynamic force on 1 disc g
Average	3.10	193.75	5.35	334.38	2.61	163.13	1.87	116.88
Maximum	4.16	260.00	7.19	449.38	3.80	237.50	2.88	180.00
Minimum	1.94	121.25	4.11	256.88	1.51	94.38	0.68	42.50

Table 203. Granite 2mm. Fixed ore flow rate, auger speed 11 rpm. Variable elevator cable speed of 2.0, 2.5, 3.0, and 3.5 m/s.

Granite 2mm	Run number 33 Sample number 23							
	Ore bin speed fixed at 11 RPM							
Results observation time period 24hour	12:43:30 to 12:43:40		12:44:20 to 12:44:30		12:45:20 to 12:45:30		12:46:20 to 12:45:30	
Elevator speed	80rpm 2.0m/s		100rpm. 2.5m/s		120rpm. 3.0 m/s		140 rpm. 3.5 m/s	
	Ore on 19discs kg	Ore on 1 disc g	Ore on 19discs kg	Ore on 1 disc g	Ore on 19discs kg	Ore on 1 disc g	Ore on 19discs kg	Ore on 1 disc g
Average	17.43	917.37	14.26	750.53	11.22	590.53	9.61	505.79
Maximum	18.05	950.00	14.73	775.26	11.84	623.16	10.79	567.89
Minimum	16.80	884.21	13.33	701.58	10.53	554.21	8.89	467.89
	Dynamic force on 16 discs kg	Dynamic force on 1 disc g	Dynamic force on 16 discs kg	Dynamic force on 1 disc g	Dynamic force on 16 discs kg	Dynamic force on 1 disc g	Dynamic force on 16 discs kg	Dynamic force on 1 disc g
Average	1.02	63.75	1.20	75.00	1.15	71.88	0.98	61.25
Maximum	2.14	133.75	1.90	118.75	1.73	108.13	1.41	88.13
Minimum	0.03	1.88	0.44	27.50	0.62	38.75	0.60	37.50

Table 204. Granite 2mm. Fixed elevator cable speed at 2.5 m/s. Variable ore flow rate, auger speed 11, 22, 33, and 44 rpm.

Granite 2mm	Run number 34 Sample number 24							
	Elevator speed fixed at 100RPM 2.5m/s							
Results observation time period 24hour	12:59:00 to 12:59:10		13:00:00 to 13:00:10		13:01:30 to 13:01:40		13:02:30 to 13:02:40	
Bin speed	11 RPM		22 RPM		33 RPM		44 RPM	
	Ore on 19 discs kg	Ore on 1 disc g	Ore on 19 discs kg	Ore on 1 disc g	Ore on 19 discs kg	Ore on 1 disc g	Ore on 19 discs kg	Ore on 1 disc g
Average	9.23	485.79	17.60	926.32	21.01	1105.79	38.17	2008.94
Maximum	9.92	522.11	18.15	955.26	23.02	1211.58	38.96	2050.53
Minimum	8.71	458.42	15.81	832.11	18.66	982.11	37.26	1961.05
	Dynamic force on 16 discs kg	Dynamic force on 1 disc g	Dynamic force on 16 discs kg	Dynamic force on 1 disc g	Dynamic force on 16 discs kg	Dynamic force on 1 disc g	Dynamic force on 16 discs kg	Dynamic force on 1 disc g
Average	0.40	25.00	1.14	71.25	1.82	113.75	5.68	355.00
Maximum	0.89	55.63	1.28	80.00	3.23	201.88	6.79	424.38
Minimum	0.02	1.25	0.77	48.13	0.81	50.63	4.85	303.13

Table 205. Granite 2mm. Fixed ore flow rate, auger speed 22 rpm. Elevator speed of 2.5 metres per second. Duplicate test.

Granite 2mm	Run number 36 Sample number 26		Run number 35 Sample number 25	
Bin speed	22RPM		22RPM	
Results observation time period 24hour	13:35:45 to 13:35:55		13:31:01 to 13:31:11	
Elevator speed	100rpm. 2.5m/s		100rpm. 2.5 m/s	
	Ore on 19discs kg	Ore on 1 disc g	Ore on 19discs kg	Ore on 1 disc g
Average	15.99	841.58	15.62	822.11
Maximum	16.84	886.32	16.47	866.84
Minimum	15.39	810.00	14.85	781.58
	Dynamic force on 16 discs kg	Dynamic force on 1 disc g	Dynamic force on 16 discs kg	Dynamic force on 1 disc g
Average	0.87	54.38	0.93	58.13
Maximum	1.25	78.13	1.53	95.63
Minimum	0.48	30.00	0.54	33.75

Table 206. Granite 2mm. Fixed ore flow rate, auger speed 44 rpm. Variable elevator speed of 2.5, 3.0, and 3.5 m/s.

Granite 2mm	Run number 37 Sample number 27					
	Ore bin speed fixed at 44 RPM					
Results observation time period 24hour	13:43:10 to13:43:20		13:44:00 to13:44:10		13:44:40 to 13:44:50	
Elevator speed	100rpm. 2.5m/s		120rpm. 3.0 m/s		140 rpm. 3.5 m/s	
	Ore on 19discs kg	Ore on 1 disc g	Ore on 19discs kg	Ore on 1 disc g	Ore on 19discs kg	Ore on 1 disc g
Average	36.48	1920.00	28.84	1517.89	24.92	1311.58
Maximum	37.71	1984.74	30.33	1596.32	27.43	1443.68
Minimum	34.42	1811.16	27.65	1455.26	23.43	1233.16
	Dynamic force on 16 discs kg	Dynamic force on 1 disc g	Dynamic force on 16 discs kg	Dynamic force on 1 disc g	Dynamic force on 16 discs kg	Dynamic force on 1 disc g
Average	6.33	395.63	4.35	271.88	3.29	205.63
Maximum	7.06	441.25	4.93	308.13	4.61	288.13
Minimum	5.60	350.00	3.93	245.63	2.92	182.50

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Table 207. Gravel 2mm. Fixed ore flow rate, auger speed 22 rpm. Variable elevator cable speed of 2.0, 2.5, 3.0 and 3.5 m/s

Gravel 2mm	Run number 915 Sample number 411							
Elevator Speed	80 rpm 2.0 m/s		100 rpm 2.5 m/s		120 rpm 3.0 m/s		140 rpm 3.5 m/s	
Ore bin speed	22 rpm		22 rpm		22 rpm		22 rpm	
Results observation time period 24hour	13:46:55 to 13:47:10		13:48:00 to 13:48:15		13:50:30 to 13:50:45		13:52:50 to 13:53:05	
	Ore on 19 discs kg	Ore on 1 disc g	Ore on 19 discs kg	Ore on 1 disc g	Ore on 19 discs kg	Ore on 1 disc g	Ore on 19 discs kg	Ore on 1 disc g
Average	20.26	1066.32	14.23	750.00	10.38	546.32	7.94	417.89
Maximum	20.53	1080.53	14.71	774.21	10.71	563.68	8.47	445.79
Minimum	20.00	1052.63	13.65	718.42	9.53	501.58	7.28	383.16
	Dynamic force on 16 discs kg	Dynamic force on 1 disc g	Dynamic force on 16 discs kg	Dynamic force on 1 disc g	Dynamic force on 16 discs kg	Dynamic force on 1 disc g	Dynamic force on 16 discs kg	Dynamic force on 1 disc g
Average	3.71	231.88	1.20	75.00	0.46	28.75	0.29	18.13
Maximum	4.64	290.00	1.70	106.25	0.95	59.38	0.56	35.00
Minimum	2.99	186.88	0.67	41.88	0.17	10.63	0.01	0.63

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Table 208. Granite 2mm. Fixed ore flow rate, auger speed 22 rpm. Variable elevator cable speed of 2.0, 3.0 and 3.5 m/s.

Granite 2mm	Run Number 919 sample number 414		Run number 921, sample number 415			
Elevator Speed	80 rpm 2.0 m/s		120 rpm 3.0 m/s		140 rpm 3.5m/s	
Ore bin speed	22 rpm		22 rpm		22 rpm	
Results observation time period 24hour						
	Ore on 19 discs kg	Ore on 1 disc g	Ore on 19 discs kg	Ore on 1 disc g	Ore on 19 discs kg	Ore on 1 disc g
Average	44.59	2346.84	11.73	613.74	9.57	503.68
Maximum	48.17	2535.26	12.61	663.68	10.09	531.05
Minimum	40.76	2145.26	11.07	582.63	9.16	482.11
	Dynamic force on 16 discs kg	Dynamic force on 1 disc g	Dynamic force on 16 discs kg	Dynamic force on 1 disc g	Dynamic force on 16 discs kg	Dynamic force on 1 disc g
Average	7.91	449.38	0.93	58.13	0.99	61.88
Maximum	12.14	758.75	2.43	151.88	1.45	90.63
Minimum	0.97	60.63	0.21	13.13	0.60	37.50

Table 209 Gravel 2mm. Elevator cable speed at 3.0 m/s. Variable ore flow rate, auger speed settings at 11, 22, 33, and 44 rpm

Gravel 2mm	Run number 916 Sample number 412							
Elevator Speed	120 rpm 3.0 m/s		120 rpm 3.0 m/s		120 rpm 3.0 m/s		120 rpm 3.0 m/s	
Ore bin speed	11 rpm		22 rpm		33 rpm		44 rpm	
Results observation time period 24hour	14:02:00 to 14:02:15		14:05:00 to 14:05:15		14:07:45 to 14:08:00		14:09:45 to 14:10:00	
	Ore on 19 discs kg	Ore on 1 disc g	Ore on 19 discs kg	Ore on 1 disc g	Ore on 19 discs kg	Ore on 1 disc g	Ore on 19 discs kg	Ore on 1 disc g
Average	5.52	290.52	11.28	593.68	18.23	959.47	23.83	1254.21
Maximum	5.95	313.16	11.81	621.58	18.64	981.05	24.60	1294.74
Minimum	4.96	261.05	10.47	551.05	17.69	931.05	23.17	1219.47
	Dynamic force on 16 discs kg	Dynamic force on 1 disc g	Dynamic force on 16 discs kg	Dynamic force on 1 discs g	Dynamic force on 16 discs kg	Dynamic force on 1 disc g	Dynamic force on 16 discs kg	Dynamic force on 1 disc g
Average	0.84	52.50	1.23	76.88	2.67	166.88	4.49	280.63
Maximum	1.17	73.13	1.57	98.13	3.17	198.13	5.98	373.75
Minimum	0.58	36.25	0.94	58.75	2.07	129.38	3.03	189.38

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APPENDIX 3

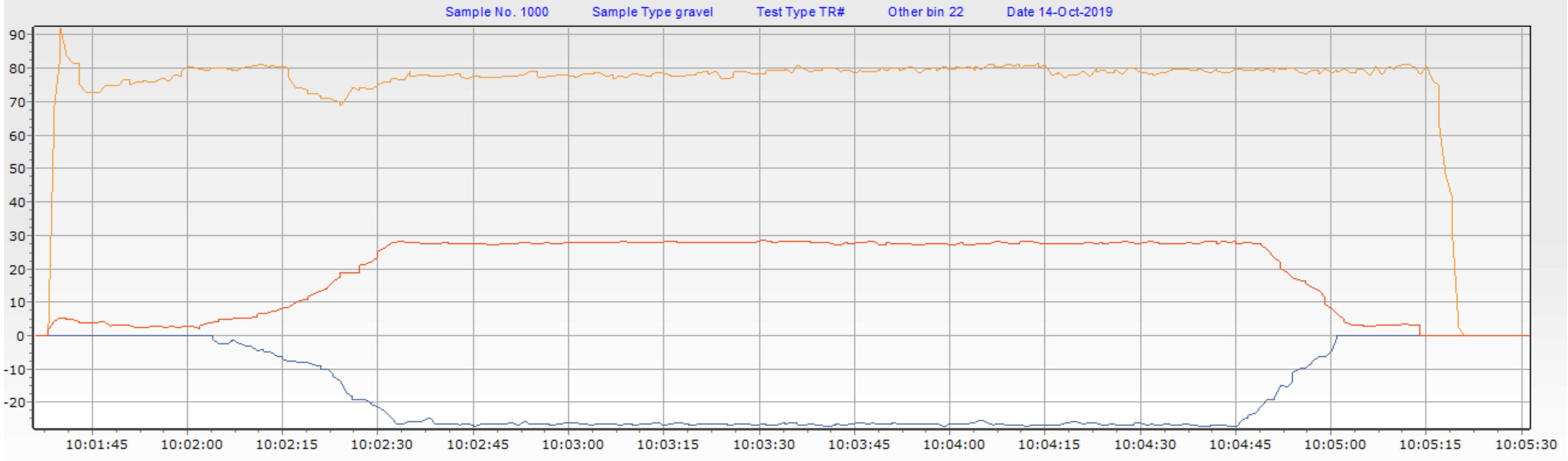
Table 210. Coal 2mm. Elevator cable speed at 3.0 m/s. Variable ore flow rate, auger speed settings at 11, 22, 33, and 44 rpm.

Coal 2mm	Run number 924 Sample number 418							
Elevator Speed	120 rpm 3.0 m/s		120 rpm 3.0 m/s		120 rpm 3.0 m/s		120 rpm 3.0 m/s	
Ore bin speed	11 rpm		22 rpm		33 rpm		44 rpm	
Results observation time period 24hour	13:47:00 to 13:47:15		13:48:30 to 13:48:45		13:50:15 to 13:50:30		13:51:30 to 13:51:45	
	Ore on 19 discs kg	Ore on 1 disc g	Ore on 19 discs kg	Ore on 1 disc g	Ore on 19 discs kg	Ore on 1 disc g	Ore on 19 discs kg	Ore on 1 disc g
Average	2.92	153.68	4.63	243.68	13.02	685.26	17.98	946.32
Maximum	3.32	174.74	5.18	272.63	13.61	716.32	19.10	1005.26
Minimum	2.56	134.74	4.30	226.32	12.24	644.21	17.11	900.53
	Dynamic force on 16 discs kg	Dynamic force on 1 disc g	Dynamic force on 16 disc kg	Dynamic force on 1 disc g	Dynamic force on 16 discs kg	Dynamic force on 1 disc g	Dynamic force on 16 discs kg	Dynamic force on 1 disc g
Average	0.26	16.25	0.24	15.00	0.49	30.63	0.39	24.38
Maximum	0.73	45.63	0.56	35.00	1.10	68.75	0.77	48.13
Minimum	0.01	0.63	0.08	5.00	0.06	3.75	0.02	1.25

Table 211. Fixed ore flow rate, auger set at 22 rpm. Variable elevator cable speed of 2.0, 2.5, 3.0 and 3.5 m/s.

Coal 2mm	Run number 923 Sample number 417							
Elevator Speed	80 rpm 2 m/s		100 rpm 2.5 m/s		120 rpm 3.0 m/s		140 rpm 3.5 m/s	
Ore bin speed	22 rpm		22 rpm		22 rpm		22 rpm	
Results observation time period 24hour	13:35:55 to 13:36:10		13:36:40 to 13:36:55		13:37:40 to 13:37:55		13:38:35 to 13:38:50	
	Ore on 19 discs kg	Ore on 1 disc g	Ore on 19 discs kg	Ore on 1 disc g	Ore on 19 discs kg	Ore on 1 disc g	Ore on 19 discs kg	Ore on 1 disc g
Average	18.10	952.63	12.50	657.89	4.85	255.26	2.63	138.42
Maximum	20.35	1071.05	12.89	678.42	5.04	265.26	3.05	160.53
Minimum	13.50	710.53	11.82	622.11	4.42	232.63	2.03	106.84
	Dynamic force on 16 discs kg	Dynamic force on 1 disc g	Dynamic force on 16 discs kg	Dynamic force on 1 discs g	Dynamic force on 16 discs kg	Dynamic force on 1 disc g	Dynamic force on 16 discs kg	Dynamic force on 1 disc g
Average	0.45	28.13	0.39	24.38	0.45	28.13	0.24	15.00
Maximum	0.63	39.38	0.88	55.00	0.85	53.13	0.69	43.13
Minimum	0.15	9.38	0.00	0.00	0.01	0.63	0.01	0.63

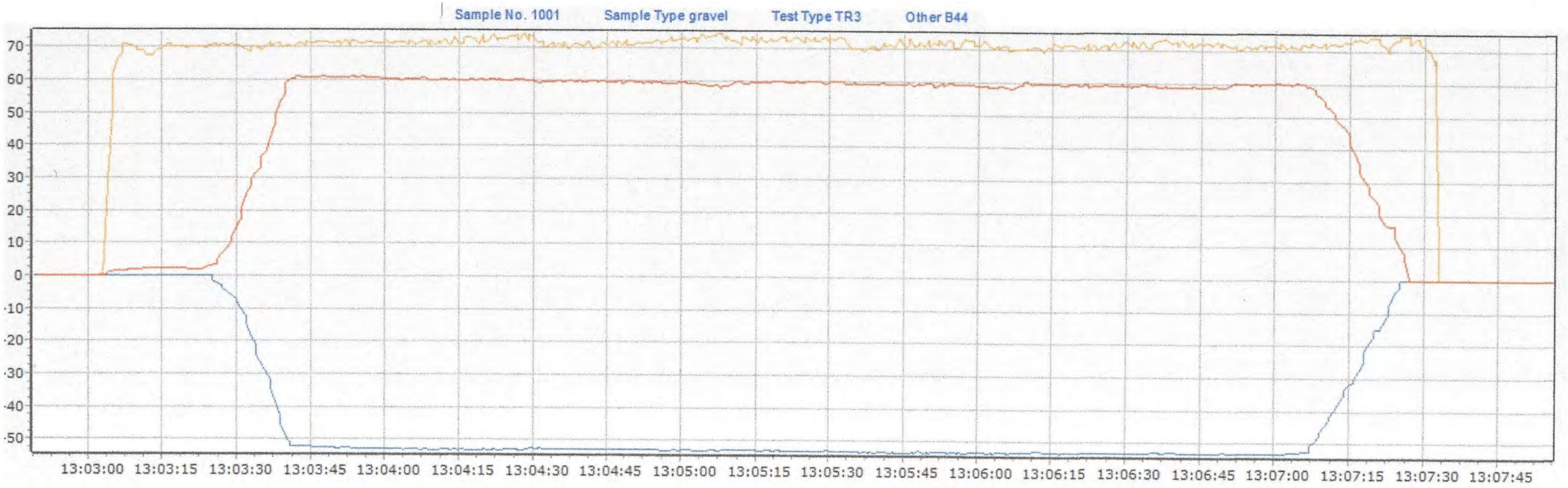
APPENDIX 4
Tables and graphs for Test Rig 3. Table and graph numbers 400-423.



Graph 400 Run 81 ungraded gravel, ore bin speed22, elevator speed 2.0 m/s.

Table 400. Ungraded gravel, data from run 81, elevator tension's and ore weight

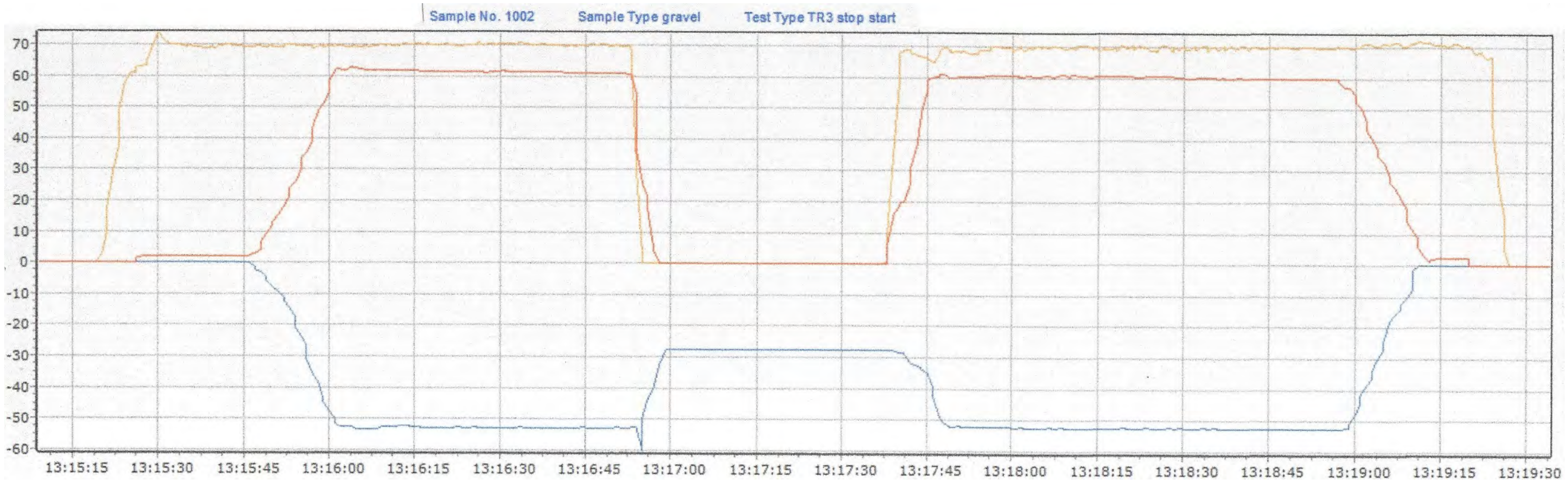
Elevator speed m/s	2.0
Time of measurement	10.03.30 – 10.04.15
Cable disc elevator tension kg	27.55
Cable disc elevator tension N	270.27
Ore bin kg	26.49
Ore bin N	259.87
Pipe conveyor tension kg	79.21
Pipe conveyor tension N	777.05



Graph 401. Run 110 gravel, ore bin speed 44, elevator speed 2.0 m/s.

Table 401. Ungraded gravel, data from run 110, elevator tension's and ore weight.

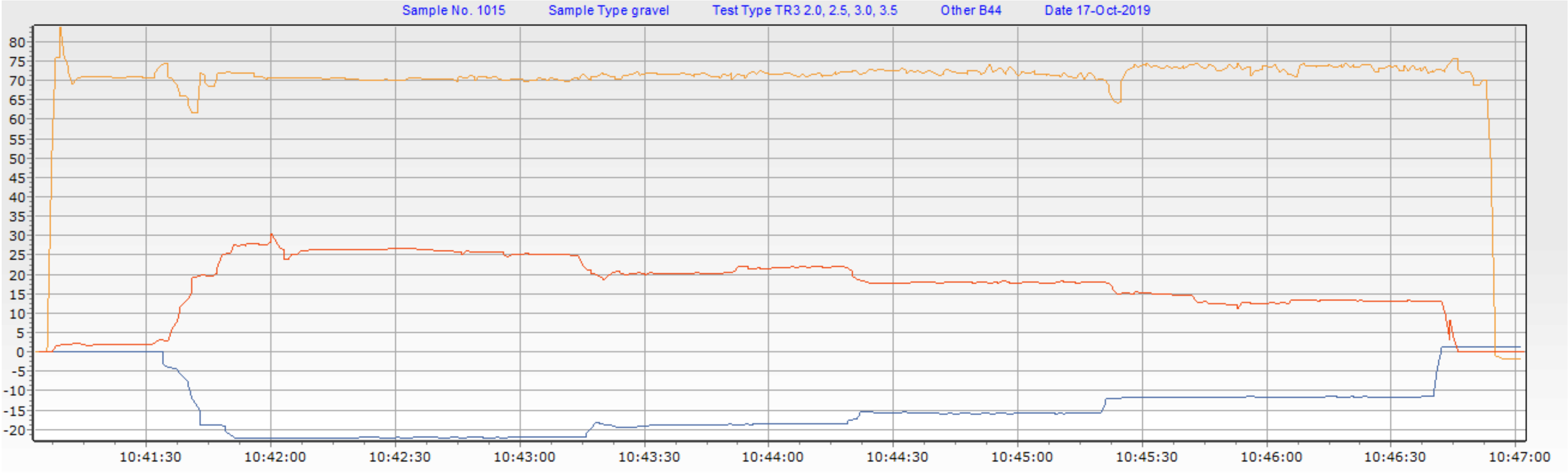
Elevator speed m/s	2.0
Time of measurement	13.05.00 – 13.06.00
Cable disc elevator tension kg	59.72
Cable disc elevator tension N	585.85
Ore bin kg	52.36
Ore bin N	513.65
Pipe conveyor tension kg	73.84
Pipe conveyor tension N	724.37



Graph 402. Run 111 gravel, ore bin speed 44, elevator speed 2.0 m/s. stop start test.

Table 402. Gravel, data from run 111, elevator tension's and ore weight

Elevator speed m/s	2.0		
Time of measurement	13.16.10 – 13.16.45	13.17.05 – 13.17315	13.18.00 - .13.18.45
Cable disc elevator tension kg	61.58	0.05	60.68
Cable disc elevator tension N	604.10	0.49	595.27
Ore bin kg	52.88	27.44	52.68
Ore bin N	518.75	269.19	516.79
Pipe conveyor tension kg	70.77	0.11	69.81
Pipe conveyor tension N	694.25	3.33	684.84



Graph 403. Run 107, gravel, ore bin speed 22. Elevator speed 2.0, 2.5, 3.0 and 3.5 m/s.

Table 403. Gravel, data from run 107, elevator tension's and ore weight

Elevator speed m/s	2.0	2.5	3.0	3.5
Time of measurement	10.42.00 – 10.42.45	10.43.30 – 10.44.15	10.44.30 – 10.45.15	10.45.30 – 10.46.15
Cable disc elevator tension kg	26.42	20.59	17.74	13.47
Cable disc elevator tension N	259.18	201.99	174.03	132.14
Ore bin kg	22.05	18.62	15.62	11.61
Ore bin N	216.31	182.66	153.23	113.89
Pipe conveyor tension kg	70.39	71.56	72.36	73.18
Pipe conveyor tension N	690.53	702.00	709.85	717.90

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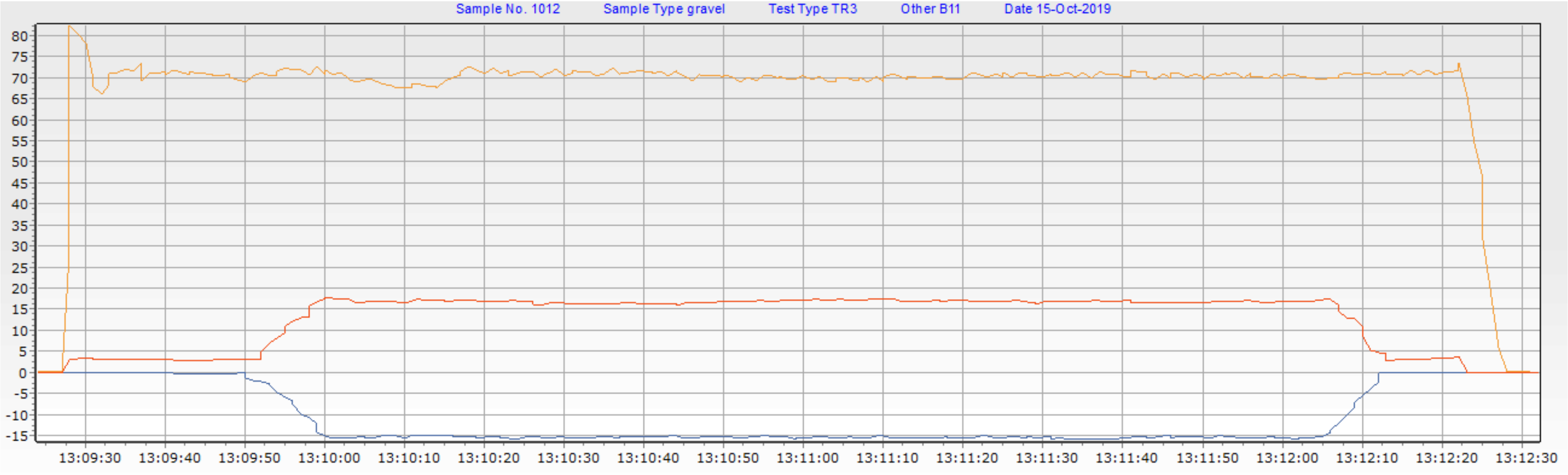
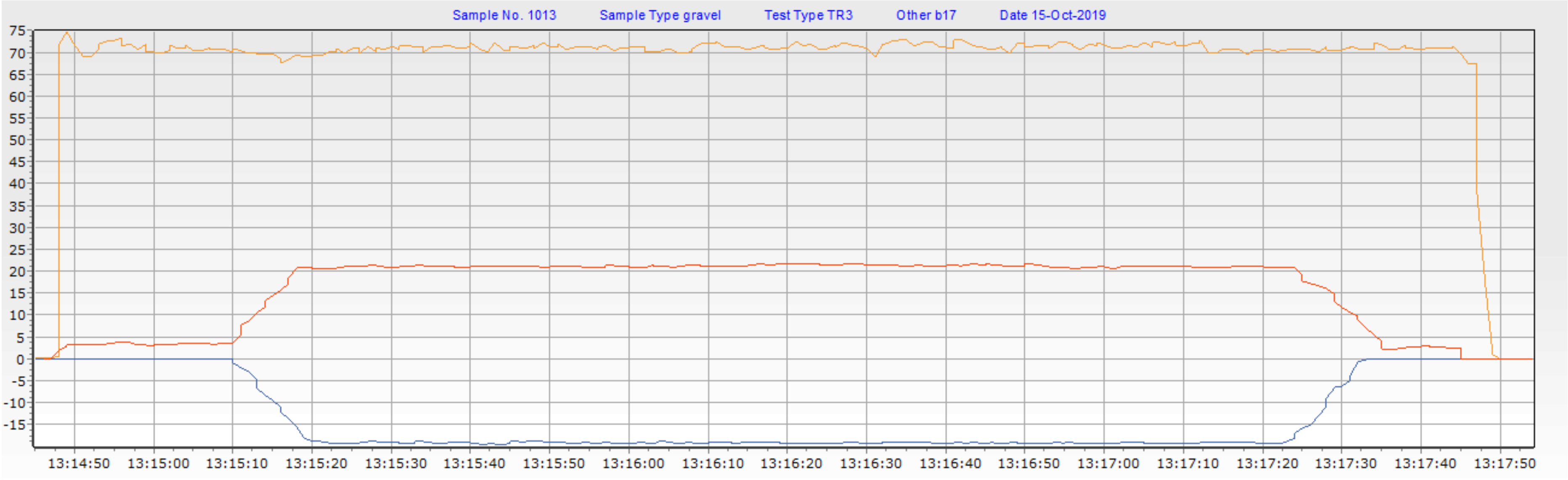


Graph 404. Run 91, ungraded gravel, ore bin speed 11, elevator speed 2.0 m/s.

Table 404. Gravel, data from run 91, elevator tension’s and ore weight.

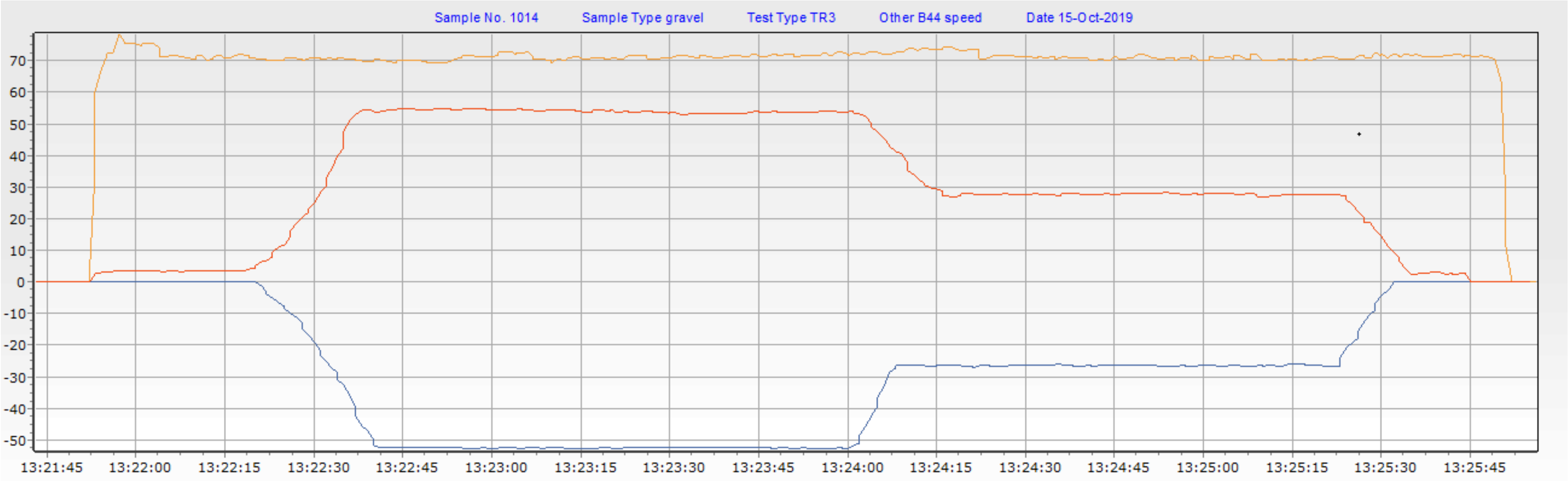
Elevator speed m/s	2.0
Time of measurement	13.10.50 – 13.11.35
Cable disc elevator tension kg	17.01
Cable disc elevator tension N	166.87
Ore bin kg	15.21
Ore bin N	149.21
Pipe conveyor tension kg	69.93
Pipe conveyor tension N	686.01



Graph 405. Run 92, gravel, ore bin speed 17, elevator speed 2.0m/s.

Table 405. Gravel, data from run 92, elevator tension’s and ore weight.

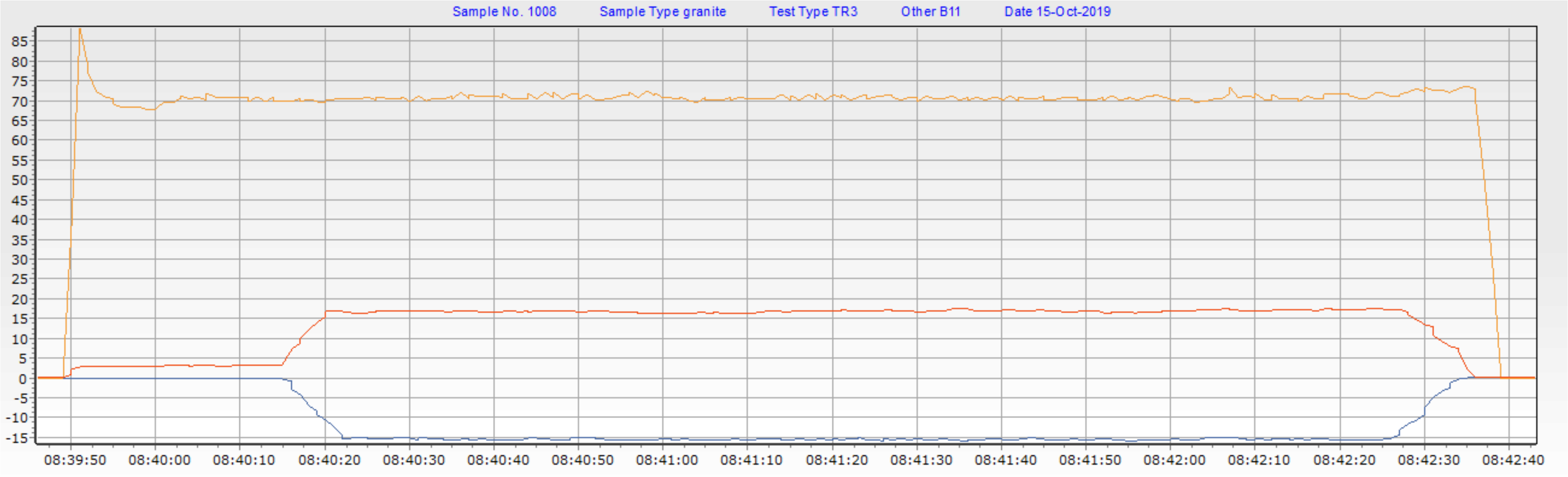
Elevator speed m/s	2.0
Time of measurement	13.16.00 – 13.16.45
Cable disc elevator tension kg	21.34
Cable disc elevator tension N	209.35
Ore bin kg	19.16
Ore bin N	187.96
Pipe conveyor tension kg	71.18
Pipe conveyor tension N	698.27



Graph 406. Run 93, Gravel, ore bin speed 44, elevator speeds 2.0, 3.5 m/s

Table 406. Gravel, data from run 93, elevator tension's and ore weight.

Elevator speed m/s	2.0	3.5
Time of measurement	13.23.15 – 13.24.00	13.24.30 – 13.25.15
Cable disc elevator tension kg	53.67	27.85
Cable disc elevator tension N	526.50	273.21
Ore bin kg	52.34	26.36
Ore bin N	513.46	258.59
Pipe conveyor tension kg	71.55	71.01
Pipe conveyor tension N	701.91	696.61



Graph 407. Run 88, granite, ore bin speed 11, elevator speed 2.0 m/s.

Table. 407 Granite, data from run 88, elevator tension’s and ore weight

Elevator speed m/s	2.0
Time of measurement	8.41.10 – 8.41.55
Cable disc elevator tension kg	17.13
Cable disc elevator tension N	168.05
Ore bin kg	15.58
Ore bin N	152.84
Pipe conveyor tension kg	70.82
Pipe conveyor tension N	694.74

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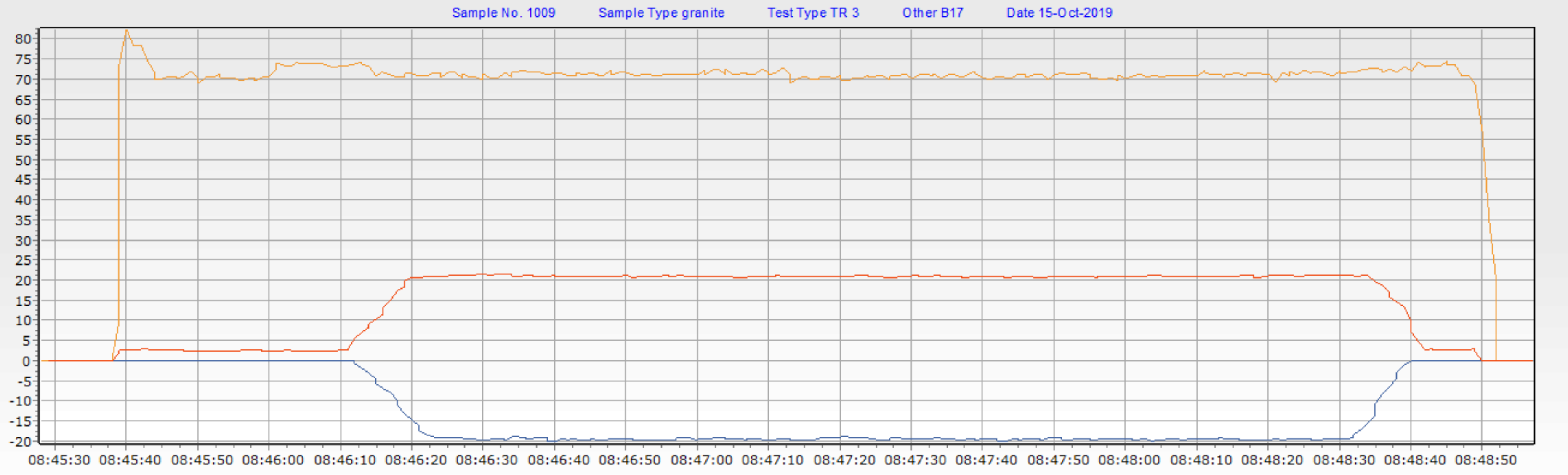
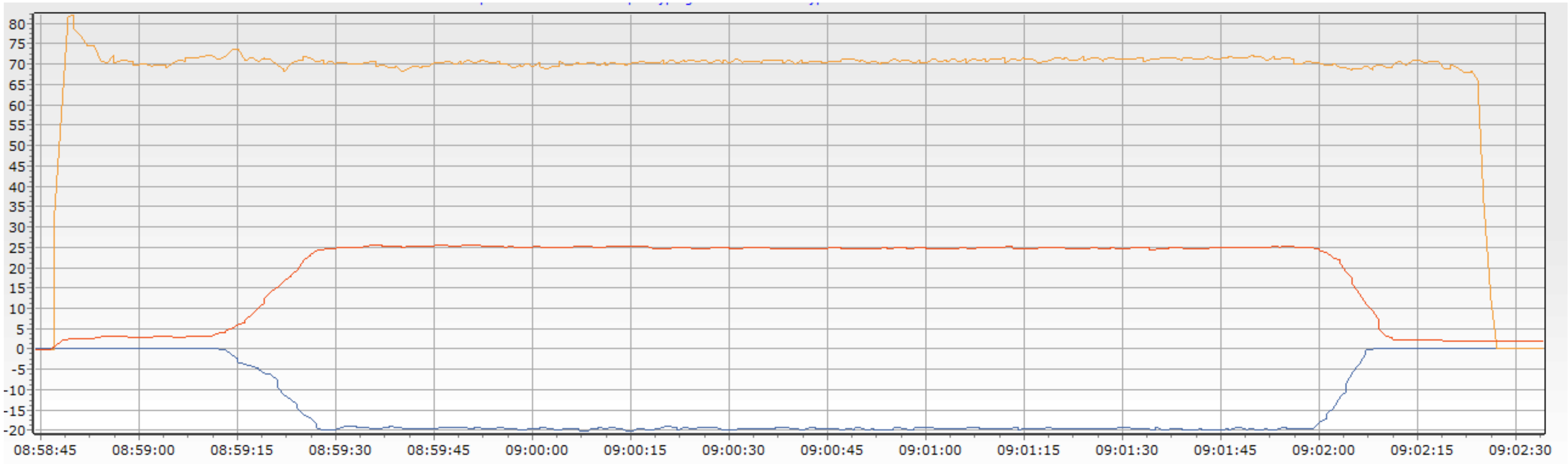


Graph 408. Run 89, granite, ore bin speed 17, elevator speed 2.0 m/s.

Table 408. Granite, data from run 89, elevator tension’s and ore weight.

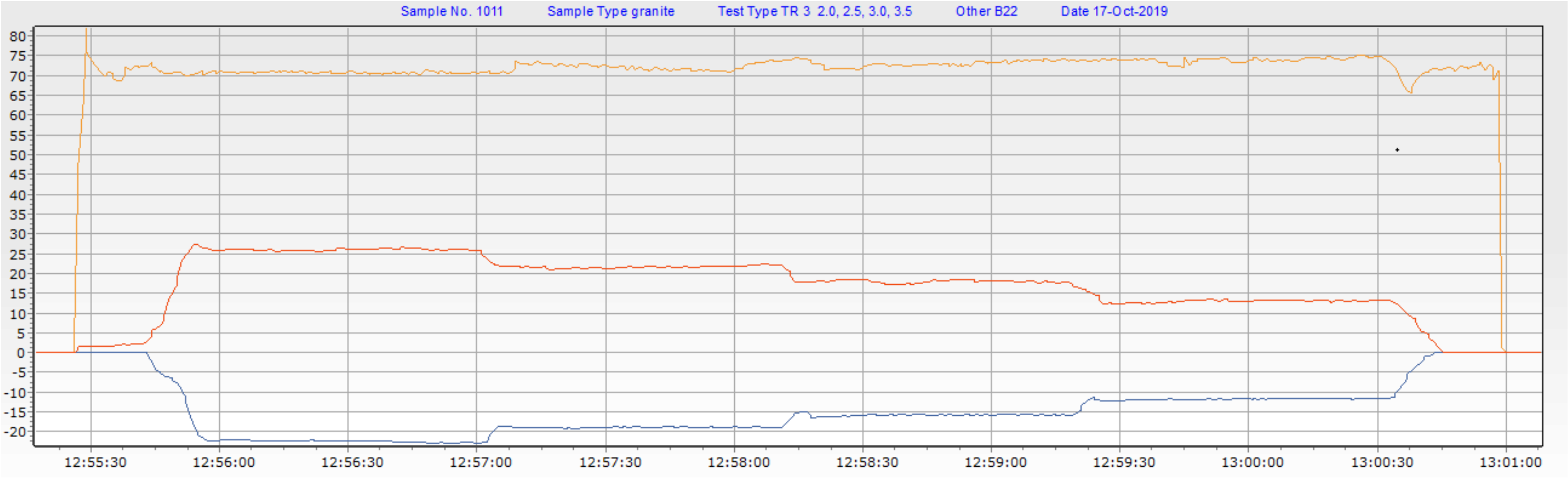
Elevator speed m/s	2.0
Time of measurement	8.47.20 – 8.48.05
Cable disc elevator tension kg	20.95
Cable disc elevator tension N	205.52
Ore bin kg	19.28
Ore bin N	189.14
Pipe conveyor tension kg	70.98
Pipe conveyor tension N	696.31



Graph 409. Run 90, granite, ore bin speed 22, elevator speed 2.0 m/s.

Table 409. Granite, data from run 90, elevator tension's and ore weight.

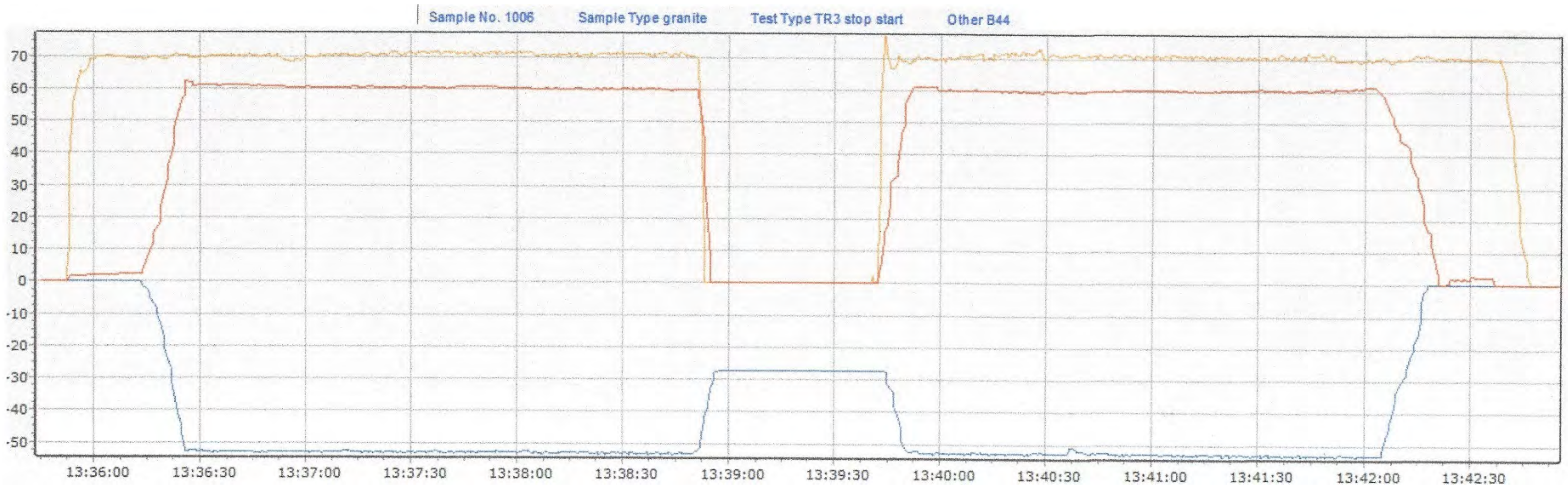
Elevator speed m/s	2.0
Time of measurement	9.00.30 – 9.01.15
Cable disc elevator tension kg	24.55
Cable disc elevator tension N	240.36
Ore bin kg	19.74
Ore bin N	193.65
Pipe conveyor tension kg	70.71
Pipe conveyor tension N	693.67



Graph 410. Run 108, granite, ore bin speed 22, elevator speeds 2.0, 2.5, 3.0, 3.5 m/s.

Table 410. Granite, data from run 108, elevator tension’s and ore weight

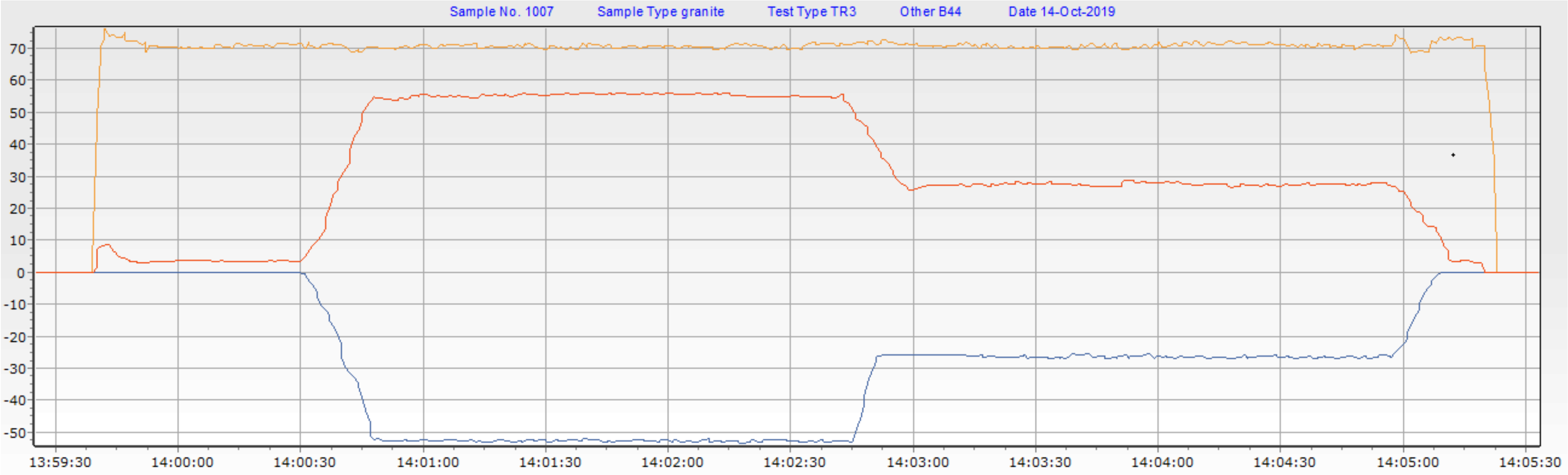
Elevator speed m/s	2.0	2.5	3.0	3.5
Time of measurement	12.56.00 – 12.56.45	12.57.15 – 12.58.00	12.58.30 – 12.59.15	12.59.30 – 13.00.15
Cable disc elevator tension kg	25.93	21.62	17.99	12.89
Cable disc elevator tension N	254.37	212.09	176.48	126.45
Ore bin kg	22.17	18.81	15.69	11.74
Ore bin N	217.49	184.53	153.92	115.17
Pipe conveyor tension kg	70 56	72.01	72.73	73.68
Pipe conveyor tension N	629.19	706.42	713.48	722.80



Graph 411. Run 113, granite, ore bin speed 44, elevator speed 2.0 m/s. Stop start test.

Table 411. Granite, data from run 113, elevator tension's and ore weight

Elevator speed m/s	2.0	0.0	2.0
Time of measurement	13.37.30 – 13.38.30	13.39.00 – 13.39.45	13.40.30 – 13.41.45
Cable disc elevator tension kg	60.46	0.05	59.95
Cable disc elevator tension N	593.11	0.49	588.11
Ore bin kg	52.33	26.15	52.45
Ore bin N	513.36	256.53	514.53
Pipe conveyor tension kg	71.46	0.01	71.32
Pipe conveyor tension N	701.02	0.10	699.65



Graph 412. Run 87, granite, ore bin speed 44, elevator speed 2.0 an 3.5 m/s.

Table. 412 Granite, data from run 87, elevator tension's and ore weight

Elevator speed m/s	2.0	3.5
Time of measurement	14.01.15 – 14.02.00	14.04.00 – 14.04.45
Cable disc elevator tension kg	55.42	27.72
Cable disc elevator tension N	543.67	271.93
Ore bin kg	52.67	26.53
Ore bin N	516.69	260.26
Pipe conveyor tension kg	70.35	71.67
Pipe conveyor tension N	690.13	703.08

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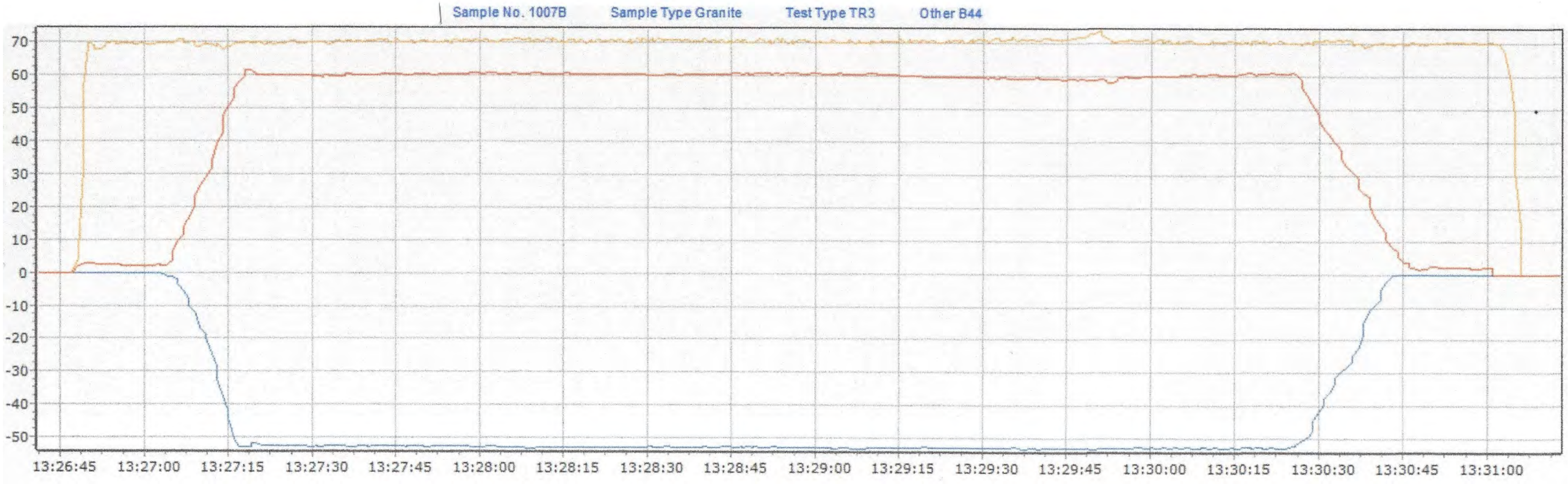
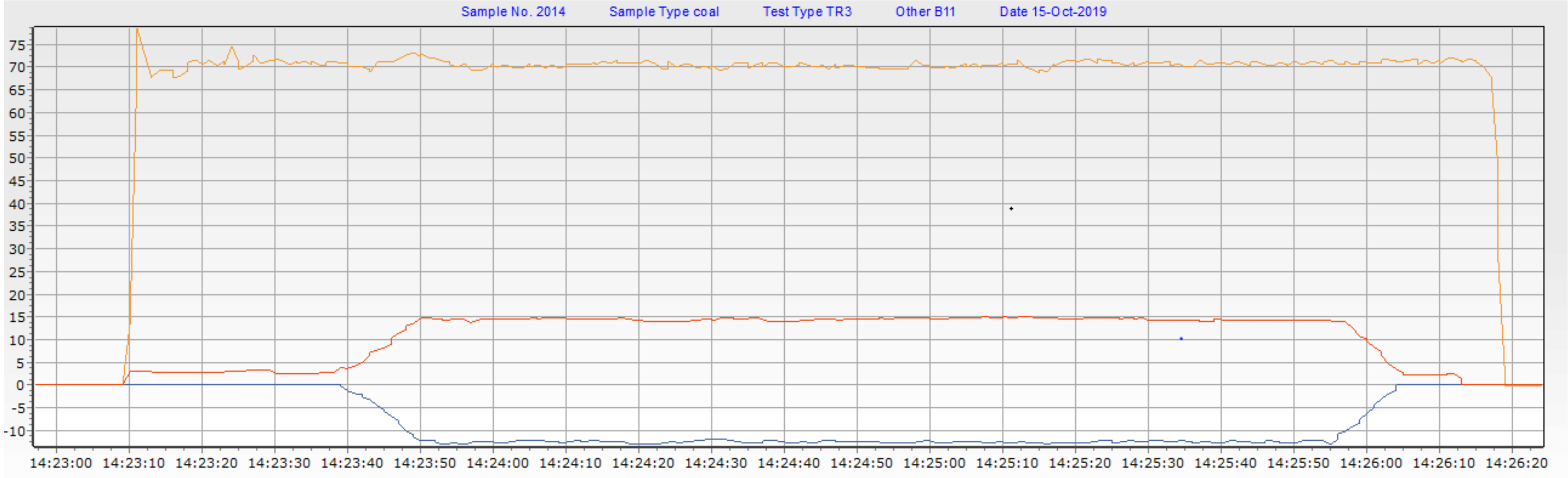


Graph 412B. Run 112B, granite, ore bin speed 44, elevator speed 2.0 m/s.

Table 412B.Granite, data from Graph 412B.

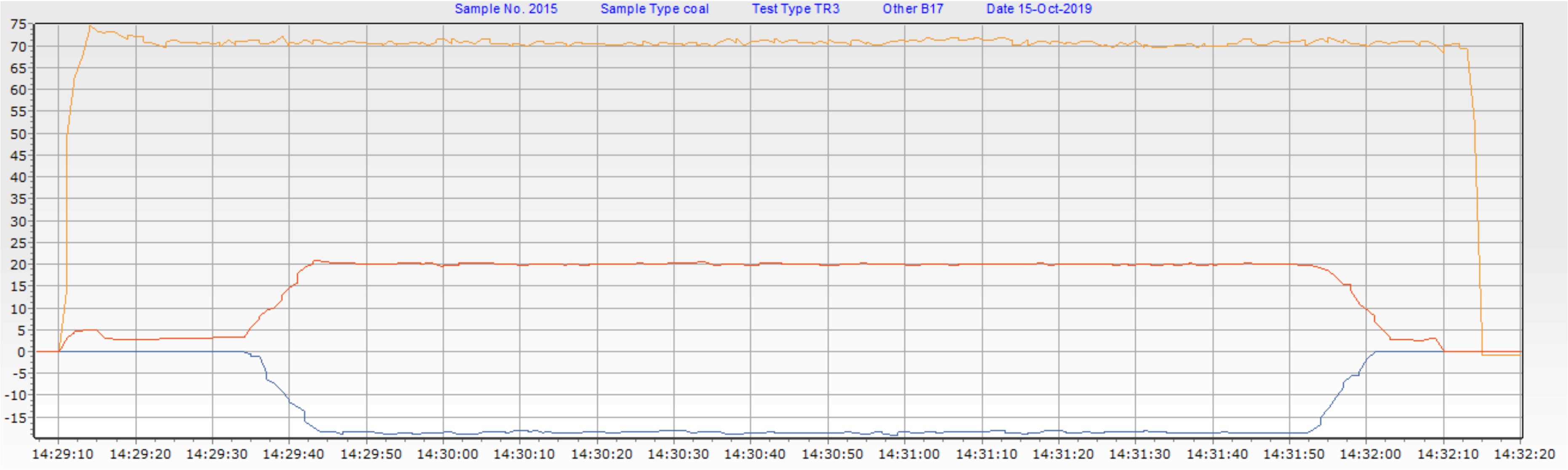
Elevator speed m/s	2.0
Time of measurement	13.28.15 – 13.29.30
Cable disc elevator tension kg	60.33
Cable disc elevator tension N	591.84
Ore bin kg	52.68
Ore bin N	516.79
Pipe conveyor tension kg	70.73
Pipe conveyor tension N	693.86



Graph 413. Run 94, coarse-coal ore bin speed 11, elevator speed 2.0 m/s.

Table 413.Coarse-coal, data from run 94, elevator tension’s and ore weight.

Elevator speed m/s	2.0
Time of measurement	14.24.15 – 14.25.00
Cable disc elevator tension kg	14.15
Cable disc elevator tension N	138.81
Ore bin kg	12.57
Ore bin N	123.31
Pipe conveyor tension kg	70.38
Pipe conveyor tension N	690.42



Graph 414. Run 95, coarse-coal, ore bin speed 17, elevator speed 2.0 m/s.

Table 414. Coarse-coal, data from run 95, elevator tension's and ore weight

Elevator speed m/s	2.0
Time of measurement	14.30.20 – 14.31.05
Cable disc elevator tension kg	20.21
Cable disc elevator tension N	198.26
Ore bin kg	18.34
Ore bin N	179.92
Pipe conveyor tension kg	70.49
Pipe conveyor tension N	691.51

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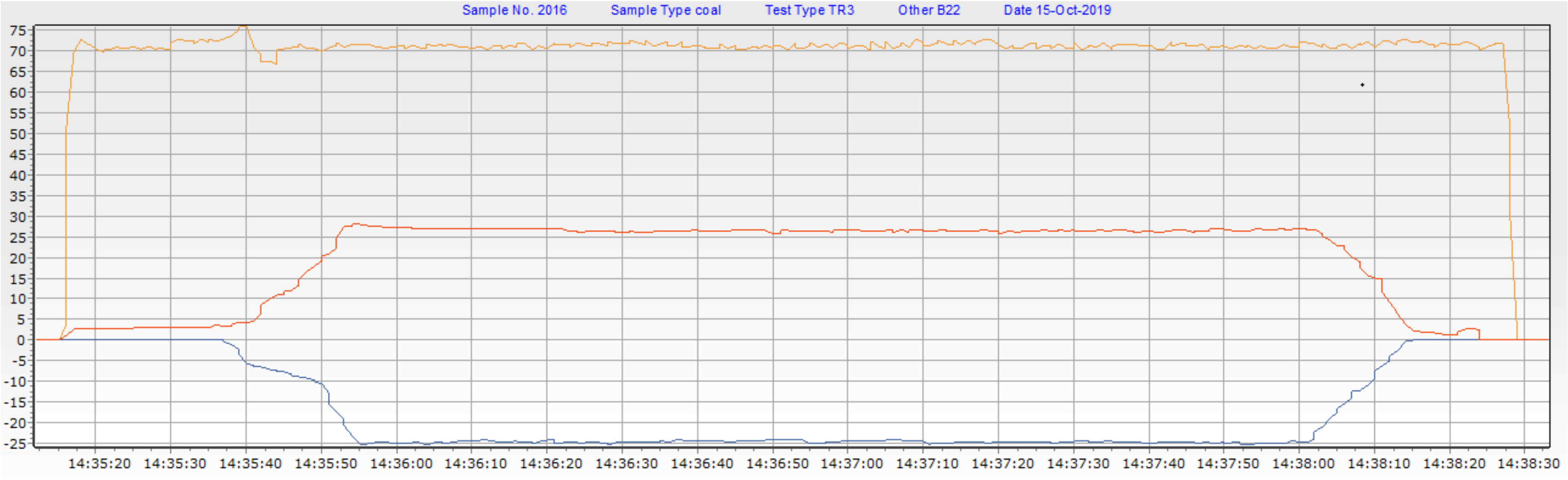
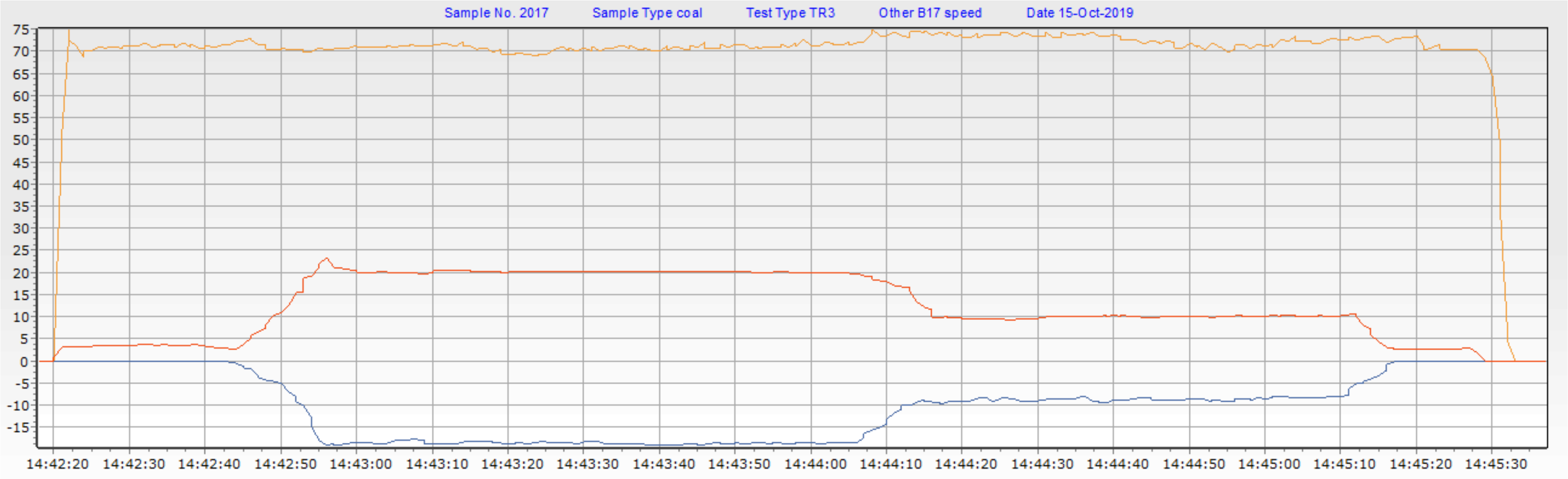


Graph 415. Run 96 coarse-coal, ore bin speed 22, elevator speed 2.0 m/s

Table 415. Coarse-coal, data from run 96, elevator tension's and ore weight.

Elevator speed m/s	2.0
Time of measurement	14.36.30 – 14.37.15
Cable disc elevator tension kg	26.58
Cable disc elevator tension N	260.75
Ore bin kg	24.32
Ore bin N	238.58
Pipe conveyor tension kg	71.10
Pipe conveyor tension N	697.49



Graph 416. Run 97, coarse-coal, ore bin speed 17, elevator speed 2.0 and 3.5 m/s.

Table 416. Coarse-coal, data from run 97, elevator tension’s and ore weight

Elevator speed m/s	2.0	3.5
Time of measurement	14.43.15 – 14.44.00	14.44.25 – 14.45.10
Cable disc elevator tension kg	20.26	10.11
Cable disc elevator tension N	198.75	99.71
Ore bin kg	18.53	8.23
Ore bin N	181.78	80.74
Pipe conveyor tension kg	70.14	72.71
Pipe conveyor tension N	688.07	713.29

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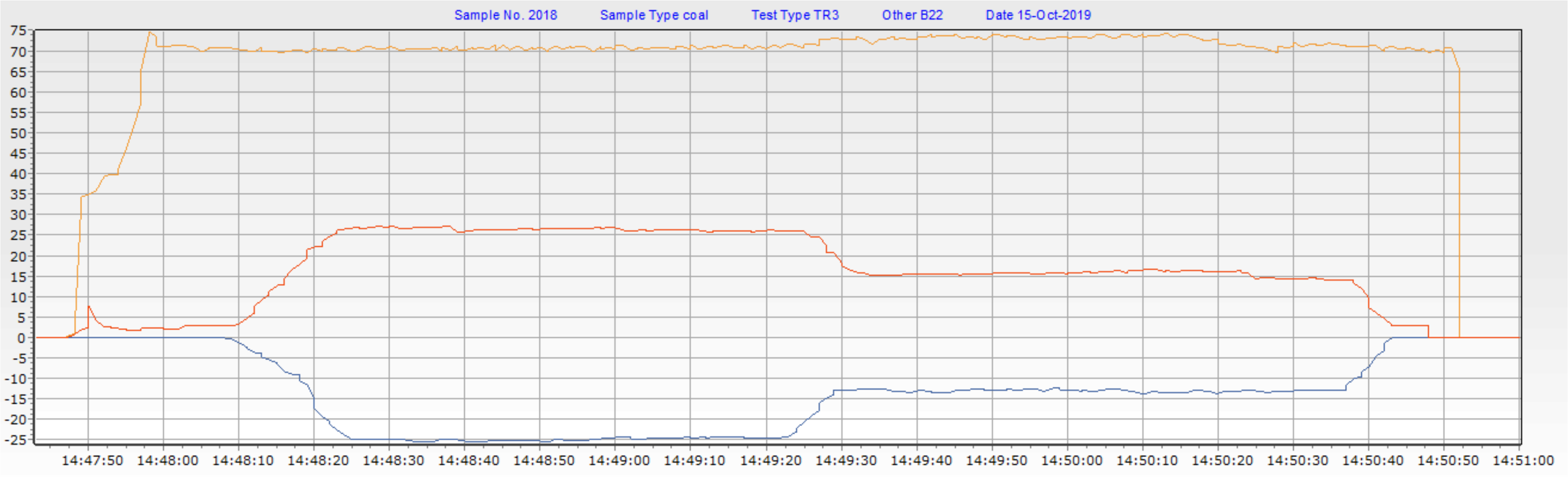

Graph 417. Run 98, coarse-coal, bin speed 22, Elevator speed 2.0 m/s.

Table 416. Coarse-coal, data from run 97, elevator tension's and ore weight

Elevator speed m/s	2.0	3.5
Time of measurement	14.48.40 – 14.49.25	14.49.40 – 14.50.25
Cable disc elevator tension kg	26.44	15.67
Cable disc elevator tension N	259.38	153.72
Ore bin kg	24.86	12.67
Ore bin N	243.88	124.92
Pipe conveyor tension kg	70.74	73.12
Pipe conveyor tension N	693.96	717.31

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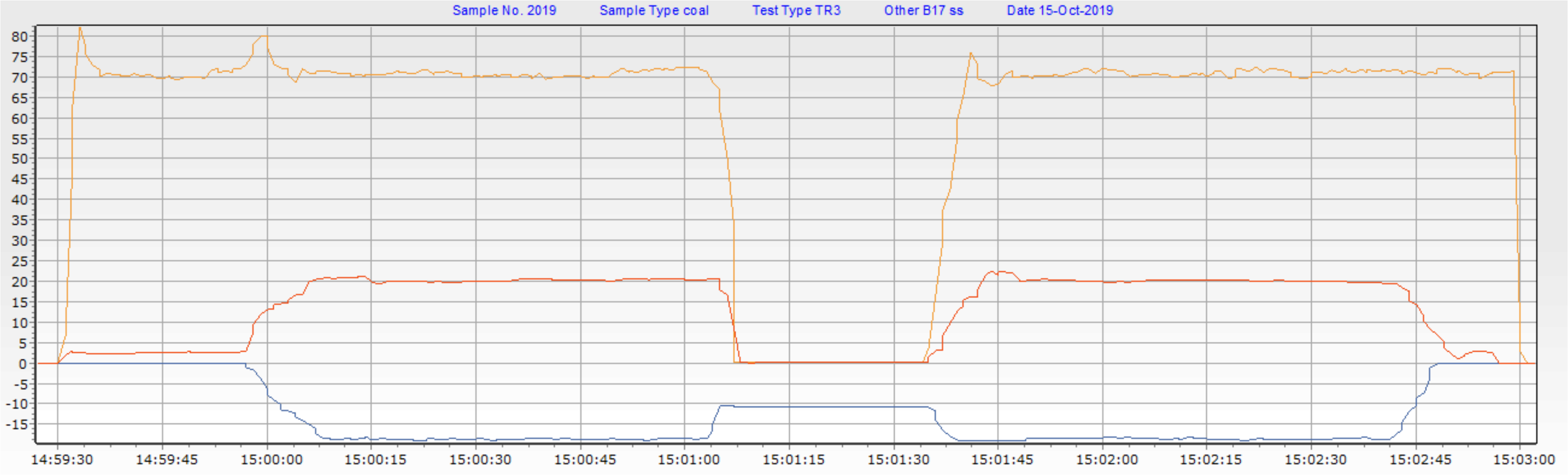
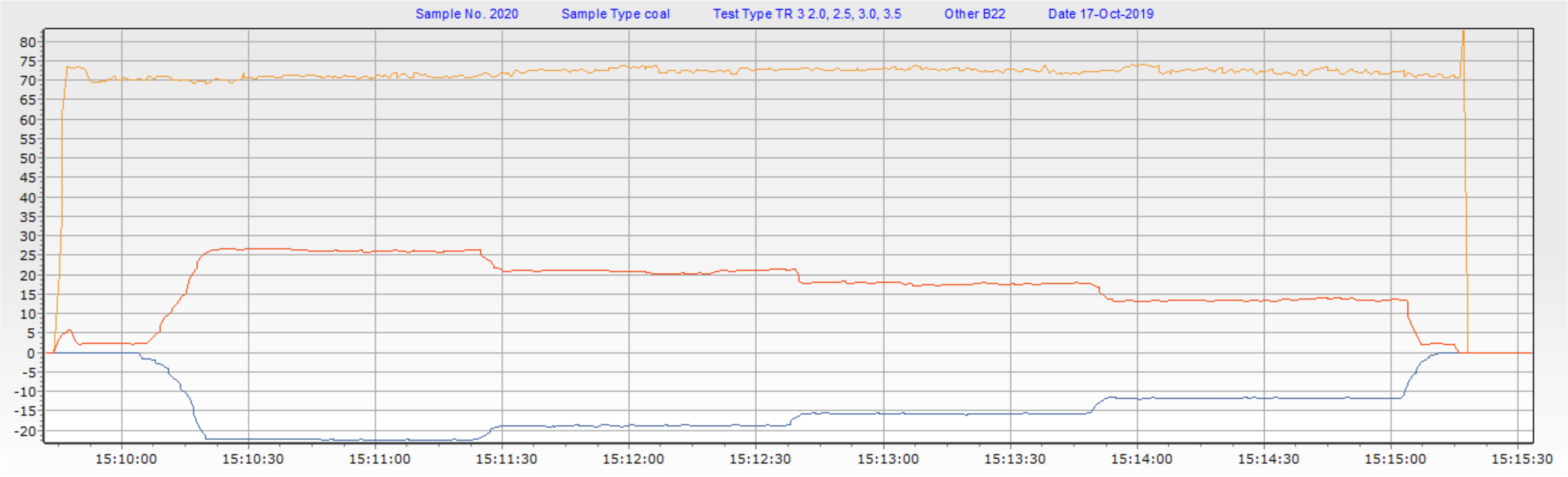


Graph 418. Run 99, coarse-coal, ore bin speed 17, stop start test.

Table 418. Coarse-coal, data from run 99, elevator tension’s and ore weight.

Elevator speed m/s	2.0	0.0	2.0
Time of measurement	15.00.15 – 15.01.00	15.01.10 – 15.01.35	15.01.50 – 15.01.35
Cable disc elevator tension kg	20.23	0.05	20.32
Cable disc elevator tension N	198.46	0.49	199.34
Ore bin kg	18.61	10.6	18.27
Ore bin N	182.56	103.99	179.23
Pipe conveyor tension kg	70.68	0.12	70.84
Pipe conveyor tension N	693.37	1.18	694.94



Graph 419. Run 109, coarse-coal, ore bin speed 22, elevator speed 2.0, 2.5, 3.0, and 3.5 m/s.

Table 419. Coarse-coal, data from run 109, elevator tension’s and ore weight

Elevator speed m/s	2.0	2.5	3.0	3.5
Time of measurement	15.10.30 – 15.11.15	15.11.40 – 15 12 25	15.12.40 – 15.13.25	15.14.00 – 15.14.45
Cable disc elevator tension kg	26.23	20.81	17.74	13.44
Cable disc elevator tension N	257.32	204.15	174.03	131.85
Ore bin kg	22.28	18.67	15.56	11.66
Ore bin N	218.57	183.15	152.64	114.38
Pipe conveyor tension kg	71.02	72.72	72.81	72.82
Pipe conveyor tension N	696.71	713.38	714.27	714.36

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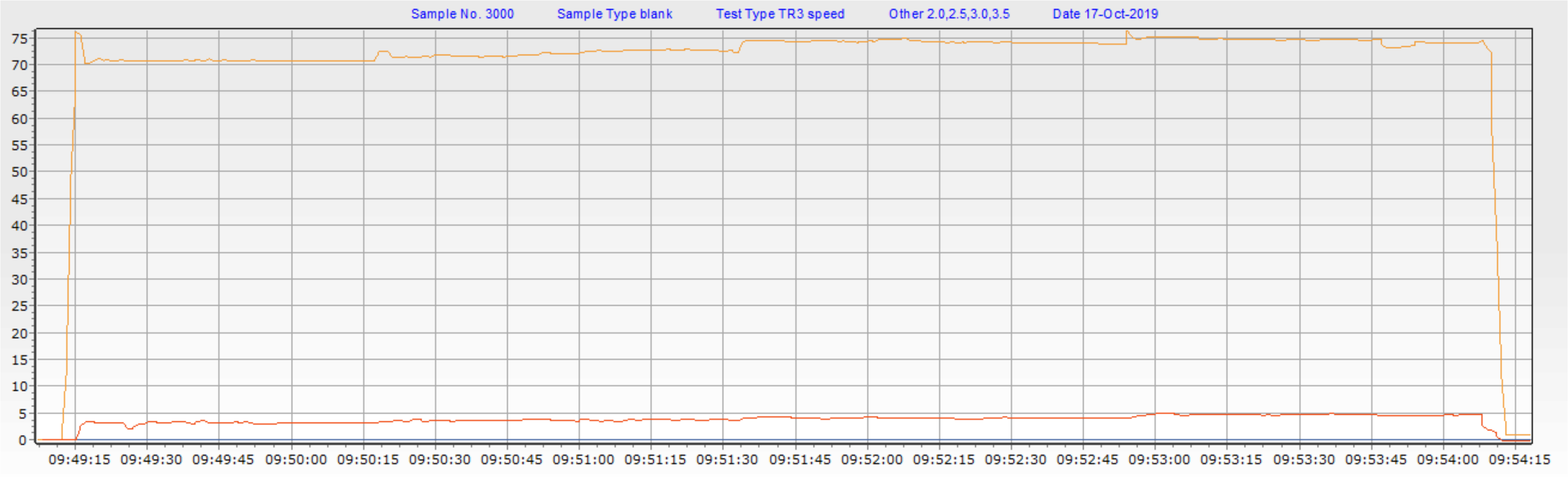

Graph 420. Run 100. No-ore. Elevator speed 2.0, 2.5, 3.0, and 3.5 m/s

Table 420. Data from run 100, elevator tension

Elevator speed m/s	2.0	2.5	3.0	3.5
Time of measurement	9.49.20 – 9.50.05	9.50.30 – 9.51.15	9.51.45 – 9.52.30	9.53.15 – 9.54 00
Cable disc elevator tension kg	3.01	3.67	4.06	4.77
Cable disc elevator tension N	29.53	36.00	39.83	46.79
Pipe conveyor tension kg	70.73	72.15	74.13	74.59
Pipe conveyor tension N	693.87	707.79	727.22	731.73

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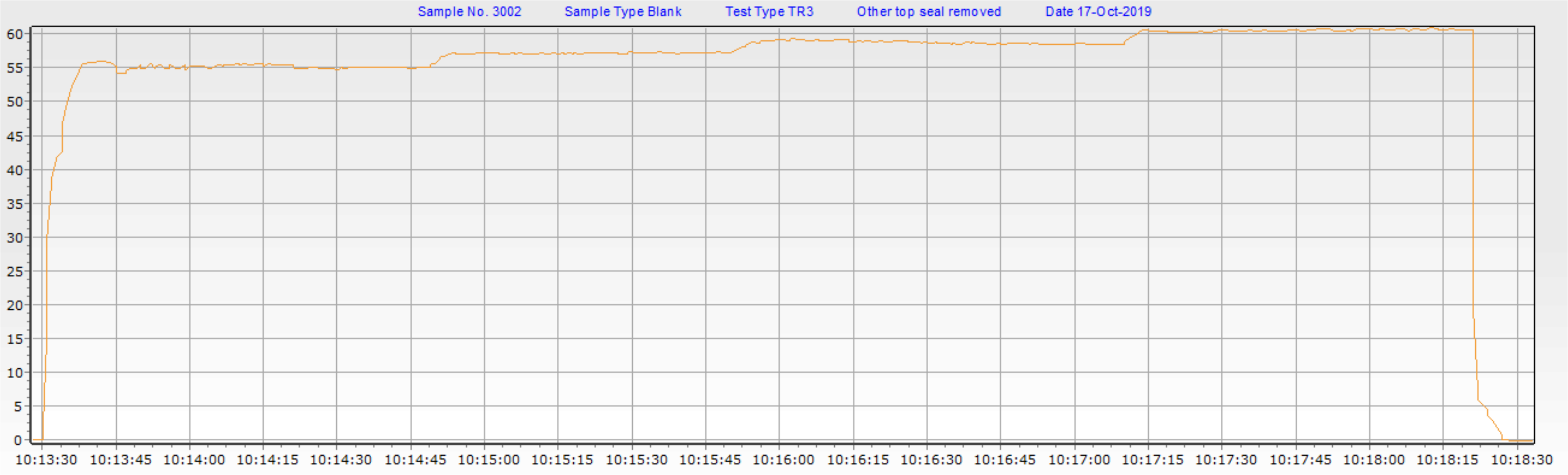

Graph 421. Run 105. No-ore and top seal removed. Elevator speed 2.0, 2.5, 3.0, and 3.5 m/s

Table 421. Data from run 105, elevator tension

Elevator speed m/s	2.0	2.5	3.0	3.5
Time of measurement	10.13.45 – 10.14.30	10.15.00 – 10.15.45	10.16.00 – 10.17.00	10.17.15 – 10.18.00
Pipe conveyor tension kg	54.33	57.11	58.99	60.44
Pipe conveyor tension N	532.98	560.25	578.69	592.92

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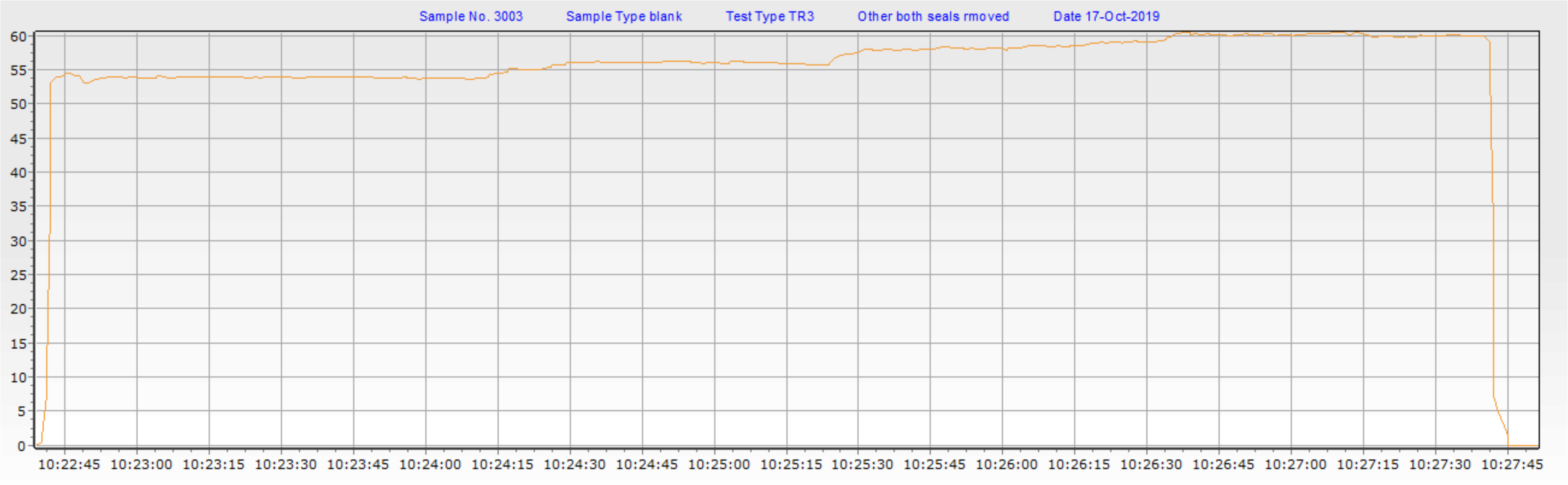
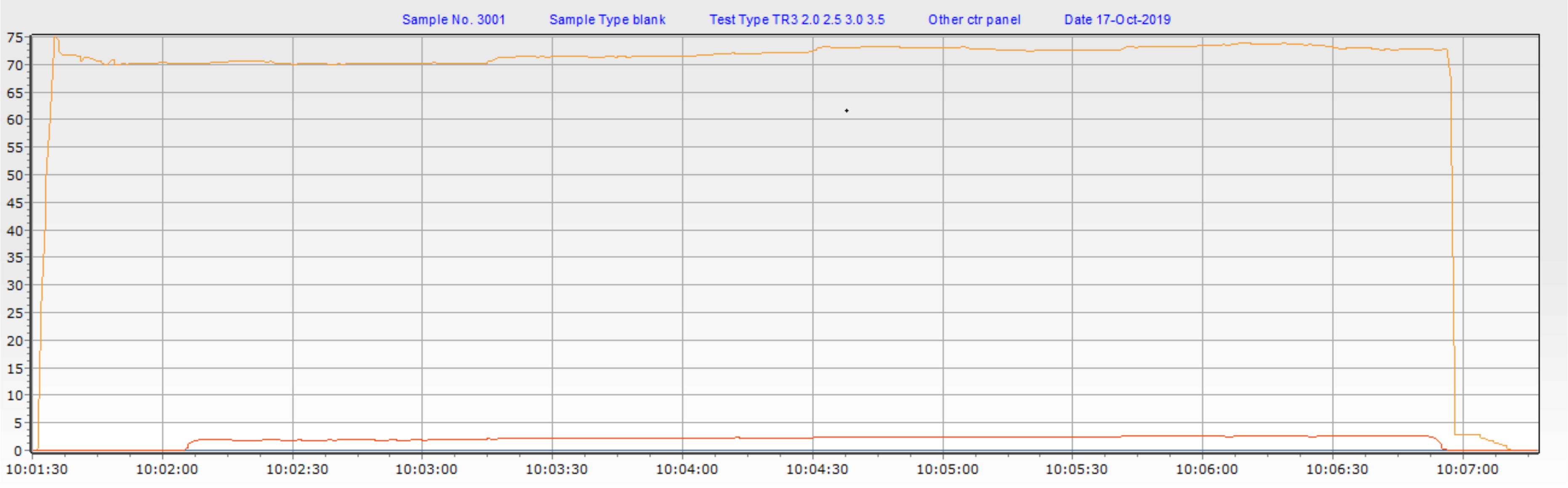


Graph 422. Run 106. No-ore and both top and bottom seals removed. Elevator speed 2.0, 2.5, 3.0, and 3.5 m/s.

Table 422. Data from run 106, elevator tension

Elevator speed m/s	2.0	2.5	3.0	3.5
Time of measurement	10.22.45 – 10.24.00	10.24.30 – 10.25.15	10.25.30 – 10.26.15	10.26.45 – 10.27.30
Pipe conveyor tension kg	53.97	56.14	58.13	60.42
Pipe conveyor tension N	529.45	550.73	570.26	592.72



Graph 423. Run number 104, no ore , pipe conveyor force and the centre panel force.

Table 423. Run number 104 Pipe conveyor roller resistance with measurement of the centre panel resistance, no ore

Elevator speed m/s	2.0	2.5	3.0	3.5
Time of measurement	10.02.10 – 10.02.55	10.03.30 – 10.04.15	10.04.40 – 10.05.25	10.05.40 – 10.06.25
Centre panel tension kg	1.89	2.18	2.40	2.59
Centre panel tension N	18.54	21.39	23.54	25.41
Pipe conveyor tension kg	70.37	71.44	72.98	73.69
Pipe conveyor tension N	690.33	700.83	715.93	722.90

APPENDIX 5
Static friction Test Rig 1 Pictures

Picture 1A. Test Rig 1 Instrumentation showing the load cell weights, two tare buttons, and computer with software programming.

Picture 1B. Full test rig showing the instrument and control panel, counter weight bucket hanging on a load cell, the test ore tube mounted on 3 load cells, and the white pipe part of the constant head water flow system that discharged through the solenoid valve.

Picture 1C. Test Rig 1 lower section in more detail. The counterweight bucket hanging on a ‘S’ shape load cell, tube base plate, the lifting disc is just under the ore tube that is mounted on 3 ‘S’ shape load cells. The water discharge solenoid valve is just above the bucket.

APPENDIX 6
Dynamic friction Test Rig 2 Pictures

Picture 2A. Test Rig 2 ore bin mounted on 4 load cells, one of the load cells is in the foreground

Picture 2B. Test Rig 2 showing the lower 2 of the 4 load cells that the lifting tube is mounted on.

Picture 2C. Test Rig 2 torque arm and load cell

Picture 2D. Test rig 2 drive shaft RPM encoder for shaft speed.

Picture 2E. Test Rig 2 weigh indicators and controllers

Picture 2F. Test Rig 2 Elevator disc segments mounted on the Crosby cable swages

Pictures left to right; Lifting disc, clamping disc, Inspection tube section open on the cable return side showing the cable and disc, Lower picture, left to right; closed inspection tube section, disc and cable at the lower sheave, cable swage. All the discs are made from cast nylon.
Not visible in the photographs, are the discs that have a slit for sliding across the cable when being fitted to the cable swages.

The top disc and bottom clamping disc are bolted together with the slits opposite to one another:

- Discs are clamped together with bolts tightly over the swage.
- The inspection tube section allows for disc replacement if needed. The discs shown in the tube inspection section are travelling down towards the bottom sheave (in the background is the ore bin auger and one of the load cells.).
- The red disc is the ore lifting disc at 122mm diameter made from cast nylon. Nylacast Nylube (Nylacast, accessed 20 June 2018).
- Superglue was used as an adhesive between the discs. (methyl 2, and ethyl 2 cyanoacrylate's).
- The cable joining disc has a machined flange with a boss replacing the swage. These use Wirelock socketing epoxy resin to terminate the cable at the flange (Wirelock, 2018; Crosby, 2014). The flanges were over laid with a normal disc and bolted insitu with the disc bolts.

APPENDIX 7
The hybrid elevator-Test Rig 3 Pictures.

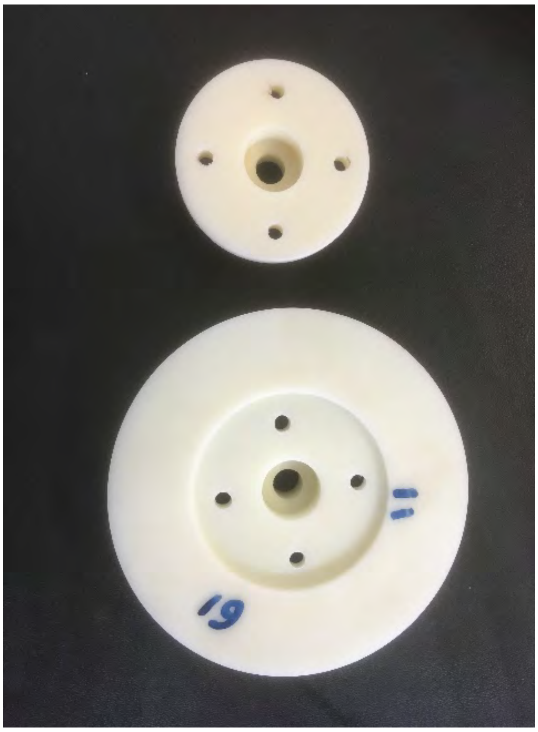
Picture 3A. Test Rig 3 control room showing the load cell weigh indicators and computer, the lower section of the hybrid elevator is partially visible through the window and in the foreground are the three VSD speed controllers for the cable disc elevator, the pipe conveyor and the ore bin discharge screw.

Picture 3B. Test rig 3 pipe conveyor 6 roller centre panel mounted on load cells

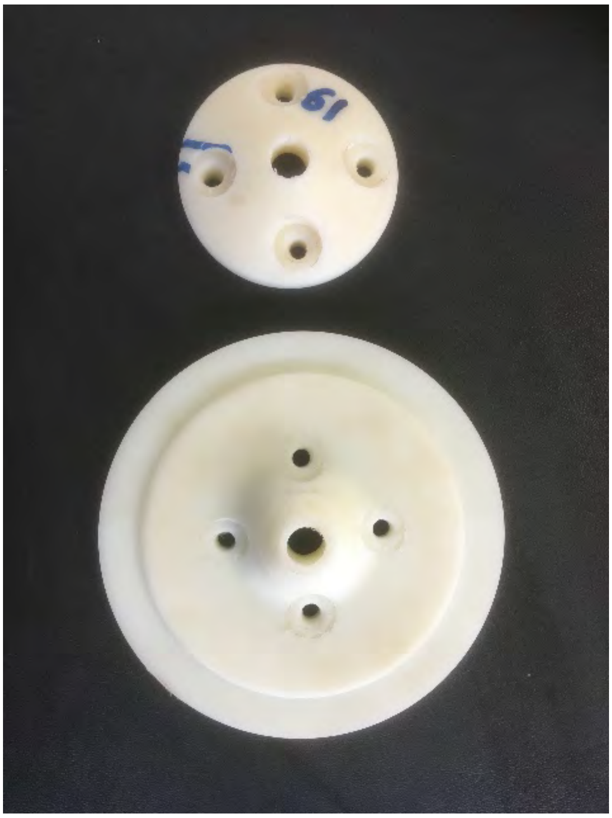
Picture 3C. Test rig 3 pipe conveyor centre panel 2 of 4 load cells

Picture 3D. Top of the hybrid elevator. Showing the load cells of the torque arms for the pipe conveyor and the cable disc elevator

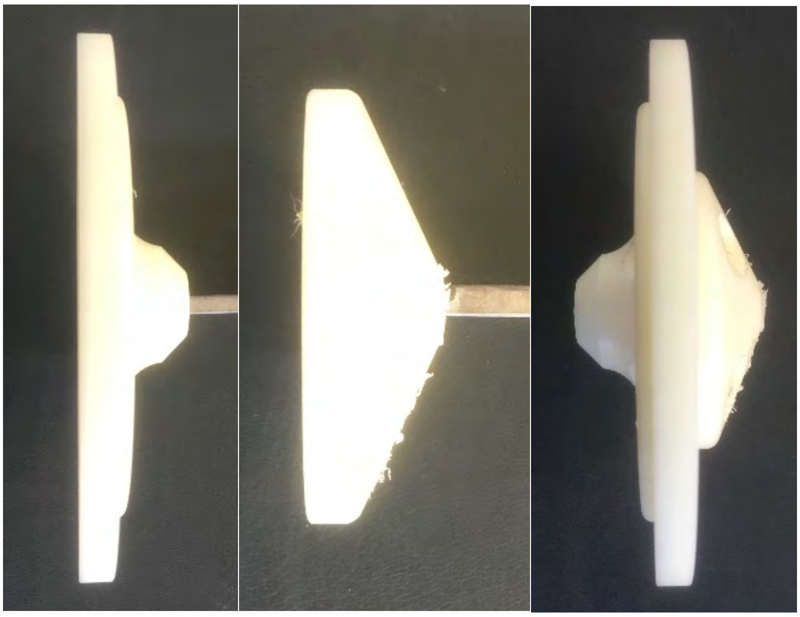
Picture 3E. The hybrid elevator. Weather cover on top and the ore bin in position for operating. The ore bin was lifted up for operation and lowered to ground level for emptying and changing the ore.



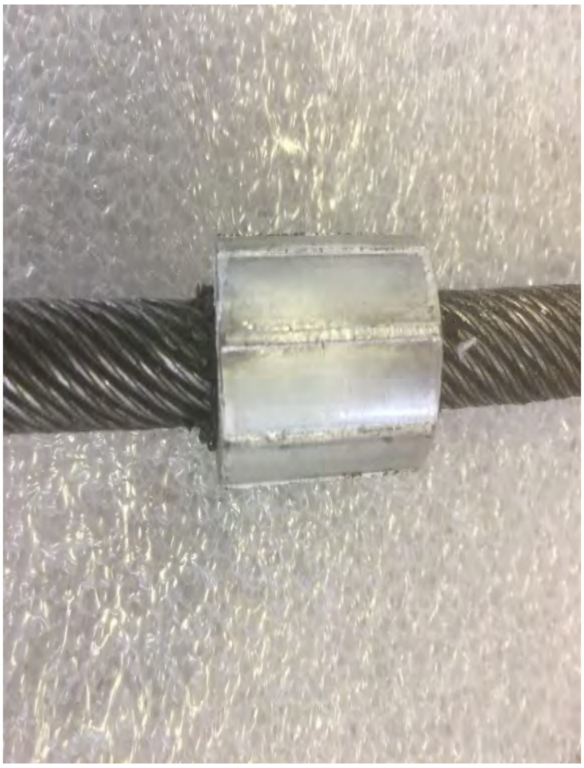
Picture 3F Cable elevator discs joining side



Picture 3G. Cable elevator discs ore lifting side



Picture 3H. Cable elevator discs side view



Picture 3I. Crosby swage on the cable disc elevator cable

Picture 3J. Cable disc elevator slot

Picture 3K Pipe conveyor section without the conveyor belt fitted

Picture 3L. Pipe conveyor drive end