Webb, C. & Tuck, M.. (2020). Cable Disc Elevator: Static Friction Investigation. *Mining, Metallurgy & Exploration. 38*.

https://doi.org/10.1007/s42461-020-00358-8

Mining, Metallurgy & Exploration (2021) 38:979–994
https://doi.org/10.1007/s42461-020-00358-8

Cable Disc Elevator: Static Friction Investigation

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Received: 14 June 2020 / Accepted: 11 November 2020 / Published online: 19 November 2020

Abstract
This paper describes the application of a cable disc elevator to continuous lift ore vertically from underground mines. Application of this system requires the tensions developed within the cable must remain within the carrying capacity of the cable including applicable safety margins. A critical element occurs at starting the system when it is fully loaded which requires the force developed by the system to exceed the static friction forces.

This paper describes the laboratory rig developed to investigate the static friction forces. Details of the results of tests on three different ores for both dry and wet conditions are given. These results are discussed.

Keywords Mining · Shaft · Hoisting · Continuous hoisting · Cable disc elevator · Static friction

1 Introduction

The test rig referred to as Test Rig 1 measures the static friction in the cable disc elevator. The measurements detailed in this paper are those of static friction between the ore on the disc and the steel tube. These measurements are for ore of different particle sizes, ore with added water and ore of different weights on the disc. The three ores used were from the Western Victoria region. These were brown coal, granite and gravel.

Static friction can also be termed 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 the following:

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

The most important data required is that of the static friction required to haul the ore up the lifting side tube. Three ores were selected, gravel, granite and coal, to test the level of static friction in the cable disc elevator. This allowed investigation of the following:

- The investigation used two tube sizes for the static friction tests; these were 12.7 cm (5 in.) diameter and 20.3 cm (8 in.) diameter.
- The lifting disc for Test Rig 1 is 5 mm smaller in diameter compared to the tube. This leaves a gap between the tube and the disc of 2.5 mm.
- The effect that ore with different particle sizes 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 being lifted.
- Tests for static friction with added free water. Wet ore would be likely from mining operations.
- The final analysis of the data for the lifting limits and cable tension requirements based on static friction.

2 Mine Haulage Systems

Throughout mining history, many systems have been developed and used to move broken ore and rock from underground mines to surface. Commonly applied techniques in the modern mining industry include haul trucks, conveyor belts and vertical hoisting systems. Each of these systems has recognised advantages and disadvantages. Bloss, Harvey, Gant and Routley [5] and Tiley [11] describe these systems. Both discuss the various system components as well as the advantages and disadvantages.

Pratt [8] and Spreadborough and Pratt [10] present the analysis of the three main systems used in modern

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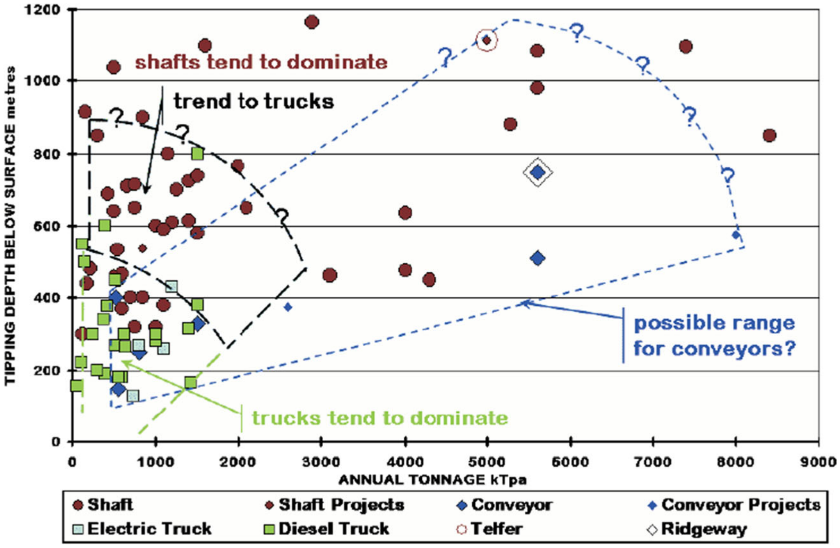


Fig. 1 Operating ranges for underground haulage systems. After Pratt [8] and Spreadborough and Pratt [10]

underground mining: haul trucks, conveyor belts and vertical hoisting systems. In particular, the operating ranges for each of these are analysed and presented as shown in Fig. 1.

Alternative haulage techniques do exist. An example is a bucket elevator. These elevators are successful for continuous vertical lifting of many granular to powdered products. These elevators are part of the inspiration behind this research, as they are efficient; however, they are not lifting ore from large depths like 1000 m. Bucket elevators are used extensively for lifting grain, superphosphate, lime, cement, flour, coal, mineral ores from crushing plants, short vertical distances and so on. The two main types are the flat single belt with buckets bolted on and a twin belt elevator with buckets between the belts. Figures 2 and 3 show both of these systems.

The limitation on the vertical depth to which bucket elevators can descend is the strength of the belt. The deeper they go, the greater the length of the belt, which results in more of the belts capacity being absorbed by the weight of the belt itself.

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

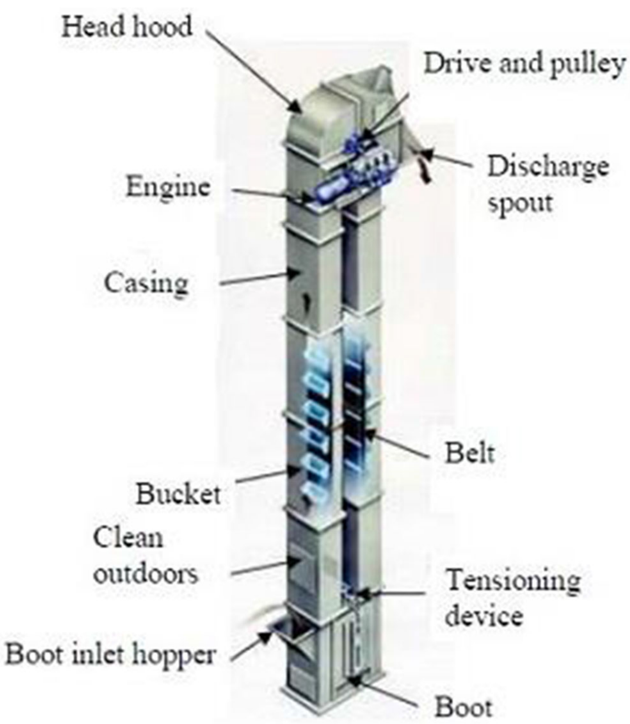


Fig. 2 Typical universal bucket elevator [9]

Fig. 3 Pocket lift elevator [1]

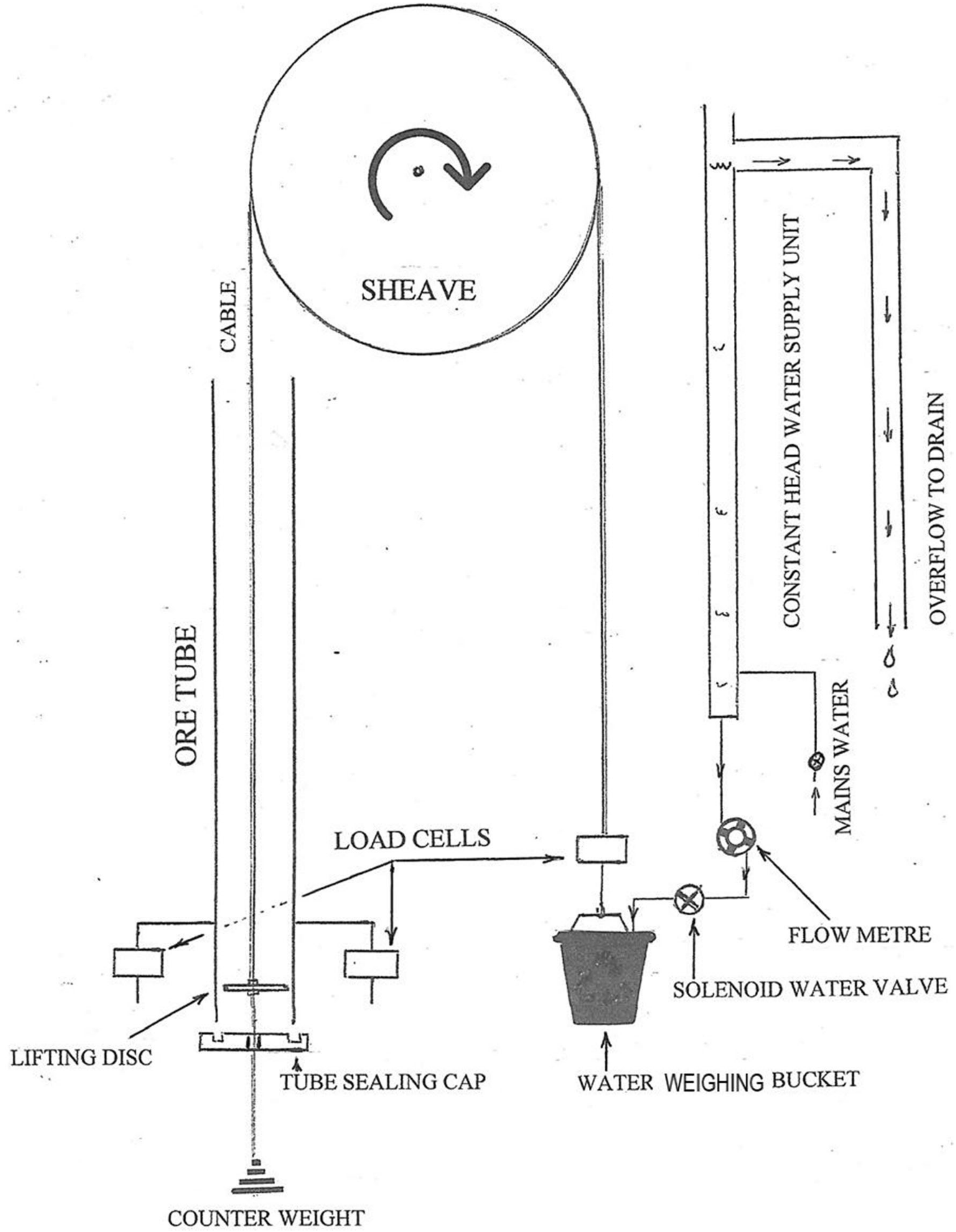


Fig. 4 Test Rig 1 for testing the breakfree force

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.

The largest bucket elevator in the world is at White County Coal Mine in Carmi, IL, USA; the gap between the centres of its rollers is 276 m. This elevator has twin belts and the pocket buckets that carry the coal are suspended between the belts. Referred to as a pocket lift elevator, it operates at 1815 tonnes per hour with a belt weight of 100 tonnes. Energy

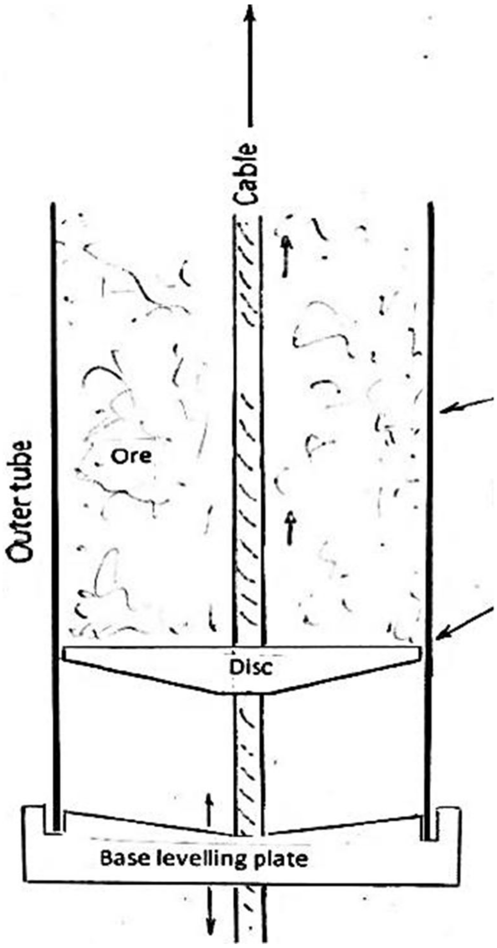


Fig. 5 The cable loaded with ore. Test Rig 1

consumption is at 0.3 kWh/t of ore per 100 m of lift [6]. Contitech built this elevator, who claim to have designs for 700-1000-m-long lifts that use a series of multiple elevators.

The next largest is a traditional bucket lift using a single belt with the buckets bolted to the belt. This is at the Indian Quest ACC cement company [7], and is built by The Beumer Group. It is 1250-mm 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:

- Continuous flow of material;
- Small entry footprint into the mine;
- Low power usage as the elevator belt is balanced;
- Streamlining for the automation of ore hauling;
- Power requirements focus on accelerating the ore and lifting it to overcome gravity, with very minor shaft bearing friction or air friction from the belt movement;
- There are few disadvantages; ore particle size needs reduction to a size that is suitable for the elevator buckets.

This research focuses on the cable disc elevator as a drag conveyor, where the discs are dragging the ore up the tube.

Fig. 6 Test Rig 1

Fig. 7 Test Rig 1, ore tube open

Fig. 8 Test Rig 1. Constant water head flow pipe (white pipe)

The selected disc diameter was 5 mm less in diameter than the internal diameter of the tube. Then, the gap between the discs and the tube is 2.5 mm. A cable disc elevator consists of a top powered drive sheave and a bottom sheave that a continuous cable with discs evenly located, travels around and between the sheaves, lifting ore on the discs.

Given the above friction or tribology is a key concept. Bharat [2] 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, interaction 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 is 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 [12]. In this case, the resistance results from the relative movement between the ore and tube.

Fig. 9 Test Rig 1. Instrumentation and load cell displays

Friction is used to measure the resistance of relative motion between two bodies [3]. 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 [4].

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 were completed with ore of different particle sizes.

Fig. 10 Gravel 2 mm particle size. Breakfree force test sample 1000 g. Water added to the bucket at 2 l per minute

3 Test Rig 1

This test rig collected data to measure the breakfree force of the ores in two steel tube sizes, an 8-in. diameter tube (203.2 mm), and a 5-in. diameter tube (127 mm).

The critical data required is the static friction force. This is the breakfree force required after the elevator has stopped during operation and needs restarting. In this situation, the elevator requires restarting without an elevator cable failure.

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.

In this paper for Test Rig 1, the terms used for static friction $\mathrm{sf}_{\mathrm{ore}}^{\mathrm{size}}$ and static friction force $\mathrm{SF}_{\mathrm{ore}}^{\mathrm{size}}$ are separated by surface area. The static friction force is known as the breakfree force $\mathrm{BF}_{\mathrm{ore}}^{\mathrm{size}}$ 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.

$$\text{Static friction } \mathrm{sf}_{\mathrm{ore}}^{\mathrm{size}} = \mathrm{SF}_{\mathrm{ore}}^{\mathrm{size}}/\mathrm{SA}\ \mathrm{N/cm^2}\text{or } \left(\mathrm{kN/m^2}\right) \tag{1}$$

To determine the maximum static friction for the ore, the test rig disc is shown in Figs. 4 and 5.

When using a fixed tube diameter, an increase of ore mass 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 ($\mathrm{sf}_{\mathrm{ore}}$) is the force per unit area calculated as N/cm^2.

$$\mathrm{sf}_{\mathrm{ore}} = \frac{\mathrm{BF}_{\mathrm{ore}}}{\mathrm{ore\ SA}} \tag{2}$$

Substituting for the surface area from Formula (1) allows determination of the static friction using the following formula:

$$\mathrm{sf}_{\mathrm{ore}} = \frac{\mathrm{BF}_{\mathrm{ore}}}{D \times \pi \times h}\ \mathrm{N/cm^2} \tag{3}$$

where D is the tube diameter in cm, h is the height of the ore in the tube in cm and $\mathrm{BF}_{\mathrm{ore}}$ is the breakfree force for the sample in N.

Photographs of Test Rig 1 are shown in Figs. 6, 7, 8 and 9.

In Fig. 6, the discs are in place, the lifting disc not visible as it is inside the tube resting on the lower closure disc. Two of the three load cells supporting the ore tube are visible. An S-shaped load cell holding the counterweight bucket is in the background, whilst the bottom of the constant flow white water pipe is at the

Fig. 11 Granite 2 mm particle size. Breakfree force test sample 1000 g. Water added to the bucket at 2 l per minute

Fig. 12 Coal 2 mm particle size. Breakfree force test sample 1000 g. Water added to the bucket at 2 l per minute

corner of the frame and the electric solenoid water valve. A water flow venturi indicator is mounted on the left hand 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 m. This allows for a compaction of the ore resulting from a disc landing speed of 5 m 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 m per second.

Figure 7 shows the lower disc used to seal the bottom of the tube, the lifting disc sits just behind the S load cells.

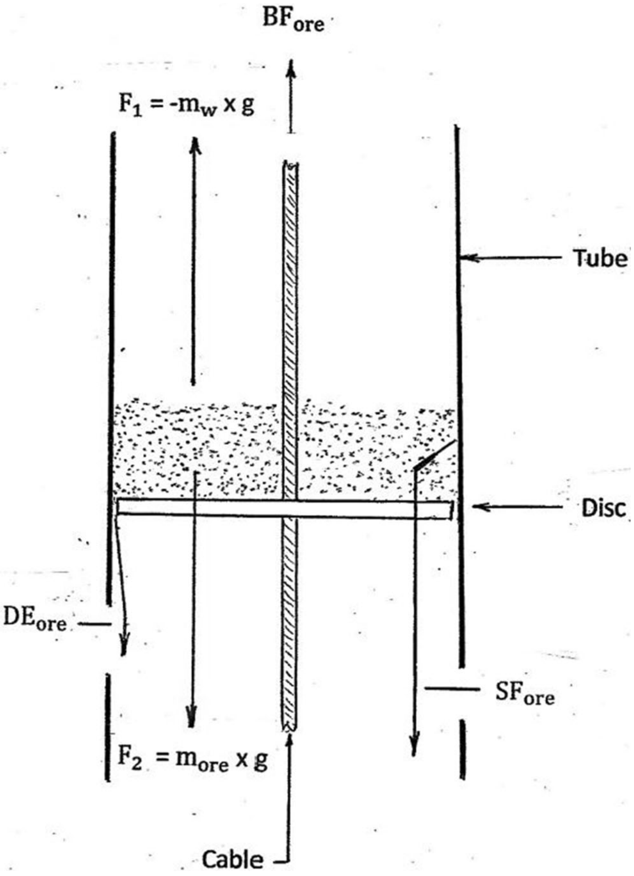


Fig. 13 Ore laid on the disc. Diagram of forces acting at the disc

Figure 8 shows the constant head water supply that fills the counterweight bucket at a fixed water flow rate of 2 l/min.

Figure 9 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.

The results of the breakfree force are shown graphically and in a data table. Figures 10, 11 and 12 are examples of those 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. The graph shows the instant the ore starts to slide. The breakfree force BF^2_{ore} is the maximum reading at the graph peak.

The maximum force on the graph for Figs. 10, 11 and 12 is where the ore breaks free from the tube. The force is shown in pounds.

Test Rig 1 is a purpose-built test rig as shown in Figs. 1, 3, 4, 5 and 6. A 3-mm 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. Two displays record the weights measured by the load cells. There is one display for the counterweight and one for the tube. Water added for the counterweight flows from a constant head pipe at 2 l per minute. The computer saves the results from the displays acting as a data logger. The test rig consists of three main parts. These parts have interconnecting functions making it possible to measure the resistance of the ore sample to movement. Each section of the test rig shown in Fig. 4 is described for the tube, the counterweight loading system and the computer recording system.

The first part is the tube, supported on three 'S'-shaped load cells each with a capacity of 45.45 kg (100 lb) (see Figs. 1 and 2). When the cable pulls the loaded disc, 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

Table 1 Breakfree force for ungraded ore 1000 g. An 8-in. (203.2 mm ID) tube on one disc

Ore ungraded 1000 g	Avg. breakfree force N. BF^{UG}_{8ore}	Max. breakfree force N. BF^{UG}_{8ore}	Min. breakfree force N. BF^{UG}_{8ore}	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

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 Figs. 10, 11 and 12). The force measured is the breakfree force BF_{ore} that is required to get the disc containing the ore to start sliding.

Part two is 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 an 'S'-shaped load cell with a capacity of 45.45 kg (100 lb) which is connected to the cable. Water addition occurs at a controlled rate. A constant head water tank made from poly pipe supplies a steady flow of water at 2 l per minute. The water flow can be seen by the venturi flow gauge (Fig. 3 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 third part is the computer recording system. The recording system comprised 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. As the load changes on the tube take place, these are recorded.

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

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

$$\text{For Force of gravity} \quad F = mg \tag{4}$$

where m is the mass weight of the ore and 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 force 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.

Figure 13 shows the forces interacting in Test Rig 1, where the ore is at rest on the lifting 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

$$\text{Breakfree force} \quad BF_{ore} = SF_{ore} + DE_{ore} + J_{ore} \tag{5}$$

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.

Addition of water to the counterweight bucket increases the lifting force. The static friction force and the disc effect force increase 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

Table 2 Breakfree force for ungraded ore 1000 g on one disc. A 5-in. (127 mm ID) tube

Ore ungraded 1000 g	Avg. breakfree force N. BF^{UG}_{5ore}	Max. breakfree force N. BF^{UG}_{5ore}	Min. breakfree force N. BF^{UG}_{5ore}	Range for 10 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

Table 3 Breakfree force for ore sizes 9.5+ mm, 5.0-9.5 mm, 2.0-5.0 mm and less than 2.0 mm. Sample size 1000 g

Ore 1000 g 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 or 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

to move. The lowest lifting force that causes the disc and ore to move is now called the breakfree force BF$_{ore}$. The static friction force SF$_{ore}$ and the disc effect force DE$_{ore}$ are at that point, defined by their maximum resistance to movement.

5 Results

Testing of the ores used the method described previously. The result recorded is the breakfree force required for the ore to start moving. The breakfree force BF$_{ore}$ comprises three interactions in the tube.

- Static friction force SF$_{ore}$ 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 DE$_{ore}$.
- The effect of jamming J_{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.

Table 1 provides a summary of the results for the ungraded ores for the 8-in. tube. Table 2 provides a summary of the results for the 5-in. tube for ungraded ore. For both, the sample size on the disc is 1 kg.

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.

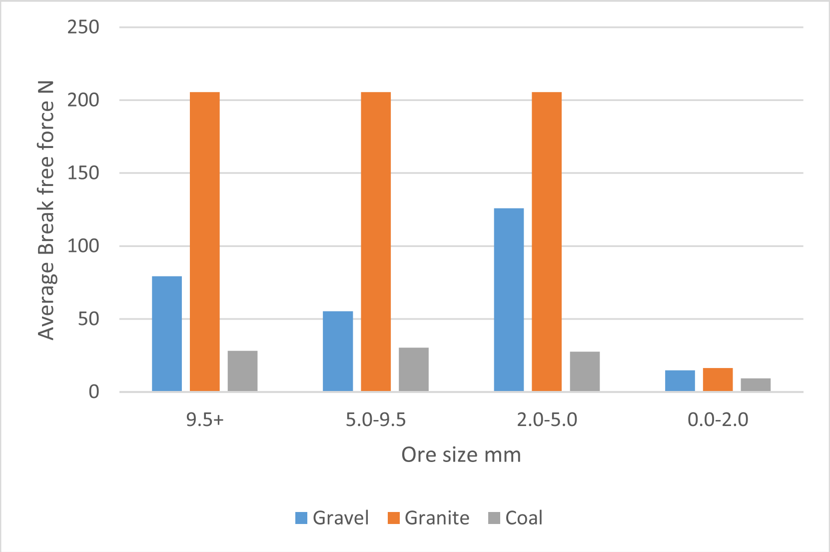


Fig. 14 Average breakfree force for 1000 g of ore for different particle sizes of gravel, granite and coal. Data plotted from Table 3

Table 4 Breakfree-force for gravel less than 2 mm. An 8-in. tube

Ore mass g	Ore tube contact surface area cm^2	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

$$T_1 = T_e^L + T_e^f + T_2 \tag{6}$$

- 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_1 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. Multiplying these results by the number of discs that may be required for an elevator of determined distance allows the forces for that lifting distance to be determined. For a cable lift of 1000 m with discs at 250 mm 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 1000 m continuous lift in a cable disc elevator. The data is applicable to any length of hoist.

Resistance to movement in the tube for static friction (T_f) comprises the following:

- Jamming force J_{ore}. This is the force required to overcome jamming between the disc and the tube. This results from the effects of shards of ore that wedge themselves. Jamming is not friction but a mechanical blocking issue that has to be added to the breakfree 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. This occurs when 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 represented in the equation below.

$$BF_{ore} = \sum J_{ore}, DE_{ore}, SF_{ore} \tag{7}$$

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

Table 5 Breakfree force for granite less than 2 mm. An 8-in. tube

Ore mass g	Ore tube contact surface area cm^2	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

Table 6 Breakfree force for coal less than 2 mm. An 8-in. tube

Ore mass g	Ore tube contact surface area cm^2	Avg. breakfree force N $\mathrm{BF}^{2}_{8\mathrm{coal}}$	Avg. static friction N/cm^2 $\mathrm{sf}^{2}_{8\mathrm{coal}}$	Max. breakfree force N $\mathrm{BF}^{2}_{8\mathrm{coal}}$	Max. static friction N/cm^2 $\mathrm{sf}^{2}_{8\mathrm{coal}}$	Min. breakfree force N $\mathrm{BF}^{2}_{8\mathrm{coal}}$	Min. static friction 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

Measuring the circumference of the disc and applying that to the lowest amount of ore on the disc allow the disc effect force $\mathrm{DE}_{\mathrm{ore}}$ to be calculated.

Measuring the surface area of the ore relative to the tube allows us to calculate the static friction $\mathrm{sF}^{\mathrm{size}}_{\mathrm{ore}}$ N/cm^2 from the static friction force $\mathrm{SF}^{\mathrm{size}}_{\mathrm{ore}}$ N.

The breakdown calculation method allows the following:

- Determination of the static friction $\mathrm{sF}_{\mathrm{ore}}$ between the ore and the tube surface area in N/cm^2. This is determined by dividing the calculated static friction force $\mathrm{SF}_{\mathrm{ore}}$ by the ore surface area contact with the tube.
- Calculation of the resistance to movement between the disc $\mathrm{dE}_{\mathrm{ore}}$ 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 $\mathrm{DE}_{\mathrm{ore}}$ by the circumference of the disc.

Friction is represented using lower-case letters.

$\mathrm{dE}_{\mathrm{ore}}$	disc effect friction N/cm.
$\mathrm{sf}_{\mathrm{ore}}$	static friction N/cm^2.

If there are no large particles that cause jamming the breakfree, force is

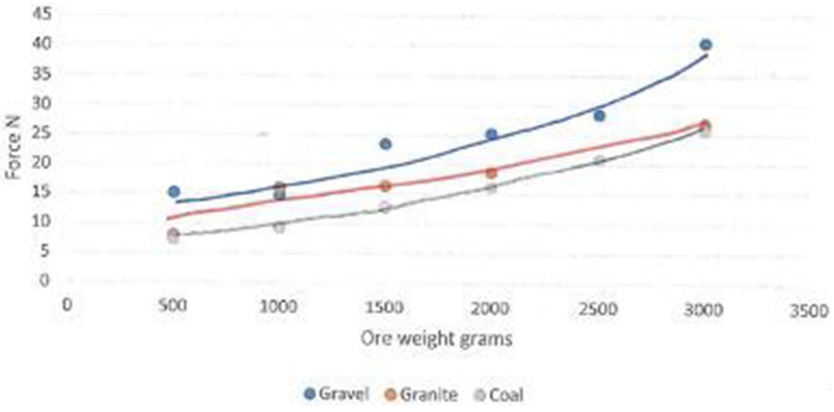
$$\mathrm{BF}_{\mathrm{ore}} = \mathrm{dE}_{\mathrm{ore}} \times C + \mathrm{sF}_{\mathrm{ore}} \times \mathrm{SA}{-}N \tag{8}$$

The ores are represented by the following abbreviations:

Gravel	Gv
Granite	Gn
Coal	coal

Ore jamming dominates the results shown in Tables 1 and 2. This means that the load on the cable will far exceed the breaking strength of the cable. The question at this stage is can ore jamming be eliminated to allow the cable disc elevator to be applicable in mining? The high resistance to movement for

Fig. 15 Breakfree force in the 8-in. tube. Breakfree force increasing with weight on the disc



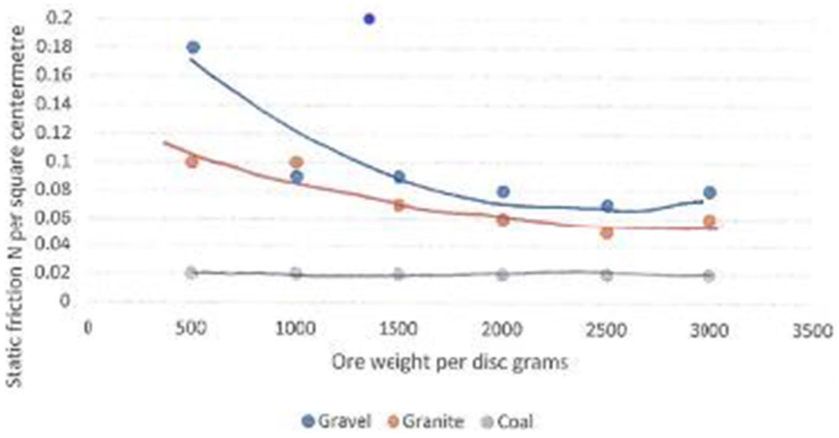


Fig. 16 Static friction as tested in the 8-in. tube. N/cm^2

Table 7 Breakfree force for gravel less than 2 mm ore. A 5-in. (127 mm) dia. tube

Ore mass g Gravel	Ore tube contact surface area cm^2	Avg. breakfree force N BF^2_{Gv}	Avg. static friction N/cm^2 sf^2_{5Gv}	Max. breakfree force N BF^2_{Gv}	Max. static friction N/cm^2 sf^2_{5Gv}	Min. breakfree force N BF^2_{Gv}	Min. static friction N/cm^2 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

Table 8 Breakfree force for granite less than 2 mm ore. A 5-in. (127 mm) dia. tube

Ore mass g Granite	Ore tube contact surface area cm^2	Avg. breakfree force N. BF^2_{5Gn}	Avg. static friction N/cm^2 sf^2_{5Gn}	Max. breakfree force N BF^2_{5Gn}	Max. static friction N/cm^2 sf^2_{5Gn}	Min. breakfree force N BF^2_{5Gn}	Min. static friction N/cm^2 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

ungraded ore requires some investigation in order to determine what part of the ore is responsible for jamming.

In the following tests, details of the results of breakfree force BF_{ore} tests for ore of various particle sizes are shown. The ore is sieved ore into a range of sizes.

These are ores:

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

This testing is done with an 8-in. (203.2 mm ID) tube. All samples tested in Table 3 below have a mass of 1000 g. This allows for an equal comparison between the ores.

Figure 14 displays the average breakfree forces for all three ores and shows the effect of jamming that has taken place with the larger size particles. Coal had the least amount of jamming

Table 9 Breakfree force for coal less than 2 mm ore. A 5-in. (127 mm) dia. tube

Ore mass g Coal	Ore tube contact surface area cm^2	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

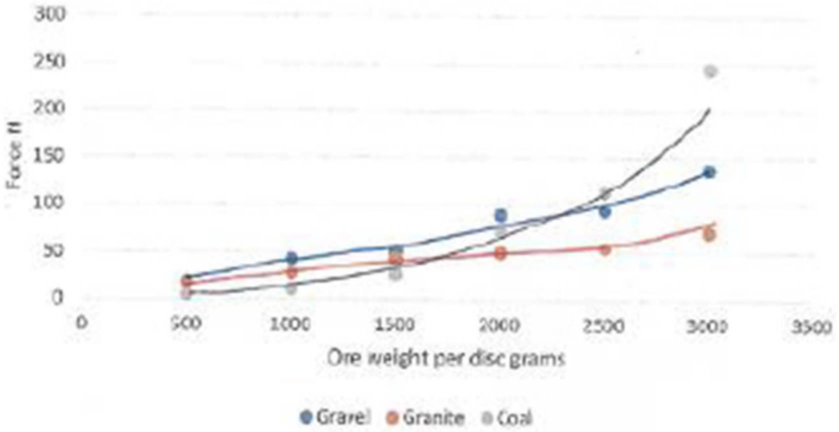


Fig. 17 Breakfree force in the 5-in. tube. Breakfree force increasing with weight on the disc

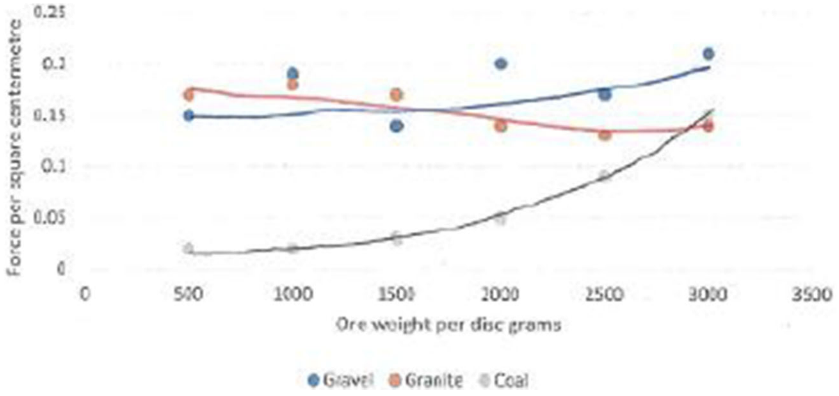


Fig. 18 Average static friction N/cm^2 for the ores in the 5-in. tube

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. Particles smaller than the gap (i.e. 2.0-0.0 mm in size) all slide and the resistance to movement is then 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. Testing then took place with ore that has passed through a 2-mm sieve and retained on the sieve pan. Using ore with a particle size of below 2 mm removes the effect of jamming J_{ore} as the particle size is less than the 2.5 mm gap between the disc and the tube. It is important to develop testing and data that will allow this elevator to operate successfully. Hence, the breakfree force BF^2_{8ore} is the same as the static friction force SF^2_{8ore} between the ore and the tube when divided by the same surface area.

Table 10 Static friction comparison for dry and wet gravel in the 8-in. tube

Ore mass g	Water added g	Ave. breakfree force WBF^2_{8Gv} N	Surface area SA cm^2	Static friction wsf^2_{8Gv} N/cm^2	Dry ore static friction sf^2_{8Gv} N/cm^2	Percent increase in static friction from added water sf^2_{8Gv}
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

$$\text{Then, } BF^2_{8ore} = SF^2_{8ore} \tag{9}$$

$$\text{and } bf^2_{8ore} = sf^2_{8ore} \tag{10}$$

Table 4 details tests on gravel less than 2 mm in size in the 8-in. tube and the measured breakfree force results. The calculation for static friction involves dividing the breakfree force by the surface area contact between the ore and the tube. Table 5 details results for granite less than 2 mm in size and Table 6 details results for coal less than 2 mm in size. Figures 15 and 16 detail the breakfree force and static friction forces.

Tables 7, 8 and 9 and Figs. 17 and 18 detail results from similar testing undertaken in the 5-in. tube.

Additional testing occurred for different weights of ore on the disc and for ores with differing moisture contents. As the weight of ore on the disc increases, the static friction also increases as the contact surface area increases between the tube and the ore.

Tables 10, 11 and 12 provide detail of the effect of moisture. These tables compared values of static friction for dry and wet ores and the percentage influence on the static friction is calculated and shown. Observations for Tables 10, 11 and 12 were as follows:

- There was a limit on the amount of water added to each ore. Too much water 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 tables are for 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), and 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.

6 Summary of Results for Static Friction Testing and Conclusions

Understanding the static friction for a cable disc elevator is important to know what tension strengths are required to restart a fully loaded elevator. The tensions relating to cable weight and the force of gravity are known, and 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 was tested for two tube diameters 8-in. (203.2 mm) and 5-in. (127 mm). The

Table 11 Static friction comparison for dry and wet granite in the 8-in. tube

Ore mass g	Water added g	Ave. breakfree force WBF^2_{8Gn} N	Surface area SA cm^2	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 12 Static friction comparison for dry and wet coal in the 8-in. tube

Ore mass g	Water added g	Ave. breakfree force WBF^2_{8coal} N	Surface area SA cm^2	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

three ores tested (gravel, granite and coal) were collected locally. Natural extracted ore that was ungraded for particle size was tested. For the ungraded ore, there were three elements of the resistance to motion:

- 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.
- The effect between the disc and the tube.

Ungraded ore was separated into particle sizes ranging 9.5+ mm, 5-9.5 mm and 2.0-5.0 mm. The larger sized ore contributed to jams. Based on these results and observations, testing concentrated on ore whose particle size was less than the gap between the disc and the tube. This ore was less than 2 mm in size. In addition, testing of ore sieved through the 2-mm screen with 100 and 200 g of water added per 1000 g of ore. Water caused doubling of static friction. This demonstrated the increased fiction that may occur when the ore has had free water added in the mine.

The next stage of the research knowing the effects of static friction was to examine the dynamic friction in a cable disc elevator. Another issue to be investigated with the dynamic friction investigation will be the possible issues of spillage and carry back and buildup of material in the system. This was not a part of the static friction investigations given the experimental setup.

Acknowledgements The authors would like to acknowledge the assistance of Federation University Australia in the conduct of this research. The authors would also like to acknowledge the following:

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.

Engineering services: Sandwith Engineering - Mechanical Services. Cooperlec electrical, wiring, power supply and motor control.

Bridon Cables for the supply and assistance and debate in selecting the best cables for the test rigs.

Manufacture of the discs. E-Plas Manufacturing.

Funding Colin Webb was supported by an Australian Government Research Training Program (RTP) Fee-Offset Scholarship through Federation University Australia.

Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

References

1. Beumer (2015) Technology in motion, conveyor technology, www.beumer.com (Accessed 2 May 2015).
2. Bharat B (2002) Introduction to tribology. John Wiley and Sons publication NY ISBN 0-471-15893-3
3. Blau PJ (2013) Encyclopedia of tribology. In: Materials, Science and Technology Division. Oak Ridge National Laboratory, Oak Ridge
4. Blau PJ (2008) Friction science and technology-from concepts to applications, 2nd edn. CRC/Taylor and Francis, Boca Raton
5. Bloss M, Harvey P, Gant D, Routley C (2011) Underground ore movement. Chapter 12.8. In: Darling P (ed) SME Mining Engineering Handbook, 3rd edn. SME, pp 1271–1294
6. Contitech (2013) Conveyor belts and design calculations, Conveyor Belt Group Contitech, Transportbandsystem GmbH Breslauer Straβe 14, 37154 Northern Germany, 5th edn. 'Peripheral Force 3.5.' Published by, Continental Aktiengesellschaft, Hanover, pp 54–63 www.contitech.de. Accessed 2 May 2015
7. 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, www.aumund.com (accessed 24 April 2015).
8. Pratt AGL (2005) Application of conveyors for underground haulage. In: Proc 9th Underground Operators Conference, Perth, WA, 7-9 March 2005. AusIMM, Melbourne, pp 273–283
9. Ramakrishna S (2018) Competent engineering. Plot No.-84, Sector -21C. Fairbad 121003, Haryana India. www.competentengineering.com. Info@competentengineering.com. Accessed 2 May 2015

10. Spreadborough JC, Pratt AGL (2008) Inclined troughed belt conveyor systems for underground mass mining operations. In: Proc 10th Underground Operators Conference, Launceston, Tas, 14 – 16 April 2008. AusIMM, Melbourne, pp 71–76
11. Tiley P (2011) Hoisting systems. Chapter 12.9. In: Darling P (ed) SME Mining Engineering Handbook, 3rd edn. SME, pp 1295–1323
12. Wang QJ, Chung YW (eds) (2013) Encyclopedia of tribology. Springer, Boston ISBN 978-0-387-92896-5