THE APPLICATIONS OF 3D PRINTING A CEMENT – BASED MATERIAL WITH SPECIFIC REFERENCE TO OPTIMUM MIX DESIGN USING LOCALLY SOURCED MATERIAL

by

Refilwe Mahlatse Lediga (200931409)

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Supervisor: Mr Deon Kruger

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ABSTRACT

This dissertation introduces an overview of a study concerning the application of additive manufacturing which is widely known as 3D printing within the construction industry. 3D concrete printing is a new and pioneering technique in the construction industry that can be utilized for the manufacturing of small scale to large scale construction structures. If designed and utilized correctly, this technique has various advantages over traditional construction techniques and presents opportunities to significantly decrease time and cost.

In order to achieve success in 3D concrete printing, an adequate design mix is required to guarantee proper feed, extrusion and hardening. The most commonly used 3D concrete printers are gantry systems. With the gantry system, the concrete is fed to the nozzle and the nozzle is programmed to move in three dimension therefore having the capacity print concrete structures layer-by-layer.

The dissertation investigate the criteria for an optimum concrete mix design to be used in a 3D concrete printing machine using Gauteng sourced materials (i.e aggregate, cement and admixtures).

DECLARATION

I pronounce that this dissertation is my own work. It is being submitted for the Master's qualification in Civil Engineering at the University of Johannesburg. It has not been submitted before for any degree or examination in any University.

……………………………………………………………… 29 December 2018

Refilwe Mahlatse Lediga (200931409)

DEDICATION

This dissertation is committed first to GOD, who gave me power and wellbeing to embrace this work; to my family, who always encouraged me to study further and keep pushing myself all the time; also to my partner for being a strong support system throughout this journey. Finally, I also dedicate this work to my supervisor who was very patient and supportive throughout this journey.

ACKNOWLEDGEMENTS

There are individuals without whom this dissertation probably would not have been composed and to whom I am extraordinarily grateful. Consequently, I want to acknowledge:

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CHAPTER 1: INTRODUCTION AND BACKGROUND

1.1 General introduction

Concrete structures are traditionally built by pouring concrete in formwork and removing the formwork when the concrete hardens. Although this approach still works, where possible, technology must be integrated to make construction processes more efficient with regard to time and cost. Automotive technologies could provide a good solution for more efficiency in construction projects considering how they have improved other industries such as large scale manufacturing.

The construction industry faces many challenges, which range from efficiency of labourers on site, accidents on site, quality control and a skilled labour force with experience is still required (Warszwski & Navon 1998). Three-dimensional printing of concrete (3DPC) has a potential for the rapid industrialization of the housing sector, with advantages of lessened construction time due to no formwork necessity, simplicity of development of complex geometries, potential high development quality and decreased waste (Paul, Van Zijl, Ming & Gibson 2018).

According to Khoshnevis (2004), in the twentieth century there has been a significant adoption of technology outside the construction industry. The reason the adoption has been moderate in construction is because fabrication technologies have been unsuitable for huge projects, the high cost of the technology that existed, the quality of the final product, traditional design approaches that are not suitable for automation and availability of material that could be used for these systems.

Various parts have been manufactured using automation in the twentieth century although the construction of large structures still remains a manual process. A technology that could be promising is additive manufacturing, widely known as 3D printing that is conventionally used for rapid prototyping to overcome the challenges stated.

1.2 Problem statement

Traditional construction materials such as reinforced concrete are still very widely used but are expensive and inflexible. When building geometrically complex structures, customized formwork has to be manufactured. For example, if you were required to construct a concave -convex surface, this would require pre-fabrication of costly formworks and cages, the mounting of complex scaffolding and manual casting. Furthermore, existing methods require a skilled work force to constantly refer to plans or blue-prints, a procedure that is costly.

1.3 Traditional 3D printing technology

3D printing is an innovation that utilizes an additive manufacturing process whereby items are built on a layer-by-layer premise, through a progression of cross-sectional slices. According to Berman (2011), a 3D printer works in a way comparable to traditional laser or inkjet printers, but instead of using multi-coloured ink, the 3D printer uses substances such as plastic or powder that are gradually incorporated with an item on a layer–by–layer premise. All 3D printers utilize 3D CAD software that measures a large number of cross-sections of every item to decide precisely how each layer is to be built. 3D printing is attaining recognition all over the world. Be that as it may, it is as of now utilized for generally small- scale items or prototyping. A noteworthy preferred position of 3D printing is that it can build a total object for which past techniques would have utilized consolidated pieces. This makes the subsequent object stronger.

1.4 3D concrete printing

3D concrete printing uses the same principles as traditional 3D printing but uses concrete as the extrusion material instead of powder. 3D concrete printers utilize a concrete mix design, which is conveyed through a pipe to the concrete extruder/nozzle. Due to the fact that this nozzle is attached to the gantry system, the nozzle/extruder is able to move in three dimensions. This nozzle/extruder is operated by a computer controlled gantry system and builds the structure layer-by-layer. The key components therefore are (1) a concrete pump, (2) an extruder, (3) CAD software and (4) a computerized gantry system. The construction process using this technology is mostly automated and requires minimal labour throughout.

One of the first attempts with a cement-based additive manufacturing process was made utilizing a moderate strategy between the old style powder bed and inkjet head and fused deposition modelling so as to glue sand layers together with a Portland cement paste. There have been many projects focused on the development of cement-based 3D printing. The difference is mainly the materials used and the type of applications considered.

One of the pioneers of large scale cement-based 3D printing was a technology called Contour Crafting Gosselin (2016). Contour crafting depends on the extrusion of two layers of cement based materials so as to create a formwork. The extruded surface roughness is smoothed out utilizing a trowel while extruding. The 3D print head is mounted on an overhead crane as the system is intended for on location construction tasks. 3D concrete printing in construction applications is a disruptive and new area of research which combines information and experience of traditional construction with computerized manufacturing (Sanjayan, Nazari, & Nematollahi 2019). Many more projects and attempts will be discussed in this dissertation.

1.5 Aims and objectives

This research introduces an overview of a study concerning the application of additive manufacturing which is widely known as 3D printing within the construction industry. 3D concrete printing is a new and pioneering technique in the construction industry that can be utilized for the manufacturing of small scale to large scale construction structures. If designed and utilized correctly, this technique has various advantages over traditional construction techniques and presents opportunities to significantly decrease time and cost.

In order to achieve success in 3D concrete printing, an adequate design mix is required to guarantee proper feed, extrusion and hardening. The development of the mix design will be the primary aim in the dissertation.

1.6 Research question

The dissertation presents an investigation into the following three topics:

- Criteria for an optimum concrete mix design to be used in a 3D concrete printing machine for various applications.
- A possible formulation of an optimum concrete mix design using South African sourced material to satisfy the criteria developed.
- The testing of a formula by printing a structure/object as an illustration of whether the concrete mix design can work for the criteria to be developed.

1.7 Proposed programme

The dissertation will present an investigation into the criteria for an optimum concrete/mortar mix design to be used in a 3D concrete printing machine as well as the formulation of an optimum concrete mix design using local materials to satisfy the criteria developed. The formula will be tested by printing a structure to investigate whether the concrete/mortar mix design has practical use in the local environment using local materials.

1.8 Dissertation outlay

Chapter Two

This chapter reviews the literature review of 3D printing and the progress made in 3D printing in the construction industry. The history and evolution of Portland cement, which is the main material ingredient, is also investigated including the properties of fresh and hardened concrete. This section will be concluded by investigating the various mix designs employed in construction using additive manufacturing technology.

Chapter Three

Presents the experimental method used in the research.

Chapter Four

Presents the results and discussion.

Chapter Five

Presents the conclusion and recommendations, followed by the list of references. Lastly, detailed experimental results were recorded in the appendices.

1.9 Conclusion

3D printing or additive manufacturing has created many opportunities with regards to the construction of physical objects with minimal labour and in a cost effective manner. Its applications in construction remain exciting and also technically challenging. One of the most significant challenges technically remains the concrete or mortar design mix. The concrete not only has to have the ability to be pumped through the system, it should be pumped without segregation, not collapse when it is extruded and have enough strength to support the next layer.

The dissertation will look at these challenges and design a concrete or mortar mix that will be able to print a concrete structure.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

High performance concrete (HPC) is known for its moderately high compressive strength and a much lower tensile strength; thus steel reinforce is required to compensate for the low tensile strength in the concrete structure(Shah and Ahmad 1994).Materials such as fibre-reinforced concrete are also alternatives to compensate for tension although steel is the most commonly used.

The mix design is vital, be that as it may, when printing with high performance concrete the mix design is considerably and increasingly vital. The nozzle size that the mix goes through is normally between 30 – 70 mm; this is in contrast to traditional techniques where the mix is poured into the formwork. Initially, the sand particles utilized in the mix must be small enough to guarantee that the mix can go through the nozzle without causing a blockage. The mix must then have adequate workability for the concrete mix to be pumped up to the highest point of the printer structure and after that go through the pipework inside the printer head. Subsequently, the concrete must have a fast setting time and needs to indicate adequate buildability. In the event that the mix is increasingly viscous it might set rapidly, however it will be hard to pump up from ground level to the printer head. Conversely, if the mix is less viscous it will be simpler to pump however it will more than likely have a more drawn out setting time.

An issue to consider regarding the matter of setting concrete is the time required for a full layer to be printed. Le (2011) claims that leaving 30 minutes between layers gives altogether lower tensile bond strength than a printing gap of 15 minutes; this is reasonable as a diminished printing time takes into consideration a stronger adhesion between the successive layers of cement during printing.

Another factor to consider in the design procedure is that when utilizing HPC as a material it is important to utilize support materials to print on a level plane or on a slant. Be that as it may, giving the mix design is optimized remembering buildability and workability then the mix will support itself when printing vertically.

2.1.2 Contour Crafting

According to Khoshnevis (2004), Contour Crafting is the most construction focused technique. It utilizes regular construction apparatuses (trowels) to form the various concrete layers. As shown in Figure 2.1, two trowels shape the layer after the material extruded. The other advantage of the nozzle is that it can use two distinct materials concurrently.

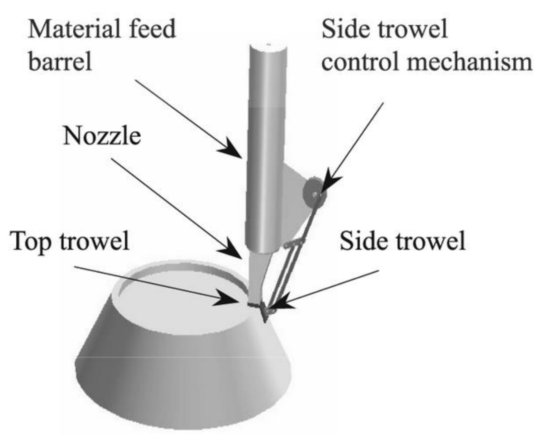


Figure 2.1 Contour crafting system (Khoshnevis, 2004)

This technique creates various conceivable outcomes in the construction industry. Steel reinforcement can also be inserted using a robotic arm concurrently with the printing. Space can also be made to embed plumbing and electrical systems.

2.1.3 D-shape

D-shape is another mechanical autonomy building system utilizing new materials to make prevalent stone-like structures shown in Figure 2.2. According to the innovators D-shape Ltd (2007), this new technology creates full-size sandstone structures made without human involvement, utilizing a stereo lithography 3D printing procedure that requires only sand and a special inorganic binder work. D-shape Ltd claims that this procedure has changed the manner in which engineering and architectural design is planned.

Even with the accessibility of machinery, for example, cranes, pumps and concrete mixers. The construction industry is dependent on the involvement of labourers who operate the machinery.

Existing materials, for example, reinforced concrete and stone work are costly. To manufacture a concave-convex structure, for instance, would require the pre-fabrication of costly formwork. The mounting of complex formwork and casting by labourers. Moreover, existing methods require skilled labour to constantly look at plans or blue-prints that are costly.

This innovation permits a degree of accuracy and opportunity of structure previously unheard of. The restriction of labourers and bricklayers will not limit the architectures vision. The D-shape procedure contends with the conventional methods which uses traditional construction materials.

Figure 2.2 D shape illustration (D-Shape Ltd, 2007)

2.1.4 Winsun 3D concrete printer

The 3D printed home is an achievement which numerous engineers and architects have been thinking about for a couple of years now. We have seen various organizations and people participating in the space as of late. In spite of the fact that China has been lingering behind the U.S and Europe as far as buyer and manufacturing based 3D printing, one China-based organization professes to lead all in the industry. With regards to the 3D printing of huge scale structures, such as homes. China-based Winsun Decoration Design Engineering Co. uncovered what many accepted was a fabrication at first; According to Winsun Decoration Design Engineering Co. (2015), 10 homes which were for the most part 3D printed with a reused solid material. They made headlines in the construction technology industry. Figure 2.3 and Figure 2.4 show some of the structures they have managed to print.

Figure 2.3 Winsun printing concrete (Winsun Decoration Design Engineering Co, 2015).

Figure 2.4 Winsun 3D concrete printed structure (Winsun Decoration Design Engineering Co, 2015)

2.1.5 Tu Eindehoven 3D printer

The 3D printer from TU/e offers a neat, streamlined look, but is very large. A Dutch University, TU/e started work on 3D concrete printing technology, equipped for printing bigger construction components and structures. It is developed of a four-pivot gantry robot with a print bed of roughly

$9.0 \times 4.5 \times 3$ m^3, and incorporates a concrete pump also, with the whole system including the robot operated by a numerical controller. According to Technische Universiteit Eindhoven (2016), their technology has displayed the ability to print very complex shapes geometrically as shown in Figure 2.5.

Figure 2.5 Printed concrete elements (Technische Universiteit Eindenhoven, 2016).

2.2 Portland Cement

Cement plays an important role in developing the correct mix for the 3D concrete printing process in this research. Much of the success of the experiment is dependent on developing the right mix. In this section, a thorough explanation and history of Portland cement will be analyzed.

2.2.1 Introduction to Portland cement

Cements are adhesive materials which have the ability of bonding particles of solid matter into a compact object (Soroka & Stern 1979). This broad definition encompasses a wide variety of adhesive materials. However, for engineering purposes it is restricted to calcareous cements that contain compounds of lime as their principal constituent. The main raw materials used in producing Ordinary Portland Cement (CEM I) are the oxides: lime (CaO), produced by heating calcium carbonate; silica (SiO_2), found in natural rocks and minerals; alumina (Al_2O_3), found in clay minerals; and ferric (Fe_2O_3), found in clay minerals (Bye 2011).

Cement as a binder is a vital element in concrete and the quality of concrete depends on the cement or binder, the aggregate, the mix design and the handling involved in making, placing and subsequently curing (Bye n2011). The performance of cement used in concrete is influenced by its chemical composition. A typical chemical composition of South African Ordinary Portland cement (CEM I) is shown in Table 2.1.

Table 2.1: Typical composition of South African CEM I (Addis, 2001)

Chemical Oxides	% by mass in cement
CaO	63-68
SiO_2	19-24
Al_2O_3	4-7
Fe_2O_3	1-4
MgO	0.5-3.5
$Na_2O + 0.658\ K_2O$	0.2-0.8

2.2.2 Properties affecting paste rheology

There are several definitions of rheology available in literature. Banfill (2003) defines Rheology as the science of deformation and flow of matter. Flow infers a relationship between force, deformation and time. Rheology can therefore be used as a tool to characterize different sorts of materials between ideal liquid and ideal solid.

Various investigations of the rheological properties of cement pastes have demonstrated that these properties rely upon numerous elements. The following have been every now and again refered to: the water to cement ratio (w/c), specific surface area, mineral composition and conditions during measurements (Greszczyk & Kucharska 1991; Banfill 1981).According to Von Berg

(1979), time dependency, mixing time and mixing intensity as well as temperature are also important.

Research has found that the concrete would have great workability with a higher w/c ratio. Water cement ratio and specific surface area have been shown to be the most significant (Greszczyk & Kucharska 1991). Conducted research on cement paste of various chemical compositions showed this factor has less impact on the rheology than the w/c proportion as well as the fineness of the cement as this is optimized in off the shelve cement. According to Bombled (1980), the most vital impact of substance structure is in the retardation of the aluminate hydration by calcium sulfate. As a result of the of the significant reaction rates of these procedures they are significant when deciding rheological elements of cement paste at early hydration stages and furthermore influence the development of rheological properties (Greszczyk & Kucharska 1991).

According to Banfill (2003), the rheology of paste is far more complex than that of concrete, because of structural breakdown in the paste. Structural breakdown occurs when a cement-based system is sheared. When the cement particles hydrate with water, a membrane forms around a group of particles. If this membrane is broken due to shear, more particles hydrate making the structure stronger. This process is irreversible and the links cannot reform when the structure comes to rest. The effect of this structural breakdown is masked or reduced in a concrete mixture. The aggregate present in the concrete changes the properties of the cement to water interface which governs the flow properties of the suspension. In the case of a Newtonian liquid, in the laminar flow region, only one experimental point is needed since a straight line relationship between shear stress and shear rate will pass through the origin as shown in Figure 2.6 Tattersall (1991).

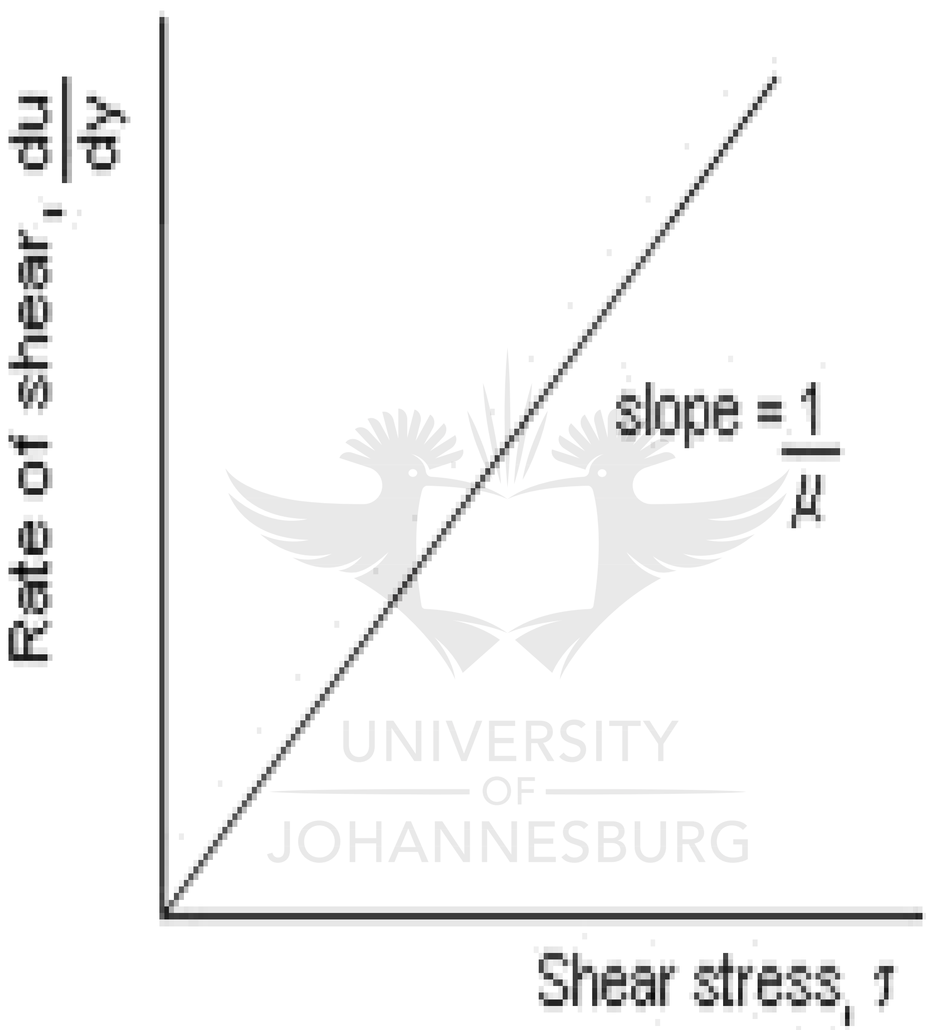


Figure 2.6 Newtonian liquid (Tattersall, 1991)

The Newtonian fluid is the simplest form to describe a fluid, but most substances (including concrete, mortar and cement paste) do not conform to this model. The Bingham model describes the non-Newtonian fluids Tattersall (1991).

Although the Bingham model can describe non-Newtonian fluids, it is still too simple for most substances used. The flow curves for these substances may not be linear, as shown in Figure 2.7 below. If the flow curve is concave towards the stress axis, it describes shear thickening because the shear stress increases more rapidly than the shear rate and the flow decreases rapidly at higher shear rates. Shear thinning on the other hand is caused when stress increases less rapidly than the shear rate, causing the flow to become easier with increasing stress. This flow curve is concave towards the shear rate axis Tattersall (1991).

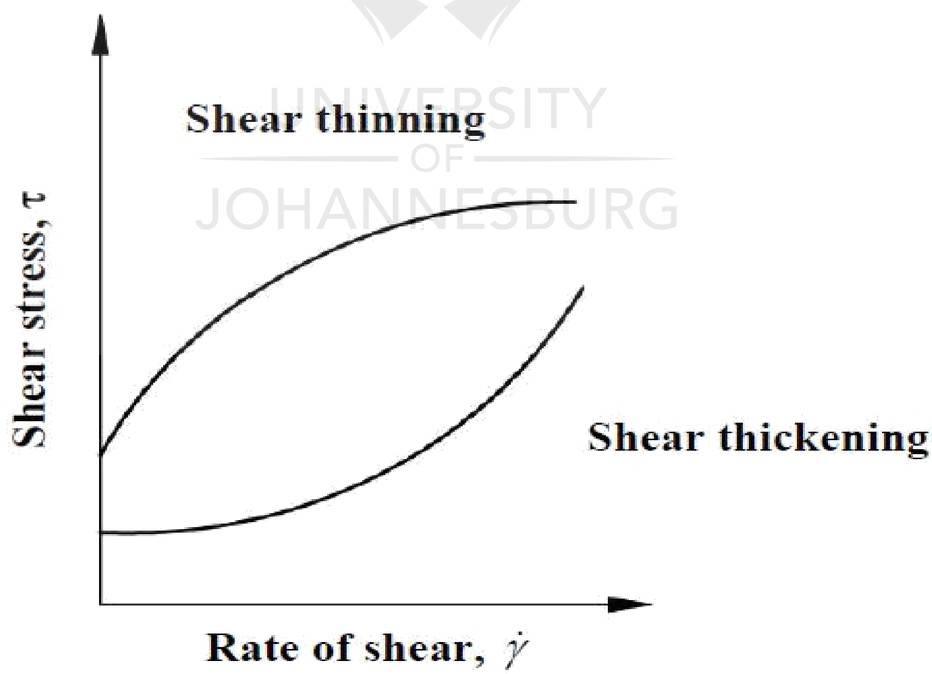


Figure 2.7 Non-Newtonian liquid (Tattersall, 1991

2.3 Properties of Fresh Concrete

Concrete is in a fresh state for only a few hours, compared with a service life that may be several decades. However, the properties of fresh concrete are significant in light of the fact that they impact the handling of the concrete, how much it can be compacted and the consistency of distribution of constituents inside. Handling of concrete has practical implications for construction, while compaction and uniformity affect the properties of hardened concrete (Kellerman & Crosswell 2009). The properties of fresh concrete are those that affect its ability to be transported, handled, placed and finished.

2.3.1 Workability

Workability is characterized by ACI Committee 116R (2000) as that property of freshly mixed concrete or mortar which determines the ease with which it can be mixed, placed, consolidated and finished to a homogeneous condition.

Workability relates to the concrete consistency and can be defined as the ease at which concrete enters formwork without significant segregation. Workability of concrete is therefore proportional placement and finishing without segregation. Concrete that needs to be placed in a high reinforced congested area has to be more workable than in the case of mass concrete. Compaction helps in eliminating entrapped air in concrete.

The main factor affecting concrete workability is the water content of the mix. Other factors are: aggregate size and characteristics, cement content, cement type, and admixture. Water content is proportional to concrete consistency. Concrete mixtures with high consistency are open to segregation (non-uniform mix) and bleeding (appearance of water on the surface of the concrete after consolidation), while mixtures that contain low consistency are generally challenging to with regards to compaction and placement. Wet mixes can lead to separation of coarse aggregate from the rest of concrete (Mehta & Monteiro 2014). The consistency of a dry mix can be improved by adding a water-reducing admixture. The workability of mortar can be accessed through flow test while the most universal method of assessing concrete workability is by measuring its consistency through the slump test.

2.3.2 Segregation

According to Soroka & Stern (1979), segregation is defined as the separation of concrete constituents within the mix making their distribution no longer uniform, which can be due to differences in the specific weights of the constituents. Inappropriate procedures of transporting and placing can be a cause of aggravation. Placing concrete from a high distance and at a high velocity may result in segregation. According to Donahue (2004), the following are contributing factors: particle size that are bigger than 25mm, mixes that are either too dry or too wet, aggregate that contain rough texture and irregular shape, high volume of aggregate, high specific gavity and a reduced quantity of fine sand or cement. Segregation can be partly overcome by careful handling.

2.3.3 Bleeding

Bleeding is defined as a form of segregation occurring when water rises onto the surface of cast concrete, Subsequently, as the solid materials settle to the bottom. Mild bleeding is normal for good concrete, it prevents drying out, prior to complete hydration but high levels of bleeding becomes harmful to the concrete structure.

Concrete becomes porous, weak and non-durable, as a result of excessive bleeding. According to Neville (2011), if bleed water is re-mixed during finishing, a weak wearing surface will be formed. It also occurs that bleeding water accumulates beneath large aggregate or underneath steel reinforcement, this decreases the bond and creates weak zones. Plastic shrinkage may also result if the bleeding water evaporates more rapidly than bleeding rates, such as in hot weather. According to Donahue (2004), for this situation, cement at the surface does not satisfactorily hydrate causing dusting and diminished strength of the wearing surface. The external manifestation of bleed is known as Laitance, which is brought about by ascending of water in the inside channel of concrete, conveying along cement and fine particles in concrete that accumulate at the surface of concrete Mehta & Monteiro (2014) resulting in a weak, porous and soft surface that is prone to dusting.

Bleeding may be reduced by modifying the mix in the following ways (Kellerman & Crosswell 2009):

- Using finer cement.
- Using CSF or very finely ground GGBS.
- Reducing the water content.
- Increasing the proportion of minus 300-µm material in the mix.
- Using an air-entraining admixture.

2.4 Properties of Hardened Concrete

Concrete strength is an important element of any concrete structure. The strength usually provides an indication of the quality of concrete. According Neville (2011), strength is directly related to the structure of the hydrated cement paste. Strength is also defined as the materials resistance without failure. In structural designing, the strength of a concrete structure is of significance as it is also used as an index for other concrete properties. The concrete in a structure is subjected to multi-axial, highly variable stresses, whereas when the strength of concrete is determined in the laboratory it is on a small specimens manufactured, handled and cured differently to the concrete in the structure and subjected to a specific loading rate and almost uniaxial stress. According to Perrie (2009), the strength of concrete determined in the laboratory is only therefore an index or indication of the strength of the concrete in the structure.

Different forms of strength measurements can be determined by subjecting the concrete to compressive, tensile and shear tests. Out of these aforementioned tests, compressive strength is the most commonly used concrete design parameter. According to Addis (1994), the relationship between tensile and compressive strength does not have a specific pattern, because the factors affecting strength do not affect tensile and compressive strength to the same degree.

2.4.1 Water/cement (w/c) ratio

Water/cement (w/c) ratio is considered as the most important factor affecting concrete strength because it affects the porosity of the hardened paste as hydration progresses. Strength of the aggregate-paste bond as well as the strength of the paste influence the strength of concrete. Both factors are affected by the water/cement ratio of the mixture. The quantity of water used in a cement paste mixture has an overall effect on volume, since the volume of the wet paste is the sum of the volume of the anhydrous cement and the mixing water. The quantity of water used also affects the flow or rheology of the mixture as well as cohesion between paste and aggregate. As a result, it influences the overall strength of concrete.

According to Abram's law, if the effect of aggregate on strength is ignored and the same degree of hydration and compaction are undergone, concrete strengths are determined soley by the ratio. The law gives the following expression:

$$S = A/B^{w}$$

Where:

w = w/c ratio

S= Strength

A and B are constants which depend on the properties of aggregate (Neville 2011).

This law is valid on the basis of full compaction of concrete. Figure 2.8 shows the relation between w/c ratio and compressive strength. Neville (2011) reported that below a certain w/c ratio value, the expected increase in strength does not occur, because limited water is available for complete hydration and therefore it results in reduction in strength. On the other hand, increase in w/c ratio beyond a certain value results in increase in porosity and weakening of the concrete matrix.

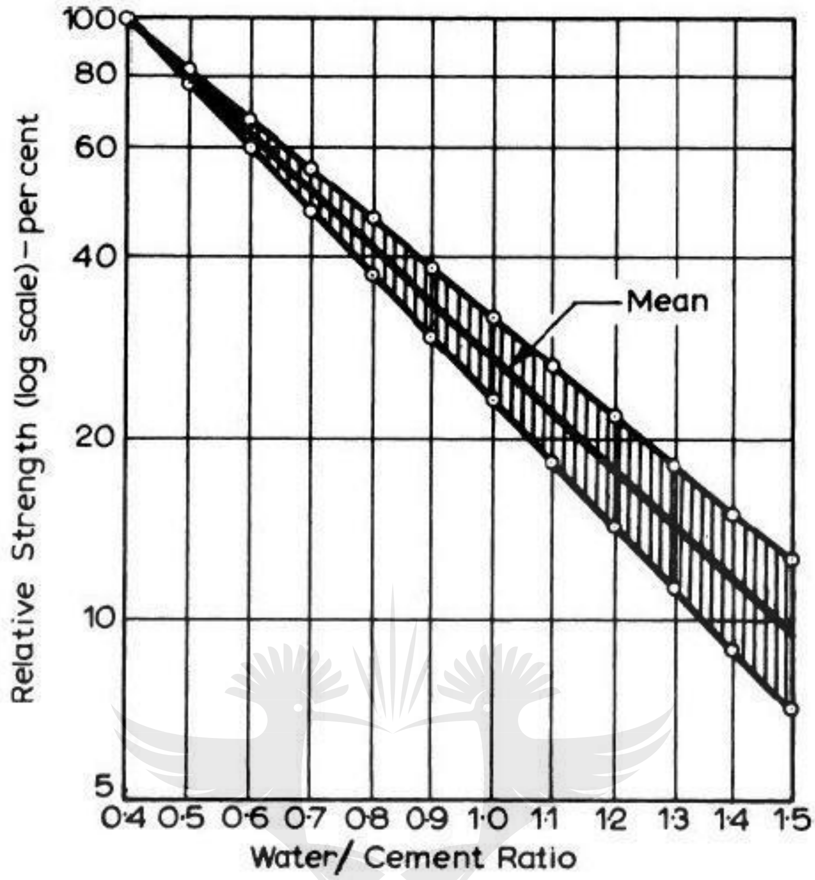


Figure 2.8 Relation between logarithm of strength and w/c ratio (Neville, 2011).

2.4.2 Concrete porosity

According to Soroka & Stern (1979), the strength of the concrete is inversely proportional to porosity.

This relationship can be expressed as shown below (Neville 2011):

$$s = s_o e^{-kp}$$

Where:

S = Strength of concrete at given porosity p

S_o = Strength of the concrete at zero porosity

k = Constant, which depends on the type of cement, age of the sample, and other factors

Figure 2.9 shows the typical results for the various materials (Mehta & Monteiro 2014). This general pattern establishes the fact that porosity is an important factor that affects the strength of materials and it explains why concrete of low porosity has high strength (Addis 1994).

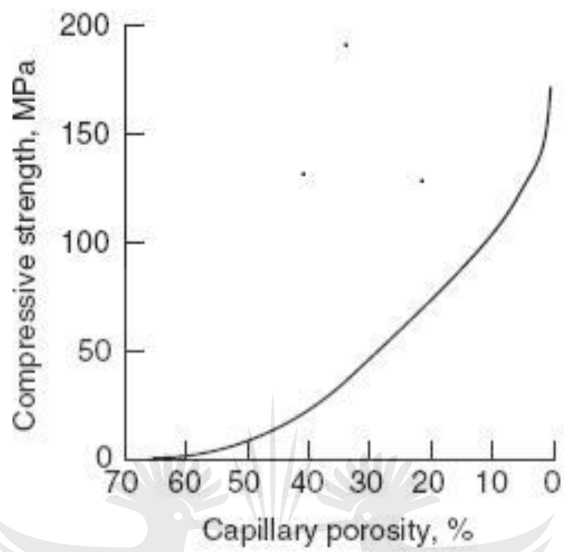


Figure 2.9 Typical results for the various materials

According to Mehta & Monteiro (2014). The volume and size is dependent on the strength of the interfacial transition zone. Overall, it can be seen that the presence of pores and cracks contribute to the overall porosity of the concrete and affect the strength of concrete.

2.5 Curing of Concrete

It has been observed that curing condition is critical to durability properties of concrete (Gopalan 1996). Water-cured concrete exhibits lower sorptivity and permeability than air-cured and steam-cured concrete (Soroka 1979). This indicates that the additional curing reduces the pore size and volume; (Martys & Ferraris 1997). Sufficient curing is needed for complete cement hydration, which is responsible for reduction of pore size and improvement of concrete durability (Neville 2011).

According to Neville (2011), curing is the procedure utilized for advancing the hydration of cement and is comprised of a control of temperature and that of moisture change from and into the concrete; with the point of keeping the concrete saturated or as almost saturated as conceivably possible until the initially water-filled space in the fresh concrete paste has been filled to the ideal degree by the results of cement hydration.

When curing is properly conducted. A reduction of moisture loss occurs and creates a constant moisture that is needed for the hydration process that lessens the porosity and gives a fine pore distribution (Alamri 1988).

The purpose of the curing process is basically to keep the concrete wet, by restricting the loss of dampness from the concrete during the period in which it is gaining strength. It can be conducted in various ways and the most suitable methods for this process might be guided by the site or the construction technique (Bai 2002).

According to experiments conducted by Gonnerman & Shuman (1928), demonstrate that concrete constantly cured in air had a lower compressive strength in contrasted to concrete that is cured in moisture (Price 1951).

According to Guneyisi & Gesoglu (2004), up to 20% of compressive strength of concrete is lost when they are air cured in contrasted with ones that were cured by moisture. Strength was captured 28 days, 90 days and 180 days for the air cured specimen. The results demonstrated that wet curing provided better results with regards to compressive strength.

Soroka & Baum (1994) findings were that at 28 days the compressive strength of the concrete that is cured by moisture was 40% higher than those concrete cubes that did not go through the same process after 90 days. His findings also demonstrated that the cubes that were constantly cured achieved a 20% higher strength than those that did not go through the same process.

2.6 Drying shrinkage

Mehta & Monteiro (2014), define drying shrinkage as the volume decrease in the concrete. It is affected as a result of the dampness change when exposed to a lower relative humid condition than the underlying one in its own pore system (Neville 2011).

It is notable that practically 50% of the water added to the mix will not contribute to the hydration process as a result it won't be bound to the solid stage. Furthermore, the point at which the curing time frame is finished and the concrete is exposed to a low relative humidity (RH) environment, the subsequent inclination goes about as a driver for moist relocation out of the material, trailed by a volume decrease of the porous material.

According to Mehta & Monteiro (2014), shrinkage causes growth in tensile stress, which may prompt cracking, inner twisting, and deflection externally, before the concrete is exposed to any sort of force. Commonly used Portland concrete experiences drying shrinkage or volume variation overtime. The volume variation in concrete is essential to take into consideration when designing and can occur in many concrete structures.

2.7 Tensile strength

In civil engineering structures, tensile strength is a factor to consider in designing (Malárics & Müller 2010). Due to the fact that concrete isn't generally designed for resisting tensile strength, as a design engineer it is important to know the load limitations for the structure. This limitation is vital to avoid erosion of reinforcement as a result of cracking. The tensile strength of concrete helps in understanding concrete although it is not generally accounted for in design. The tensile strength helps us analyze and understand unreinforced concrete structures that are built.

2.8 Concrete mix design

According to Teychenné (1988) it was common practice for the United Kingdom to design concrete mixes, such as the ratio of sand to cement and aggregate, and other ratios. The materials were weighed and the proportions were calculated.

Studies show that most of the structures built on the African continent are cast-in-situ. Generally, the process conducted to produce concrete is manual and not automated on site. Commonly, a bucket or wheel barrow is used to move the concrete to the structural members as shown in Figure 2.10 (Msinjili 2012). Proportions for different strength categories using 19 mm stone are shown in Table 2.2. According to Addis (2009), once workability is achieved, experience and judgment by eye determines the suitability of the mix.

Table 2.2: Nominal mix proportions for different strength categories, using 19 mm stone (Addis, 2009)

Nominal Proportions	Batch based on 1 bag of cement, 50 kg				Concrete strength category
	Proportions			Approx. yield, Litre (L)	
	Cement	Sand in the loose moist state	Stone		
1:4:4	1 bag	130 L	130 L	190	Low, eg House foundation
1:3:3	1 bag	100 L	100 L	150	Medium, eg Domestic drive ways Floors on ground
1:2:2	1 bag	65 L	65 L	105	High, eg workshop Floors

2.9 Admixtures

Admixtures are viewed as additional parts inside the mix design to blend with the cement, water and aggregate as these are the basic constituents in a typical mix design. The only reason behind the inclusion of these admixtures is to change concrete's properties.

Admixtures have the ability to change the time it takes for the concrete to set, they can also modify the strength of the mix design and various other aspects such as workability and colour.

During the last six decades, the concrete admixture industry has grown, this is as a result of the effects of admixtures in both hardened and fresh concrete. In more advanced nations, majority of manufactured concrete products contain admixtures. It is therefore important for structural designers to understand the various admixtures and their advantages thereof.

Figure 2.10: Mixing and transporting concrete at a construction site in Dar es Salaam, Tanzania (Msinjili, 2012)

ACI Committee 212 compiled a list of some significant purposes for admixtures which are the following:

1. Increase the durability of concrete.
2. Reduce the rate of heat evolution.
3. Increase early stage strength.
4. Accelerate or retard concrete's setting time.
5. Reduce bleeding.
6. Reduce segregation.
7. Increase plasticity without adding water.

When the awareness that properties of concrete could be modified, the admixture industry grew significantly. As a result, in the 1940s more than 500 various products were available in England and German combined with 20 years of the realization of the altering impact admixtures have on concrete properties. Many admixtures have more than one function but they are commonly chemical compositions.

Some chemically composed admixtures immediately react to the cement- water system, they do so by inducing surface tension of the water. They also absorb cement particles on the surface. Others admixture affect the chemical reaction of cement and water. This reaction goes on for different durations.

Finely ground materials which are used to redress or substitute piece of the Portland concrete either from characteristic sources or created as results of certain industries, are called mineral admixtures. The physical impact of the existence of these mineral admixtures on the rheological conduct of new fresh concrete turns out to be obvious, however it can take a few days to a while for the compound consequences for hydration to show.

The dissolvable salts and polymers, both surface-dynamic operators and others, are added to concrete in extremely limited quantities (regularly under 2% by weight of cementations material) for purposes, for example, entrainment of air, plasticization of fresh concrete mixes, or control of setting time. By plasticizing a concrete mix, it is conceivable either to build the consistency without expanding the water content, or to diminish the water content while keeping up a given consistency. In this manner, in the United States, the plasticizing synthetic concoctions are called water-reducing admixtures.

The ASTM has separate requirements for air-entraining synthetic substances and for water-reducing as well as set-controlling synthetic substances. ASTM C 260, Standard Specification for Air-Entraining Admixtures for Concrete, sets constrains on the impact that a given admixture under test may apply on bleeding, time of set, compressive and flexural strength.

There is no category that can incorporate all admixture. The convenient approach would be to categorise them in the following way:

1. Mineral admixtures
2. Surface-active chemicals.
3. Set-controlling admixtures.

2.9.1 Accelerators

As the name suggests these are forms of admixture that are utilized to decrease setting time, be that as it may, they do have other valuable capacities as well, for example, increased workability and compressive strength. A few accelerator agents additionally lead to an increment in the improvement of early compressive strength which is particularly helpful in this specific procedure as various layers of cement must be over one another. One of the fundamental downsides to utilizing accelerating agents is that they will in general lead to an increase of plastic shrinkage, nonetheless, different admixtures, for example, superplasticisers can be utilized to offset this impact (Le 2011).

2.9.2 Retarders

This kind of admixture has the contrary impact of an accelerator agent due the fact that it is utilized to delay the setting time of a concrete mix. The retarder accomplishes this as it is artificially intended to anticipate hydration responses happening in the concrete. Retarders are useful on construction projects where rapid setting must not occur, for instance, in areas with hot climates where the retarder is important to anticipate the high surrounding temperature making concrete set too early. It is likewise valuable on projects where there is a postponement among mixing and pouring.

2.9.3 Superplasticisers

According to Le (2011), the consideration of this admixtures in a concrete permits the utilization of less water without changing the workability or pumpability of the concrete. This has evident advantages for 3D concrete printing procedures as it permits lower w/c (water/cement) ratios to be utilized (0.26 and 0.35), which then will give a lower setting time and guarantees the procedure is less tedious.

Accelerators, retarders and superplasticisers are the main categories of admixtures for the modification of concrete. Both a retarder and a superplasticiser can be found in both mix designs for this procedure as a polycarboxylate-based superplasticiser and an amino-tris, citrus acid and formaldehyde retarder.

2.9.4 Silica Fume

According to Khan & Siddique (2011), fine powder is created as a waste by-product in the generation of silicon and silicon compounds and can be found in most HPC mix designs. Silica fumes are fundamentally silicon dioxide (SiO_2) and exist mainly as silica in non-crystalline as shown in Table 2.3; nonetheless, there exists magnesium and iron that are a part of its composition. This added substance is normally utilized in HPC as it envelops the capacity to not just give the concrete a higher compressive strength (over 100 MPa) it provides a diminished setting time. It is hard to decide the setting time of cement without the utilization of research techniques yet, trial information has demonstrated that the incorporation of 30% silica rage can diminish the underlying set time to as low as 30 minutes (Rao 2003).

Table 2.3: Physical properties of Silica Fume (Khan, 2011)

Physical Properties	Value
Particle sizes	< 1 µm
Bulk density as - produced	130 – 430 kg/m^3
Bulk density (densified)	480 – 720 kg/m^3
Specific gravity	2.22
Surface area (BET)	13, 000 – 30, 000 m^2/kg

Research that has been conducted shows that there is a general reduction in water prerequisites when high quantities of silica fume are added to a concrete mix given that there exists adequate superplasticiser Sellevold (1983). The inclusion of silica fume (>5%) without the inclusion of a superplasticiser will prompt diminished workability and greatly expands water demand. The superplasticiser scatters the cement and silica fume particles in the mixture and diminishes the contact point between various grains which implies that less water is required to attain a particular consistency.

2.9.5 Fly Ash

Fly ash is a by-product in the combustion of pulverised coal in power generation stations, Table 2.4 shows the chemical composition of cement CEM I 52,5, fly ash and Limestone powder. According to Longarini, Creapi, Zucca, Giodano & Silvestro (2014), one of the benefits of fly ash is its ability to increase concrete's pumpability especially when it is required to maintain a low content of water and cement at a constant water to cement ratio. Fly ash acts as a cement substitute and is applicable to most types of concrete, not just HPC. Due to the boom of coal based power since the oil crisis of the 1970s, there is no shortage of fly ash available for use in concrete mixtures, in fact fly ash features a very high quantity in ready mixed cements (Liu Deng, De Schutter, & Yu 2011).

Table 2.4: Chemical composition of Cement CEM I 52,5 - fly ash and limestone powder (Liu, Deng, De Schutter & Yu 2011)

Code (%)	C(I) CEM I 52.5	C(III) (HSR) NHSR LA	Fly ash (FA)	Limestone Powder (LP)
SiO_2	19.60	19.94	53.31	0.86
Al_2O_3	4.90	3.13	26.3	0.08
Fe_2O_3	3.10	4.76	7.53	0.34
CaO	63.60	61.56	4.46	56.3
MgO	0.90	-	2.54	0.58
K_2O	0.77	0.66	3.58	0.05
Na_2O	0.41	0.24	1.15	0.08
SO_3	3.30	2.54	0.9	-
LOI	2.10	5.45	4.10	42.0

The use of fly ash in a mix design has various benefits.Fly ash just like silica fumes decreases the permeability of the concrete to water. As a result, the possibilities of steel reinforcement eroding is reduced if the concrete is cured adequately. The size of the pores in the concrete additionally decreases permeability and possibly enhances the strength of the mixture. The fine particles in fly ash (and silica fume) help to decrease bleeding and segregation in the concrete and creates fresh concrete that showcases improved pumpability and workability which thus allows the printing of designs with high architectural features. Fly ash does not only improve the workability of new cement it additionally allows the utilization of a lower w/c ratio.

2.9.6 Clay and Concrete bricks

Bricks are one of the most used and versatile building materials in use today in the construction industry. The Clay Brick Association (2002) characterizes bricks as modular units connected by mortar in the formation of a building system or product. The most widely used bricks are clay bricks and concrete bricks, which are made from clay and concrete respectively. Clay bricks being the most utilized in the construction industry by volume.

In spite of the fact that various speculations exist, it is still not known when it was discovered that a hard and tough product that can be used for construction purposes could be produced by heating clay in a mould.

One of the main reasons why clay bricks are widely used in the construction industry is due to the fact that their manufacturing process is simple. Kaolinite, commonly known as clay can generally be removed inexpensively from the earth.

In recent times, the manufacturing of clay bricks has been conducted through extrusion. Prior to this, the most common manufacturing techniques were through the utilization of moulds as they gave the manufacturer the ability to produce identical bricks because clay becomes mouldable with the addition of water.
The required temperature in a kiln for some clay types is 1000° C and more. Figure 2.11 shows how clay brick manufacturing can be highly mechanized (left image), the image on the right shows the traditional rudimentary kiln.

Figure 2.11: Clay brick processing (Left) and brick processing in a redimentary kiln (right)

There are 7 seven stages detailing how modern clay bricks are manufactured as shown in Figure 2.12 below:

1. Mining
2. Size reduction
3. Screening

4. Forming and Cutting (Extrusion)
5. Coating or glazing (surface treatment)
6. Drying
7. Firing and cooling

Of all the seven stages, firing is the most energy intensive. Due to the high energy demand, coal, gas or oil are the most commonly used energy source for the kilns used in firing and cooling of clay bricks (Clay Brick Association 2002).

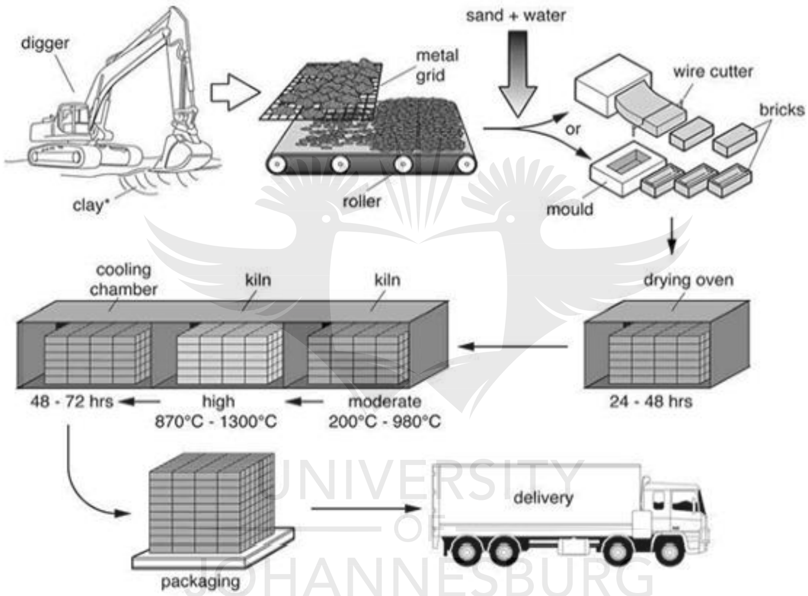


Figure: 2.12: Modern brick manufacturing

2.10 Mix designs

In order for the 3D concrete printing process to progress, an integral part of the process is the mix design. This process requires a level of accuracy regarding materials (i.e cement, aggregate and admixtures) at the right proportions in order for it to have the required workability, setting time, tensile strength and compressive strength for 3D concrete printing.

Below are mix designs from various researchers for 3D concrete printing. Unfortunately, not much research has been done with concrete mix designs for 3D printing applications. The design mix below has been the most used and published design mix for 3D concrete printing.

2.10.1 Loughborough University mix design

Loughborough University has developed a basis for 3D concrete printing mix designs. Table 2.5 details the mix that has been used for other applications all over the world (Le,2011). The mix design had the following properties:

- 3:2 sand-binder (sand aggregate contains no particles larger than 2 mm).
- Binder: 70% cement, 20% fly ash and 10% silica fumes.
- 1.2 kg/m^3 micro polypropylene fibres (12/0.18 mm in length/diameter)
- 0.26 water-cement (w/c) ratio.
- 1% polycarboxylate – based superrplasticizer and 0.5% retarder (amin –tris, citric acid and formaldehyde)

Table 2.5: Composition of denser high performance concrete (HPC) in weight % (Le, 2011)

Component	Composition (wt. %)
Sand	53.5
Cement CEM I 52,5	25.0
Class F Fly Ash	7.1
Silica Fume	3.6
Water	9.3
Polypropylene	0.05
Superplasticiser	1.0
Retarder	0.5

In order to be able to pump concrete, a water to cement ratio of more than 0.4 must be achieved. Superplasticiser forms part of the mix design as it has the ability to maintain workability and reducing Le (2011) the water cement ratio of the mix design.

To achieve adequate open time, a retarder was used. This allowed the mix design to remain workable for more than a hour during the printing. Table 2.6 shows the composition of less dense HPC in terms of weight percentage.

Table 2.6: Composition of less dense high performance concrete (HPC) in weight % (Le, 2011)

Component	Composition (wt. %)
Sand	51.9
Cement CEM I 52,5	24.2
Class F Fly Ash	6.9
Silica Fume	3.5
Water	12.1
Polypropylene	0.05
Superplasticiser	1.0
Retarder	0.3

Blockage in the system can be caused by large aggregate particle sizes. To avoid this, the maximum particle size was 2mm in order to avoid suspending printing activity due to blockage. To decrease plastic shrinkage, propylene fibre was used in the mix design. The fibre has also shown to provide good adhesion for the concrete mix. Silica fume and fly ash are also included on the mix design to improve workability and pumpability.

2.10.2 Loughborough University mix design 2

The high dense mix and less dense mix essentially contain the same materials. The significant difference is that the latter mix has a higher water to cement ratio. As a result, the less dense mix has greater workability. The retarder dosage was increased in the mix design due to the fact that the setting time would be longer as shown below:

- 3:2 sand – binder ratio (sand aggregate contains no particles larger in diameter than 2 mm).
- Binder: 70% cement, 20% fly ash and 10% silica fumes.
- 1.2 kg/m³ micro polypropylene fibres (12/0.18 mm in length/diameter).
- 0.35 water/cement (w/c) ratio.
- 1% polycarboxylate – based superplasticizer and 0.3% retarder (amino-tris, citric acid and formaldehyde).

2.10.3 Concrete Mix Designs for 3D Printing by utilizing 6DOF industrial robot

The 6DOF industrial robot is different from the previous 3D concrete printers used in this research. The machine used in the Loughborough University mix design was a computerized gantry system with a nozzle operating with the structure. The 6DOF industrial robot extrudes the concrete mix using a robotic arm, the advantage of this system is that it is more flexible and can print concrete further from the centre of the machine.

Althougth the machine is different, the requirements for the mix design remain similar. The materials used in the mix design are detailed below:

- Portland cement (General Purpose cement)
- Fine and coarse aggregate
- Superplasticizer
- Water reducer
- Accelerator

- Retarder

Figure 2.13 shows the 6DOF industrial robot that was used in the research. Table 2.7 shows the trials prepared by an extruder for cement mortar and Table 2.8 shows the trials for crushed coarse aggregate by an extruder.

All the 12 mix designs were printed but only 3 were chosen namely: trial 5, trial 7 and trial 8 which were cement mortars and trial 12 had crushed coarse aggregate.The choice of the results were based on the printing quality.

After tests were conducted, a compressive strength of up to 110 MPa was reached.The superplasticizer contributed a range of 0.95% to 2.5% with regards to weight relative to water. To optimize the mix design, a water to cement ratio was 0.39%. To increase the flowability of the mix, superplasticizer was added and contributed 1.9% of the weight. A retarder and an accelareator was also added for rheological purposes. According to Shakor, Renneberth, Nejadi and Paul (2017), the required nozzle size for this mix was 20 mm.

Figure 2.13: 6DOF Industrial Robot

Table 2.7 :Trail prepared by an extruder for cement mortar

Trial No.	C (g)	FS (g)	W (ml)	R (ml)	Acc (ml)	SP (ml)	WR (ml)	Noz (mm)
1	1000	0	360	8	4	10.4	-	Ø20
2	1000	500	300	8	4	10.4	-	Ø20
3	500	500	150	4	4	5.2	-	Ø20
4	750	750	292.5	4	4	5.5	-	Ø20
5	750	750	250	4	5	5	-	Ø20
6	1500	1500	550	8	10	11	-	20 x 20
7	1000	1000	361.6	5.33	6.6	6.67	-	20 x 20
8	1000	1000	343	5.33	6.6	6.6	-	20 x 20
9	1000	1000	350	5.33	6.6	6.5	-	20 x 20
10	1000	1250	375	5	6	5	3	Ø10

C: cement, FS: fine sand, W: water, R:retarder, Acc: accelerator, SP: superplaticizer, WR: water reducer, Noz: nozzles, A: aggregate

Table 2.8: Trails for crushed coarse aggregate by an extender

Trial No.	C (g)	FS (g)	A (g)	W (ml)	R (ml)	Acc (ml)	SP (ml)	WR (ml)	Noz (mm)
11	750	750	250	300	4	5	5	-	20 x 20
12	750	750	250	250	4	5	5	-	20 x 20

As show in Figure 2.14 below, trial 5 produced a successful print and was buildable, trail 7 was very wet as to compared to the other mixes. Trail 8 showed good cohesion and rigidity. Finally, trial 12 displayed bad cohesion and cracks were visible on the surface.

The results also show that voids in the mix design play a significant role in 3D concrete printing, due to the minimal voids in the mortar the printing was more successful in contrast to the mix design that was composed of coarse aggregate (Shakor, Renneberh, Nejadi & Paul 2017).

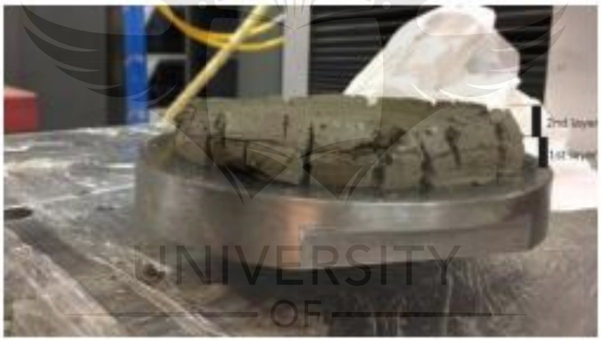
Trial Number	Image	Comment
Trial 5		Successful print
Trial 7		Slightly flow
Trial 8		Good layers
Trial 12		Not good

Figure 2.14: Several printed Specimen shapes

CHAPTER 3: EXPERIMENTAL PROGRAMME AND METHODS

3.1 Introduction

The experimental work was broken down into four phases. The first phase focussed on the machine that was used to conduct the research called a 3D concrete printer. Details regarding its design parameters and its capacity will be thoroughly discussed. The second phase will look at the mix design criteria and properties, which include workability, extrudability, buildability, open time and compressive tests. The thirds is the mix design and the formulation approach. The fourth will be validating whether the design mix achieves all criteria that were set out.

3.1.1 3D concrete printer

The only available printer that could be used for research for concrete printing was a printer by 3D Printcrete which is a company that aims to designs and manufactures 3D concrete printers for low income houses.

The printer was designed to be able to be disassembled and assembled quickly and to make it as mobile as possible for construction purposes. The top part of the printer can slide off from the base and then lay flat. It needs at least two people to assemble/disassemble the system. The system will be supplied from 220V AC power. This design can print a cement-based material to create structures. Figure 3.1 shows the digital design of the printer and Figure 3.2 shows the manufactured printer in a laboratory.

Figure 3.1: Digital design of 3D concrete printing structure

Figure 3.2 3D concrete printing structure

Standard steel sizes were used in the design to keep machining to a minimum. The base of the printer is a standard universal beam on which a rail is welded for the horizontal movement of the printer assembly as shown in Appendix A. The rest of the structure is made from standard rectangular tubing with cross members for stiffness. The printing head assembly is mounted on linear bearings to provide vertical movement of the head assembly. The printing head is hanging from two gliders to provide the horizontal movement of the printing head. The flexible hose for the printing material is also connected to the glider system to provide easy movement.

The printer has the following design properties:

- Concrete filament print width: 20 mm
- Machine print speed: 200 to 1500 mm/s
- Printable area: 4 x 3 x 4 m^3

3.1.2 Electronics

The printer system has five drives, two for X-axis, two for Z-axis and one for Y-axis. The X and Y drives are Nema 34 size stepper motors and the Z axis is a Nema 42. The X-axis and Z-axis motors are connected in parallel and are stepped in tandem. The motor drive controllers are housed in an IP 65 steel enclosure as shown in Figure 3.3. The driving mechanism on all drives is a toothed gear with a tooth belt which will give a resolution of 0.88 mm per step with a speed of up to 2.5 m/s.

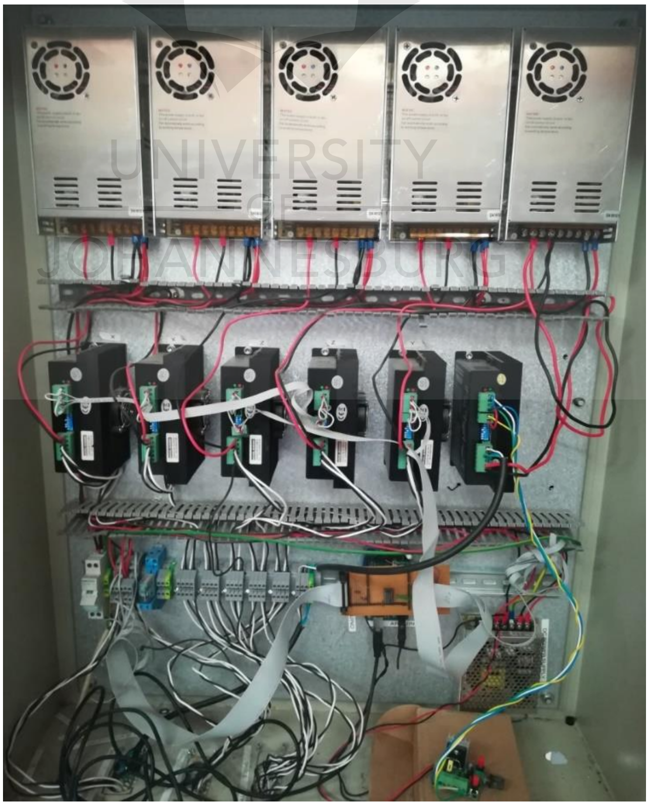


Figure 3.3: Electronics and control systems running the machine

3.1.3 Control system

The control system is based on the Arduino Mega controller with a 128 x 64 graphic display. The system also has on-board capabilities. A new design can be loaded from a USB drive and then printed. The control system is housed in a metal enclosure mounted on the pumping system structure with a trailing cable running to the moving structure.

3.1.4 Pumping and Extrusion System

The material will be pumped through a printing head/nozzle with a constant pressure flow pumping system shown in Figure 3.6 and Figure 3.7 respectively. The system has a reservoir for mixing the materials shown in Figure 3.4. The material will be transported to the head through a 20 mm diameter flexible hose shown in Figure 3.5. Flow rate of material will be between 0.4 m^3/h and 1.5 m^3/h, depending on the printing speed. At the slowest printing speed the time that material will spend in the system after mixing will be 17 seconds at 0.5 m/s printing speed with a 20 mm feeding pipe. The pipe length from the mixer to the printing head will be 5.5 m in length. Figure 3.8 shows the fully integrated system.

Figure 3.4: Concrete mix reservoir

The most significant problem will be to ensure that the additives are mixed thoroughly enough to ensure repeatable results on the end product. A large batch of materials will be mixed dry at one time for consistency, water will then be added before the mix is fed into the machine.

Figure 3.5: Flexible hose for transporting concrete

Figure 3.6: Concrete printing head

Figure 3.7: Concrete Pump

Figure 3.8 Fully integrated system pumping water

3.2 Concrete tests to be conducted - Concrete criteria

As discussed in section 1.5 in the dissertation, one important task is to compose a set of criteria for the concrete mix design. This section will focus on the concrete criteria.

3.2.1 Workability of fresh concrete

Workability is defined by ACI Committee 116R (2000) as that property of freshly mixed concrete or mortar which determines the ease with which it can be mixed, placed, consolidated and finished to a homogeneous condition. It is also defined as the relative ease with which concrete can be mixed, transported, moulded and compacted.

The commonly used method for testing working of mix designs is the slump test method. It is used, indirectly, as a means of checking that the correct amount of water has been added to the mix. The test is carried out in accordance with BS EN 12350-2, testing fresh concrete. This replaces BS 1881: Part 102.

The steel slump cone is placed on a solid, impermeable, level base and filled with the fresh concrete in three equal layers. Each layer is rodded 25 times to ensure compaction. The third layer is finished off level with the top of the cone. The cone is carefully lifted up, leaving a heap of concrete that settles or 'slumps' slightly. The upturned slump cone is placed on the base to act as a reference, and the difference in level between its top and the top of the concrete is measured and recorded to the nearest 5 mm to give the slump of the concrete.

Some of the challenges with the slump test method is that it does not measure the fundamental physical properties of the mix design. It does not render adequately robust rheological results for the 3D concrete printing.

To measure the relative ease with which concrete can be mixed, transported, moulded and compacted, a cone was selected and then the mix was pushed through the cone to study the ease with which the mix design goes through the cone. This method does not provide the perfect solution but it provides a good guideline.

The sheet shown in Figure 3.10 was used to measure the spread with the cone shown in Figure 3.9 with the following properties:

- Lower diameter: 60 mm and top diameter of 85 mm.

- Height: 50 mm.

The mixed material was inserted in the cone and then lifted. The spread of the mix on the sheet was then measured every time to see how workable the mix is.

This will be the strategy for measuring workability. Additional to this, there are two key measurements that will be observed and will be also used as a guideline and measurement in this experiment. The mixture will be deemed workable if it satisfies the following:

- Workable enough to go through the cone.
- Will not completely collapse after going through the cone (spread).

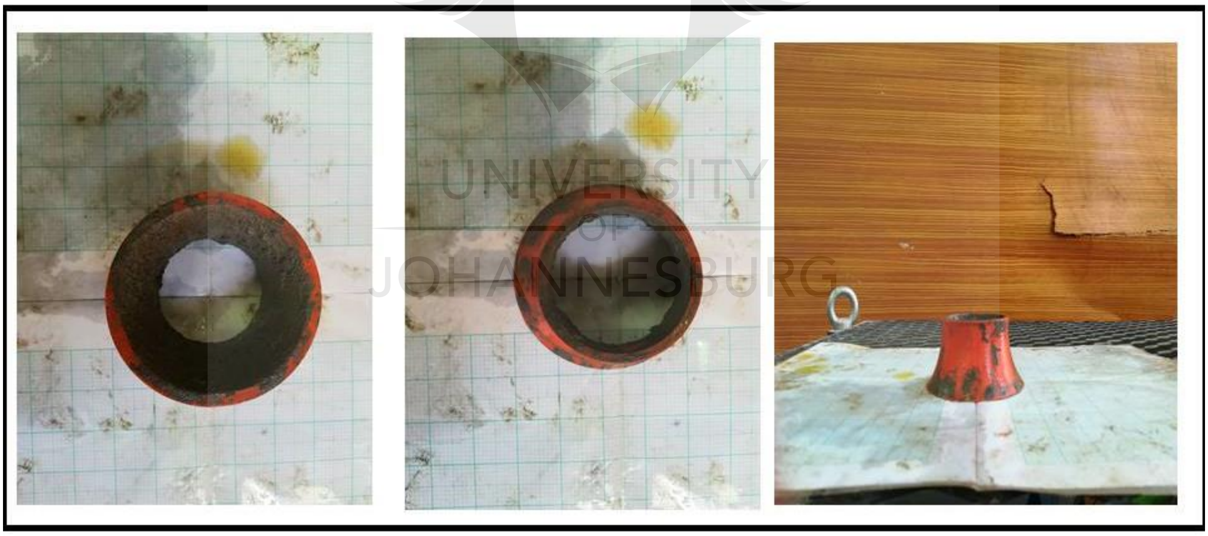


Figure 3.9: Cone used to measure for workability

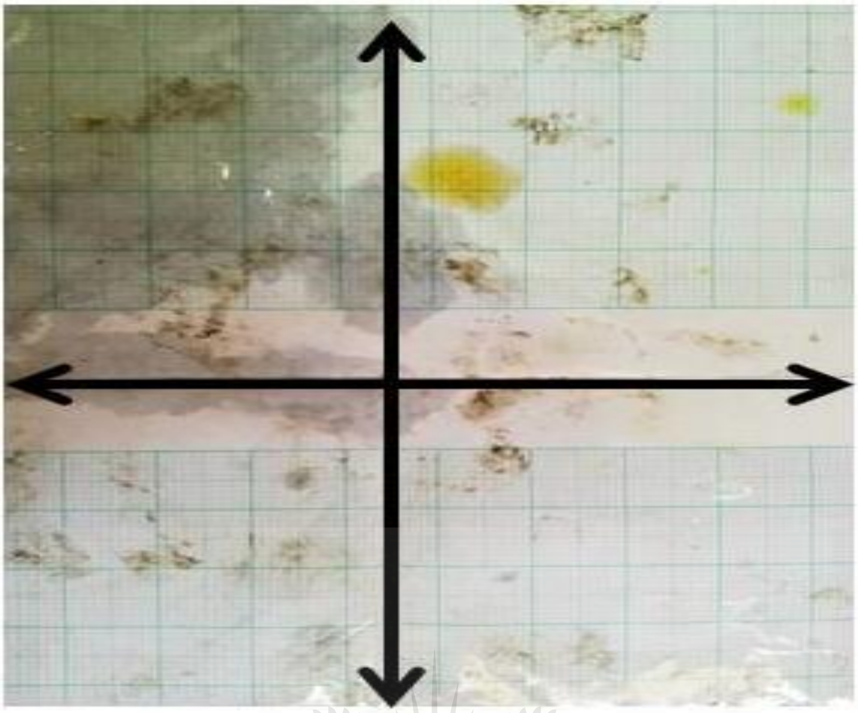


Figure 3.10: Sheet used to measure spread

3.2.2 Extrudability

Extrudability in this research as the ability to pump the concrete through the system to the nozzle where it must be extruded as a continuous filament.

Below is the process taken to measure extrudability:

- A nozzle size of 20 mm will be used for the experiment.
- An attempt to print a continuous filament will then be undertaken.
- A 500 mm strip will be printed.
- The filament should not be fractured and there must not be any blockage in the system

3.2.3 Buildability

Buildabilty is defined as the number of layers printed without noticeable deformation of lower layers (Malaeb, Hachem, Tourbah, Maalouf, Zarwa & Hamez 2015). For the structure to be buildable, the mix should first be workable and extrudable. Therefore, buildabilty is a function of workability and extrudability. For the purposes of this experiment, 35 layers will be printed.

The following approach was taken to measure buildabilty:

- The mix must be workable.
- The mix should also be extrudable.
- The mix must support the extrusion of 35 layers.

If all the above criteria is achieved then the mix is deemed to be buildable. Table 3.1 was used to assess buildability.

Table 3.1: Buildability table

Description	Yes	No
Workability		
Extrudability		
Layers (minimum of 35)		
Buildability		

3.2.4 Open time

A cementitious material has a direct relationship with the time it takes to set and this duration is called open time. In this investigation, the open time will be defined as the duration of concrete workability and will end when the concrete is no longer workable. The following approach was taken to investigate open time:

- The concrete mix was inserted in the concrete container.

- Continuous filaments were printed.
- Extrusion was measured in 5 minutes intervals until extrusion was no longer possible.
- The mix was deemed to have sufficient open time if continuous filament printing could continue for at least 30 minutes.

Table 3.2 was used to capture the information.

Table 3.2: Open time table for mix

Mix	Time (Min)	Extrudable (Yes/No)	Comments
	0		
	5		
	10		
	15		
	20		
	25		
	30		

3.2.5. Compressive strength

The compressive strength of concrete is defined as the resistance to failure under the action of compressive forces Le (2011). Concrete's compressive strength is an important parameter to determine the performance of the material during service conditions.

Compressive strength is a key property which was tested with cast and printed structures. The target strength is approximately 20 MPa at 28 days which is higher than a standard face brick used as a guideline.

The maximum load failure will be taken and the average compressive strength determined in accordance with SANS 5863:2006. The following approach was taken in this investigation:

- 6 cubes were cast.
- 100 mm cube moulds were used.

- The cubes were demoulded after 24h then cured at ambient temperature in water.
- The targeted compressive strength of at least 20 MPa at 28 days qualified the mix as successful in this investigation. The reference for this strength is the typical strength of a brick used to build houses which requires that the nominal compressive strength for face bricks be not less than 17.0 Mpa (SABS 227:2002).

Table 3.3 was used to capture the different compressive strengths after 24 hours, 7 days and 28 days.

Table 3.3: Compressive strength table

Age (days)	Strength
1	
7	
28	

It is also important to state that the compressive strength test was only conducted when workability, extrudabilty, open time and buildability tests were deemed successful. Once the four tests were successful, the mix design was tested for compressive strength.

3.3 Concrete mix design - formulation

Mix design can be defined as the process of selecting suitable ingredients of concrete and determining their relative proportions with the object of producing concrete of certain minimum strength and durability as economically as possible Le (2011).

The concrete mix design is a critical aspect of this investigation and this was an iterative process. The goal was to meet the criteria in Section 3.2 of this dissertation. The following procedure was followed to achieve the objectives set out in Section 3.2:

- The first mix was a Mapei pre-packaged formulation; this mix was readily accessible and met our minimum criteria based on its properties. Used for repairing new and old concrete structures or reinforced concrete elements. Through an investigation, this mix should yield results that are close to desired criteria and objectives.
- The second mix design that was investigated was a formulation developed by the Department of Civil Engineering and Building Engineering at the University of Loughborough on the hardened properties of high-performance printing concrete. The mix reached a compressive strength of 110 MPa which is high for this research. An amended Loughborough University mix will be investigated.
- Thirdly, based on experiments with the two mixes stated above, a mix design was developed that was suitable for our objectives using local materials.

3.3.1 Mapei Mix – Mapegrout T60 ME

Mapegrout T60 ME is usually used to repair both new and old concrete structures or reinforced concrete elements which have been subjected to aggressive atmospheric conditions including chloride and sulphate attack Mapei (2016).

Mapegrout T60 ME is a single component, thixotropic cement-based mortar formulated to compensate for hygrometric shrinkage. Mapegrout T60 ME is composed of pre-blended hydraulic binders, synthetic polyacrylonitrile fibres, organic corrosion inhibitors, selected aggregates and special water-retaining additives, developed in the MAPEI Research Laboratories. Table 3.4 shows properties of Mapegrout T 60 ME in more detail.

Table 3.4: Technical data for Mapei pre-packaged mix

Class according to EN 1504-3	R4
Type	CC
Consistency	Powder
Colour	Grey
Max. size of aggregate (mm)	2.5
Bulk density (kg/m^3)	1450
Dry solids content (%)	100
Application data of product (at +20 degrees- 50% R.H	
Colour of mix	Grey
Mixing ratio	Mapeigrout T60 ME with the folllowing quantities of water: • 3.75 – 4.25 L per 25 kg bags. • 250 ml for 4 bags of Mapegrout
Consistency of mix	Thixotropic
Density of mix (kg/m^3)	2280
pH of mix	>12.5
Application temperature range	From + 5 degrees to 50 degrees
Pot life of mix	1 hour
Waiting time between each layer	Max 1-2 hours

3.3.2 Amendment of Loughborough University mix design

The original Loughborough University mix design discussed in section 2.11.1 was amended. The target strength for our research is around 20 MPa, The South African Standard Specification for burnt clay masonry units (SABS 227:2002) requires that the nominal compressive strength for face bricks be not less than 17.0 Mpa, with individual strengths greater than 12.5 MPa.

The only available nozzle size diameter is 20 mm. w/c ratio changed from 0.26 to around 0.7 which provided a compressive strength of about 20 MPa Neville (1981) as shown in Figure 3.11.

The mix is composed of a 3:2 Sand to binder ratio respectively. The binder is composed of 70% Cement I 32, 20 % Fly Ash and 10% Silica Fume. Additionally, Polypropylene fibre 0.02 kg, 1.7 kg of water (W/C ratio of +/- 0.7) to reduce strength were also added. This was for 5 kg mix. The amended mix design is shown in Table 3.5.

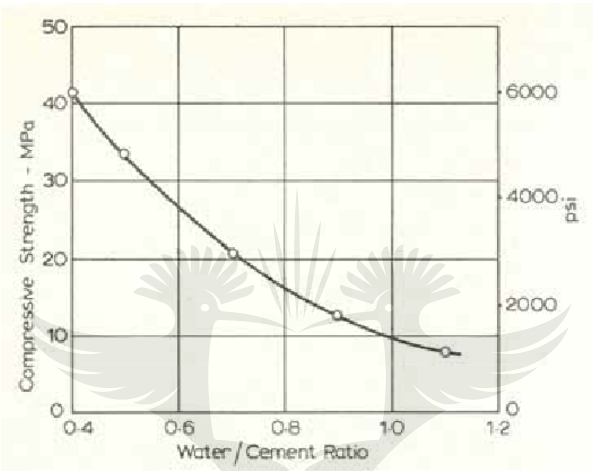


Figure 3.11: Water/cement ration against compressive strength (Neville, 1981).

Table 3.5: Concrete mix design of amendment of Loughborough University mix design

Components	Composition (wt. %)
Sand	44.64
Cement CEM I (32,5N)	20.83
Fly Ash	5.95
Silica Fume	2.98
Propylene fibre	0.3
Water	25.30

3.4 Validating of mix design formulation

The last task was to validate the formulation by printing a structure that was at least 150mm high and that met all criteria and objectives mentioned earlier in the dissertation. This confirmed that the mix design works and can be used for 3D printing of concrete.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Introduction

The concrete printer setup were made to efficiently conduct the research. The concrete criteria were clearly defined and methods for investigating workability, extrudability, buildability, and open time were addressed. The mix design formulation approach was also covered. Finally, the process of validation of the mix design was addressed in the previous chapter. This chapter will assess the results obtained followed by a discussion at the end of this chapter.

4.2 3D Concrete Printer

4.2.1 Concrete printing process

As stated in Chapter 3, the concrete printing process was conducted as follows:

- Mix the concrete mix on the ground.
- Transfer the mix to the container.
- Pump the concrete from the container through a pipe.
- Extrude the concrete through the nozzle.

Figure 4.1 demonstrates the 3D concrete printers original extrusion system. The same process was followed with the mix design.

Figure 4.1: Original 3D concrete printing extrusion system

During priting of the concrete mix, the following challenges were experienced with the original 3D printer setup and design:

- The mixture could not be consistently pumped from the tank to the nozzle because the material would experience blockage in the pipe. A more powerful and expensive pump was required to conduct the experiment.
- When the material ocassionally reached the end of the nozzle, there was no consistency with the extruded material.

Due to the issues raised above, the following changes were made to the system:

- The concrete reservoir was removed from the system.
- The pipe or conduit was removed from the system.
- The original nozzle was removed from the system.
- A localised container system was designed that has properties of a concrete container, pump and could also act as a nozzle as shown in Figure 4.2 and Figure 4.3

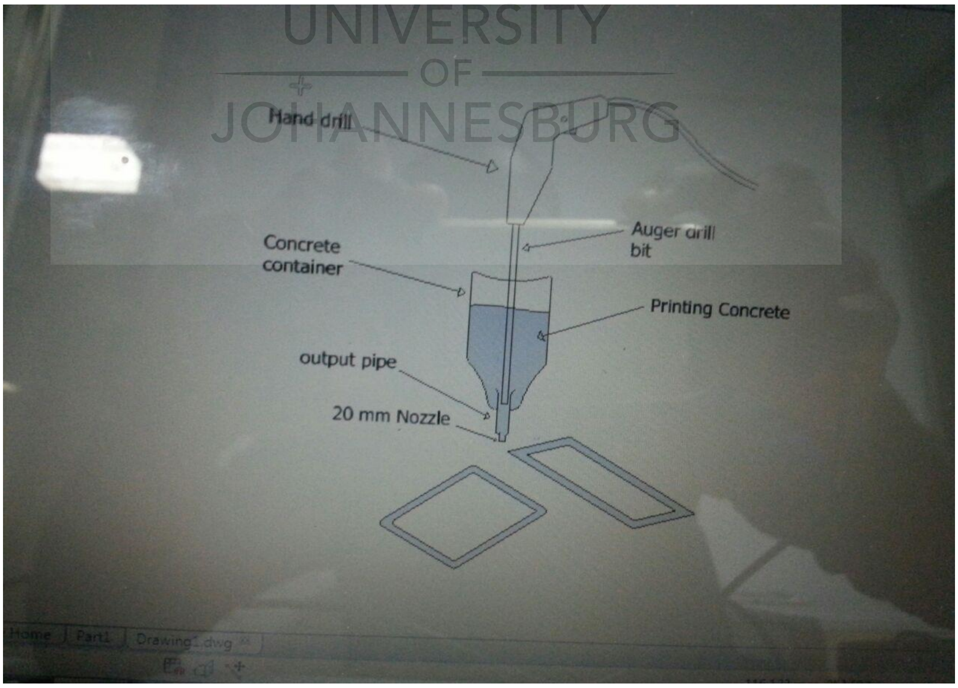


Figure 4.2: Concept concrete printing system

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Figure 4.3: Manufactured concrete container and nozzle

The system in Figure 4.3 shows a container that has a compartment for adding the concrete mix to the system (left side of container). This system also has a nozzle below for extrusion with a nozzle diameter of 20 mm.

A drill system was attached to the container with a drill bit to drive the concrete through the system effectively replacing pump for extrusion as shown in Figure 4.4.

Figure 4.4: Inclusion of drill to drive concrete extrusion

4.2.2 Final design

The drilling machine was succesful in being utilized as an extruder but ran independent of the rest of the machine making coordination difficult.

The challenges encountered were the that there was no coordination with the gantry and the drill. The gantry system would start moving before the drill would begin to extrude the mix. Also, the drilling system was sometimes unstable and affected the concrete extrusion with regards to consistency and quality.

The solution was to mix the material directly from the container system and replace the drill that was previously used with a Nema 32 stepper motor for the mixing as shown in Figure 4.5.

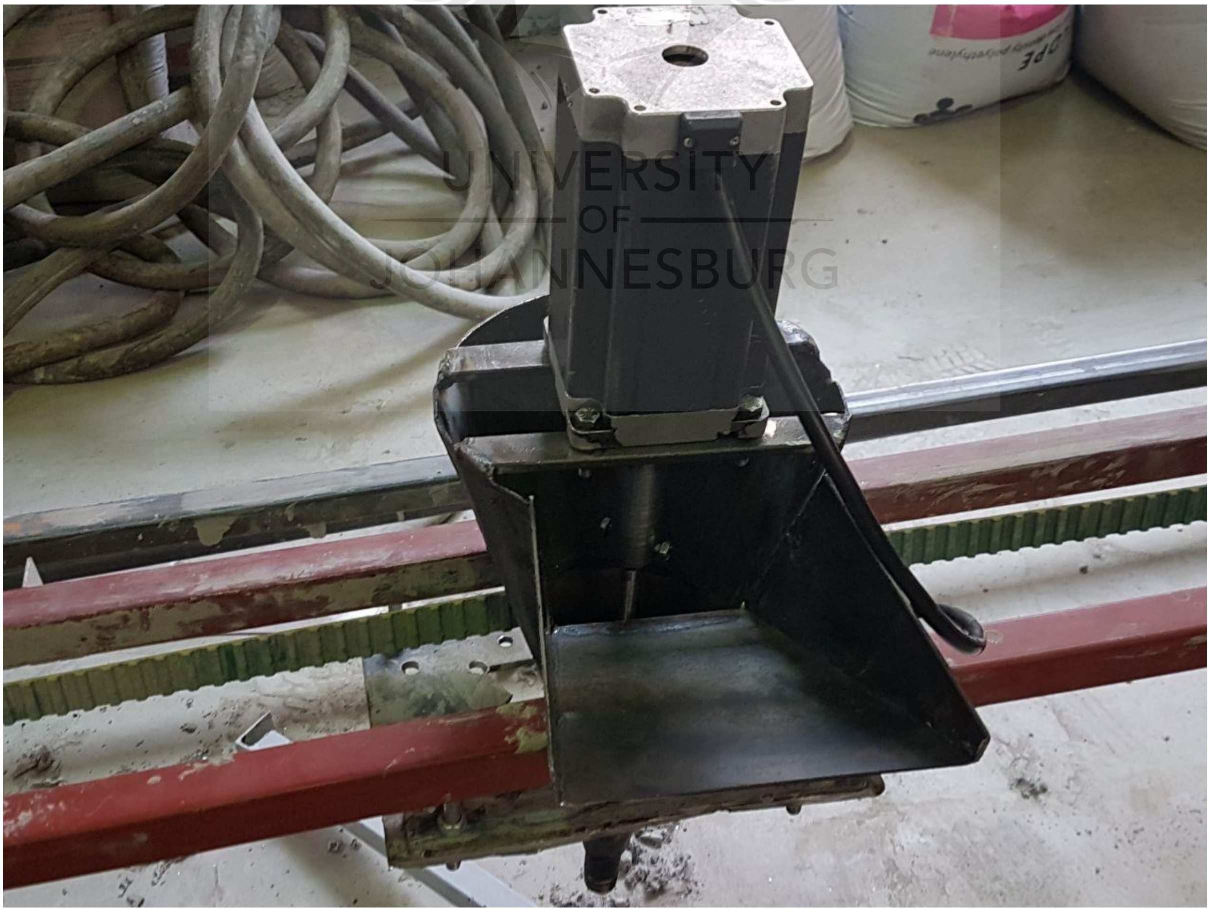

Figure 4.5: Nema 32 Motor connected to the container system replacing the drill

The motor was successfully connected to the system. This final system effectively replaced the following:

- Concrete container/reservoir shown in Figure 3.4
- The pump shown in Figure 3.7
- The piping/hose shown in Figure 3.5
- The independent nozzle shown in Figure 3.6
- The drill as shown on Figure 4.4

The changes implemented allowed for better coordination between the gantry system and the extrusion system and created more stability for printing which is demonstrated in section 4.3.

4.3 Material design experiments

This section will focus on the concrete mix designs and the criteria previously discussed in Section 3.2:

1. The concrete mix must have good workability.
2. The concrete must have good extrudability.
3. The concrete must have sufficient open time (30 minutes at least).
4. The concrete must have sufficient compressive strength (+/- 20 MPa after 28 days).

4.3.1 Mapei - Mapegrout T 60 ME

4.3.1.1 Workability

As per the procedure discussed in Section 3.2.1, the workabilty of the mix was measured using a cone and sheet for the Mapei mix and shown Figure 4.6 and Figure 4.7.

Figure 4.6: Mapei mix on sheet

Figure 4.7: Mapei mix next to cone

The mix readily went through the cone without challenges. The results are shown in Table 4.1.

Table 4.1: Workabilty table - Mapei mix

Description	Yes	No
Goes though cone	x	
Does not completely collapse	x	
Therefore Workable?	**x**	

The mix satisfies the criteria setout for workability. Therefore the mix is deemed workable.

4.3.1.2 Extrudability

Extrudability is defined as the ability to pump the concrete through the system to the nozzle where it must be extruded as a continuous filament Le (2012).The criteria were discussed in Section 3.2.2 and Figure 4.8 shows a continosly printed strip for the Mapei mix.

Figure 4.8: A continuous printed strip using the Mapei mix

The continuous strip was printed successfully, the results are shown in Table 4.2.

Table 4.2: Extrudability table – Mapei mix

Description	**Yes**	**No**
Mix workable	x	
Continous filament	x	
No blockage and fracture	x	
Achieved 500 mm filament length	x	
Therefore Extrubable?	x	

Based on the extrudabilty criteria in Table 4.2, the mix was suitable for extrudable as it met all four criteria.

4.3.1.3 Open time

As per discussion in Section 3.2.4 , the approach was conducted as follows:

- The concrete mix was inserted in the concrete container.
- Continuous filaments were printed.
- The extrusion process took place at least every 15 minutes.
- The extrusion process continued until extrusion was no longer possible.
- The mix was deemed to have sufficient open time if continuous filament printing could continue for at least 30 minutes.

The continuous strip was printed successfully as shown in Figure 4.9, the results are tabulated in Table 4.3.

Figure 4.9: Continuous printed strips over time using Mapei mix

Table 4.3: Open time table –Mapei mix

Mix	Time (Min)	Extrudable (Yes/No)	Quality
Strip 1	0	Yes	Good
Strip 2	5	Yes	Moderate to Bad
Strip 3	10	Yes	Bad

The mix design showed very short open time. After 5 minutes it became difficult to extrude the mix. After 10 minutes the mix printed only with bad quality. Therefore based on the criteria, the mix did not pass the open time criteria.

4.3.1.4 Buildability

Buildabilty is defined as the number of layers printed without noticeable deformation of lower layers. Due to its short open time, buildabiity test were not conducted as shown in table 4.4.

Table 4.4: Buildability Table – Mapei mix

Description	**Yes**	**No**
Workability	x	
Extrudability	x	
Open time		X
Layers (minimum of 35)		N/A
Buildability		**X**

The mix was therefore failed for buildabilty as this is a function of workability, extrudability and open time.

4.3.1.5 Compressive strength

The compressive strength will only be measured when all criteria were met as discussed in Section 3.2.5. Therefore, compressive strength was not measured as a result.

4.3.2 Amended Loughborough University design mix

4.3.2.1 Mix design

The mix design shown in Table 3.5 was used to test the criteria as per Section 3.3.2.

4.3.2.2 Workability

The workabilty of the mix was measured using a cone and sheet for the Amended Loughborough University desing mix and shown Figure 4.10 and Figure 4.11.

Figure 4.10: Amended Loughborough University mix on sheet

The mix does not completely collapse and shows good workabilty based on the criteria mentioned in section 3.2.1. The only difference compared to the Mapei mix is that it is slanted to the side after removing the cone as shown in Figure 4.11.

Figure 4.11: Amended Loughborough University mix next to cone

The mix readily went through the cone without challenges. The results are shown in Table 4.5.

Table 4.5: Workability table - Amended Loughborough University design mix

Description	Yes	No
Goes though cone	x	
Does not completely collapse	x	
Therefore Workable?	**x**	

Based on our criteria the mix was deemed workable as it readily went through the cone and did not completely collapse.

4.3.2.3 Extrudability

Extrudability was tested for the amended mix design from Loughborough University. Figure 4.12 shows the extruded strip from amended Loughborough university mix.

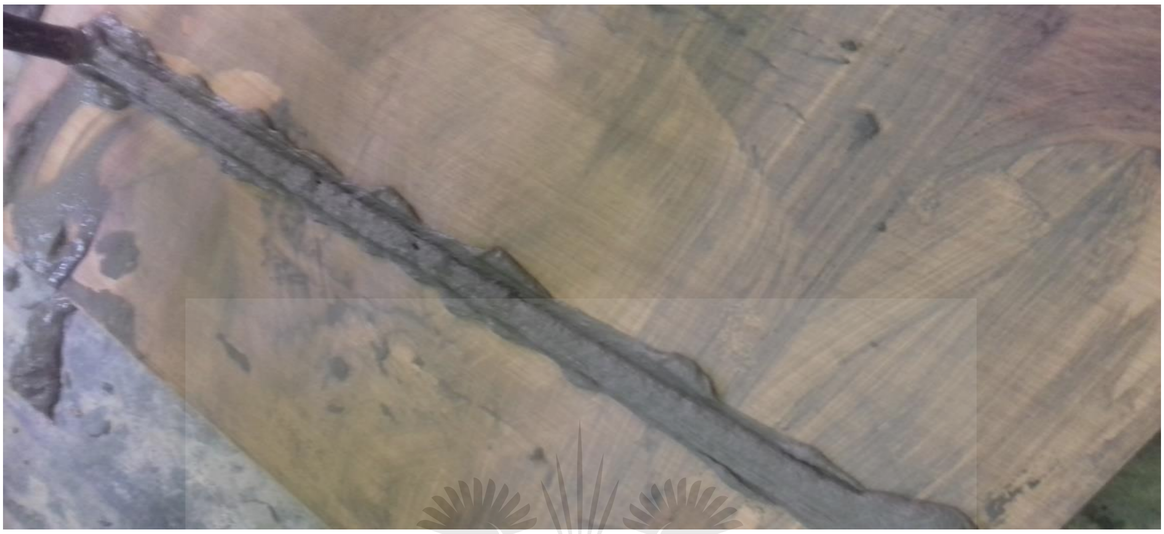

Figure 4.12: Continuous printed strip using the Amended Loughborough University mix

The continuous strip was printed successfully, the results are shown in Table 4.6.

Table 4.6: Extrudability table - Amended Loughborough University mix

Description	Yes	No
Mix workbable	x	
Continous filament	x	
No blockage and fracture	x	
Achieved 500 mm filament length	x	
Therefore Extrubable?	x	

The mix design showed good workability and the filament was printed continously without blockage or fracture. The mix also managed to achieve a printable length of 500 mm. Therefore meeting the criteria for extrudability.

4.3.2.4 Open time

Open time was also tested for this mix. By observation, the mix was more damp relative to the other mixes. Three strips were printed as shown in Figure 4.13 and the results were captured in Table 4.7 below.

Figure 4.13: Continously printed strips over time using the Amended Loughborough University mix

Table 4.7: Open time table - Amended Loughborough University

Mix	Time (Min)	Extrudable (Yes/No)	Quality
Strip 1	5	Yes	Good
Strip 2	10	Yes	Good
Strip 3	45	Yes	Good

Due to how wet the concrete mix , the extrusion occured after 5 minutes, 10 minutes and then to 45 minutes. All the criteria to deem this mix extrudable were met. This mix displayed the longest open time amongst the mixes tested in the research.

4.3.2.5 Buildability

Buildabilty is defined as the number of layers printed without noticeable deformation of lower layers. The same procedure was conducted for this mix because the mix was successful for workability, extrudability and open time. As shown in Figure 4.14, the mix design's buildabilty was relatively high but only managed to print 10 layers. This was primarily because the mix was wet and collapsed when it reached 10 layers. Overall this showed good buildabilty but did not meet our minimum criteria of 30 layers. The results are displayed in Table 4.8.

Figure 4.14: Buildability of the Amended Loughborough University

Table 4.8: Buildability table - Amended Loughborough University design mix

Description	**Yes**	**No**
Workability	x	
Extrudability	x	
Open time	x	
Layers (minimum of 30)		x
Buildability		**x**

4.3.2.6. Compressive strength

Compressive test did not go ahead due to the fact that buildability was unsuccessfully; not all criteria were achieved so the compressive strength test was not conducted.

The mix showed good workabilty, extrudability and open time as per our criteria. The only criteria it did not meet is buildability as it only achieved 10 layers for the amended mix. The mix was changed in Section 4.3.3 to design a mix that met all criteria.

4.3.3 Revised Amended Loughborough University mix design

The amended Loughborough University mix design showed good signs of a printable mix the only major issues that had to be resolved were the following:

- Limitation with regards to buildability due to lack of early yield strength.
- Structural integrity.

To solve the two issues above, the following decision was taken:

1. To achieve early yield strength by using early yield strength cement. For this study, PPC's OPC CEM I 52,5 N cement was used.
2. The second was to print structures with bracing properties such as trusses.

Table 4.9 shows the composition of the revised mix design.

Table 4.9: Revised mix design formulation

Components	Composition (wt. %)
Sand	44.64
Cement CEM I (52,5N)	20.83
Fly Ash	5.95
Silica Fume	2.98
Propylene fibre	0.3
Water	25.30

4.3.3.1 Workability

Workabiltiy test of the revised mixed design was also conducted and shown in Figure 4.15 and Figure 4.16 below. The mix did not readily go through the cone initially but it did eventually fit through. It was a bit stiffer than the previous mix designs and there was no spread.The mix also did not collapse, hence meeting all citeria for workability. The results are shown in Table 4.10.

Figure 4.15: Revised mix on sheet

Figure 4.16: Revised mix next to cone

Table 4.10: Workabilty table - Revised mix

Description	Yes	No
Goes though cone	x	
Does not completely collapse	x	
Therefore Workable?	x	

4.3.3.2 Extrudability

The next test that was conducted was for extrudability. Figure 4.17 shows the strip that was printed.

Figure 4.17: Continuous printed strip using the revised mix

The filament also showed continuity with no blockage and managed to achieve a length of 500 mm. Based on the criteria, this mix was deemed extrudable as shown in Table 4.11.

Table 4.11: Extrudability table - Revised mix

Description	Yes	No
Mix workable	x	
Continous filament	x	
No blockage and fracture	x	
Achieved 5 mm filament length	x	
Therefore Extrubable?	x	

4.3.3.3.Open time

Open time was then tested for the revised mix. As per standard procedure, three strips were printed against time for the various strips shown in Figure 4.18.

The mix showed good open time. Open time was tested after 5 and then after 10 minutes. The mix still seemed wet and extrudable and the filament was printed again after 30 minutes. The quality of the print remained good. The mix design therefore met all criteria with regards to open time as shown in Table 4.12.

Figure 4.18: Continuous printed strips over time using the revised mix

.

Table 4.12: Open time table - Revised mix

Mapei mix	Time (Min)	Extrudable (Yes/No)	Quality
Strip 1 (Bottom)	5	Yes	Good
Strip 2 (Middle)	10	Yes	Good
Strip 3 (Top)	30	Yes	Good

4.3.3.4 Buildability

The same procedure was conducted to test for buildability. As per discussion in section 4.2.3, the design of the structure that should be printed would have bracing for structural integrity. This was done for buildability as the Figure 4.19 and Figure 4.20 shown below.

Figure 4.19: Buildability of the revised mix

Figure 4.20: Elevation view of printed object – revised mix

The mix design performed relatively well for buildabilty as it managed to build 25 layers in total.Unfortuantely, it still did not meet the 30 layer criteria that had been established as shown in Table 4.13.

A build up of the polypropylene fibre at the bottom of the nozzle was observed. The fibre built up over time causing a loss of consistency overtime during printing.

Table 4.13: Buildability - Revised mix

Description	Yes	No
Workability	x	
Extrudability	x	
Open time	x	
Layers (minimum of 30)		x
Buildability		**x**

4.3.3.5 Compressive strength

As per discussed procedure, the compressive test was only to be conducted when workability, extrudabilty, open time and buildabilty is achieved. For these reasons, the compressive test was still not conducted.

4.3.4 Final mix.

4.3.4.1 Final changes

The revised mix met almost all of the criteria that were set out based on the results from the previous tests conducted in Section 4.3.2. The only new addition was to replace the propylene fibre with 0.1 kg's of glass fragments to reduce blockage during extrusion as a replacement. The Final mix and glass fragments that were used are shown in Table 4.14 and Figure 4.21 respectively.

Table 4.14: Final mix design with glass fragments

Components	Composition (wt. %)
Sand	44.12
Cement CEM I (32,5N)	20.59
Fly Ash	5.88
Silica Fume	2.94
Glass Fragments	1.47
Water	25.00

Figure 4.21: Glass fragments to be added to mix

4.3.4.2 Workability

As with previous mixes, the workability was measured by observing that the mix design goes through the cone with relative ease. The second test was to make sure that the mix does not completely collapse afterwards. Figure 4.22 and Figure 4.23 below show the final mix design outcomes with the inclusion of the glass fragments for workability. The mix went through the cone and did not collapse afterwards. This then qualifies this mix as workable as captured in Table 4.15.

Figure 4.22: Final mix on sheet

Figure 4.23: Final mix next to cone

Table 4.15: Workability table - Final mix

Description	Yes	No
Goes though cone	x	
Does not completely collapse	x	
Therefore Workable?	x	

4.3.4.3 Extrudability

The next test was for extrudability. The mix showed the requisite qualities to be workable, continuously printed, had no blockage or fracture and managed to achieve 500 mm of length as shown in Figure 4.24. As a result, this mix was deemed extrudable as captured in Table 4.16.

Table 4.16: Extrudability table – Final mix

Description	Yes	No
Mix workable	x	
Continous filament	x	
No blockage and fracture	x	
Achieved 500 mm filament length	x	
Therefore Extrudable?	x	

4.3.4.4 Open time

The open time for the mix was exceptional. The strips were printed after 5 minutes, 10 minutes and lastly after 30 minutes as shown in Figure 4.25. The consistency was also good.

Figure 4.24: Continuous printed strip using final mix

As per criteria, the mix was still extrudable after 30 minutes. The mix therefore has sufficient open time as captured in Table 4.17.

Table 4.17: Open time for final mix

Mapei mix	Time (Min)	Extrudable (Yes/No)	Quality
Strip 1	5	Yes	Good
Strip 2	10	Yes	Good
Strip 3	30	Yes	Good

Figure 4.25: Continuous printed strips over time using final mix

4.3.4.5 Buildabilty

As per standard procedure, the buildability test was also conducted in this section. The printing process did not accumulate blockage next to the printing head. The glass fragments were effective in eliminating this problem as shown in Figure 4.26.

Figure 4.26: Buildability of the final mix

As a result, the system was able to continue printing for 35 layers of the concrete mix. The mix is therefore workable, extrudable and exceeded the 30 layers set out as a criteria for buildability. The results are captured in Table 4.18 below. Figure 4.27 shows the buildability summary of the all mixes that were worked on.

Table 4.18: Buildabilty for final mix

Description	**Yes**	**No**
Workability	x	
Extrudability	x	
Open time (30 minutes)	x	
Layers (minimum of 30)	x	
Buildability	x	

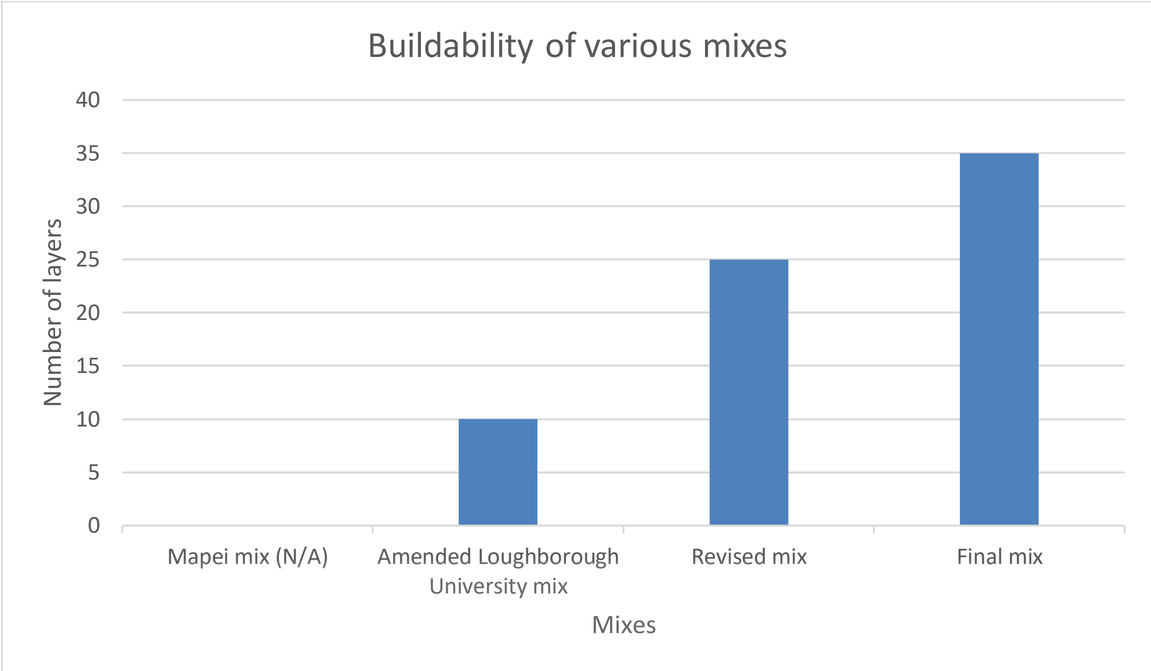

Figure 4.27: Buildability of the various mixes

4.3.4.6 Compressive strength

For this investigation, the compressive strength would only be tested if the specified criterias were met, these being workability,extrudabiltiy, open time and buildabilty. The criteria were met as captured in Table 4.19 below.

Table 4.19: Compressive test table – Final mix

Description	Yes	No
Workability	x	
Extrudability	x	
Open time	x	
Buildability	x	

The compressive test was conducted and 6 cubes were cast as per SANS 5863:2006 and thereafter cured as shown in Figure 4.28.

Figure 4.28: Cast cubes for compressive testing

They were then crushed and Table 4.20 below are the results of the tests.

Table 4.20: Compressive test results – Final mix

Duration	**Strength**
24 hours	1.3 MPa
7 days	4 MPa
21 days	21 MPa
28 days	25 MPa

The target strength was Around 20 MPa, which is about 3 MPa higher than the compressive strength of a typical facebrick (SABS 227:2002). At only 21 days the compressive strength had already exceeded the 20 MPa strength. This indicates that the final mix design was successful with regard to compressive strength.

The final mix adheres to all criteria set out.This mix was then used to print a 3D concrete printed structure in the next section of the research.

4.3.5 Validation

To recap, the following were the objectives that were set out in the dissertation:

1. To develop criteria for a suitable concrete mix design to be used in a 3D concrete printing machine.

2. To formulate an optimum concrete mix design using local materials to satisfy the criteria developed.

3. To test the formula by printing a concrete structure as an illustration of whether the concrete mix design has practical use in construction.

The first two objectives have been satisfied in the dissertation so far, only remaining with the third criteria which is to print a structure based on our formulation. This will demonstrate one of the most significant advantages of 3D concrete printing which is architectural flexibility.

3D printing technology allows you to print/manufacture any structure you can design using CAD (computer aided drawing). The structure was designed and was set out to print 35 layers with the final formulation we developed earlier in the dissertation. Figure 4.29 below was designed and printed.

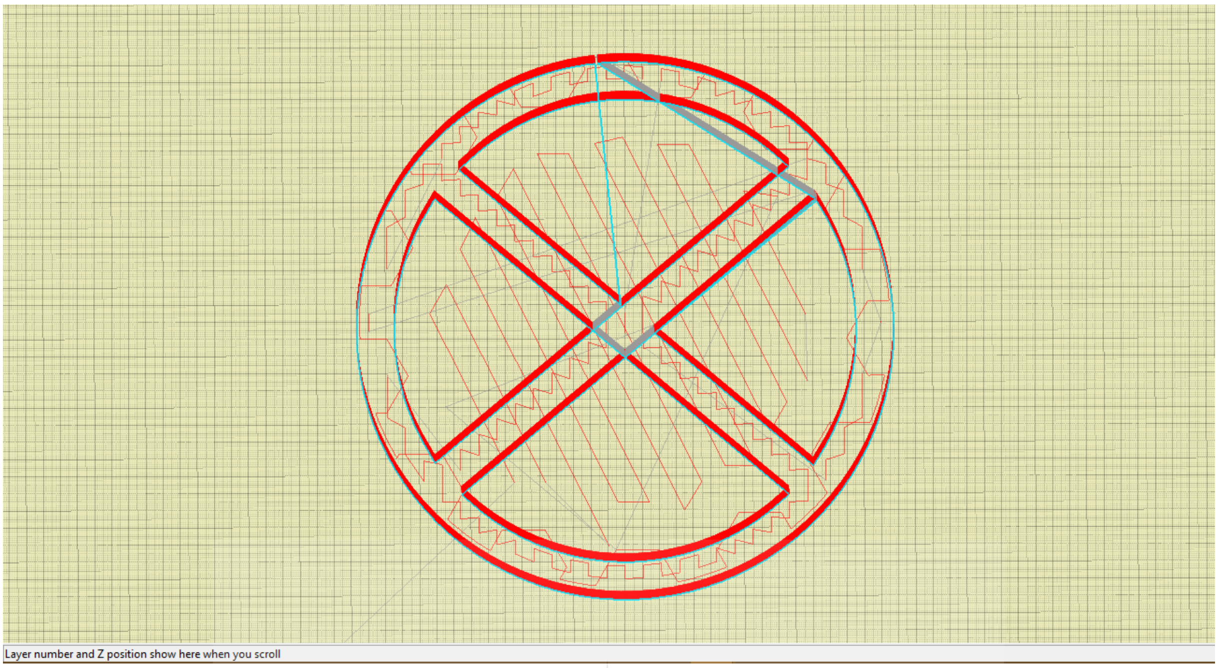

Figure 4.29: G code drawing of object to be printed

After an hour the object was printed successfully. This had a relatively good finishing and did not collapse after 35 layers of printing. Figure 4.30 shows the elevation view of the successfully printed object, it is a cylindrical shape with four compartments in the centre. Figure 4.31 shows the side view of the object, it has a rough texture and finishing.

In conclusion, the final mix works and therefore achieved all the objectives to formulate a mix design using local material for 3D printing concrete structures.

Figure 4.30: Elevation view of printed structure

Figure 4.31: Side view of 3D concrete printed structure

CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

This research was focused into the application of additive manufacturing commonly known as 3D printing for the construction industry with a focus on South African sourced materials. As stated previously, 3D concrete printing is a new and innovative way of construction that can be used for the manufacturing of micro to macro high precision construction components. If correctly designed and used, this method has various advantages over traditional construction methods as it creates opportunities to reduce time and cost in construction.

A crucial component for success is an optimized concrete or mortar mix to ensure proper feed, extrusion, placement and hardening during the 3D printing process. This dissertation presented the results of an investigation into the following:

- Criteria for an optimum concrete mix design to be used in a 3D concrete printing machine.
- Formulation of an optimum concrete mix design using local materials to satisfy the criteria developed.
- Testing of the formula by printing a structure/object as an illustration of whether the concrete mix design has practical use for construction purposes.

Based on the outcomes and observations determined from the results of the above experiments, the following conclusions were made:

To optimize the final concrete mix, the system that produces the mix should also be efficient. For this investigation, this is the 3D concrete printing system/structure.The concrete was originally in the reservoir and a pump was used to to push it through the pipe and eventually through the nozzle. The best sytem for this investigation was to create one unit that would serve as the reservor, the pump and the extruder. This aparatus was manufactured for the purpose of this investigation and the new system made it easy to conduct experiments for the research.

The main experiments conducted were for workability, extrudability, buildability, open time and compressive strength. The approach to workability gave a good indication of the concrete mix design that would be investigated with regards to the mix rheology. The workability of the mix designs was determined by its ability to go through the cone and also whether the mix would not subsequently collapse.

The Mapei mix readily went through the cone and did not collapse and also displayed good extrudability. The filament printed was continuous and there were no signs of blockage or fracture and the 500 mm filament was achieved. The difficulty experienced with the mix was its open time. After just five minutes, the mix started hardening which made it difficult to extrude. After 10 minutes it could not print continuous filaments and therefore failed for open time as per our criteria. Due to its short open time, it could not proceed with measuring its buildability. The compressive strength as a result was also not measured. The mix was therefore not ideal for 3D concrete printing according to the criteria that were set.

The amended mix from Loughborough University showed good workability. It went through the cone readily and formed an angular/slanted position when the cone was lifted. Its extrudability was good and managed to print a 500 mm continuous filament with no blockage or fracture. Its open time was tested after 5 minutes and 10 minutes and the mix remained relatively wet. Due to this, the open time was only tested again after 45 minutes and the mix was still extrudable. It therefore achieved our threshold of 30 minutes. The mix also showed fairly good buildability as it managed to print 10 layers but then collapsed after that. The criteria threshold for buildability was 30 layers therefore failed to achieve the threshold.

To improve the amended mix from Loughborough University, the specified cement was changed to PPC's OPC 52,5N which is used to achieve early yield strength. The second was to print structures with bracing or trusses for structural integrity and strength. The workability was similar to the amended mix that was previously used. The mix also showed good extrudability and managed to print a continuous filament with no blockage or fracture, easily achieving the 500 mm filament length. The open time for this mix was measured after 5, 10 and 30 minutes and the quality of the filaments was good and met the criteria. The most significant improvement was the buildability, 25 layers were achieved. What was also a good contributor to this was the geometry of the design. Although the layers reached 25, the mix still did not achieve our threshold of 30 layers.

With the final mix, the only change that was made was to the fibre that was used. The polypropylene fibre clogged up and made it difficult to continue printing after an extended duration. The polypropylene fibre was replaced with glass fragments. The mix readily went through the cone and did not tilt to the side, as a result achieving our criteria for workability. The second test was for extrudability. A continuous filament was extruded and the mix showed no signs of fracture or blockage. The mix also readily achieved a 500 mm filament length. The open time for the mix was tested after 5, 10 and 30 minutes. After 30 minutes, the mix was still workable and extrudable. As a result, the mix achieved the criteria for open time as it achieved the 30 minutes threshold. Due to the lack of blockage as a result of the glass fragments, the printing process continued with no challenges. The mix printed 35 layers. The printing process was then stopped to avoid the structural collapse. The 30 layer threshold was achieved, although the mix still had potential to print more layers. The compressive strength of the concrete was 1.3 MPa after 24 hours, it then achieved 4 MPa after seven days. After 21 days the compressive strength reached just over 20 MPa. This was sufficient as our criterion was to achieve a compressive strength test of around 20 MPa after 28 days based on the average face brick strength.

To validate the mix design an object was created to test whether the mix design can be used in printing object/structures. A CAD drawing was designed for an object that would exhibit strong architectural features for the purposes of construction. The CAD drawing was then converted to G-code for the machine to understand the various printing coordinates it has to follow. After an hour of printing, a cylindrical object with four compartments was produced to validate the mix design was successful.

5.2 Recommendations

A number of important issues were identified during this investigation, they were not addressed as this research was not focused on them and hence more work still needs to be done. The following recommendations are therefore suggested for future work:

i. Researh of this caliber requires collaboration of individuals with different expertise as one factor affects the other. A multi-disciplinary approach is very important. The individuals involved should specifically have a strong background in mechanical engineering, electronic engineering, material science and architecture.

ii. The concrete extrusion system is mainly controlled by software. There is currently no commercial software you can buy off the shelf for 3D concrete printing. Therefore, the development of this could make research easier.

iii. A pre-packaged commercial concrete mix design should be developed. The same way general purpose cement is readily available. This will create opportunitites for research and development in this space.

iv. Further research on compensating for the lack of significant tensile strength for 3D concrete printing should be conducted. this will cretate opportunities to print larger components that are subjected to greater tensile loads.

v. More research has to be conducted around the structural behaviour and properties of the mix design similar to structures built using conventional methods. This should include developing industry codes for 3D concrete printing.

vi. Layer cohesion plays a very important part for structural integrity. Further research must be conducted to assess this property.

vii. The durability of the structures that are printed should also be investigated as these experiments are normally conducted in laboratories.

viii. 3D concrete printing finishing is still not smooth. Research must also be conducted on ways the finishing could be similar to plastering of traditional structures.

In closing, the objective of this dissertation was to investigate the applications of 3D printing technology for the construction industry. Special emphasis was placed on sourcing local materials. Evidently, local materials can be used for 3D concrete printing as per the outcomes of our investigation which creates opportunities for the utilization of this technology for rapid construction and for the local construction industry.

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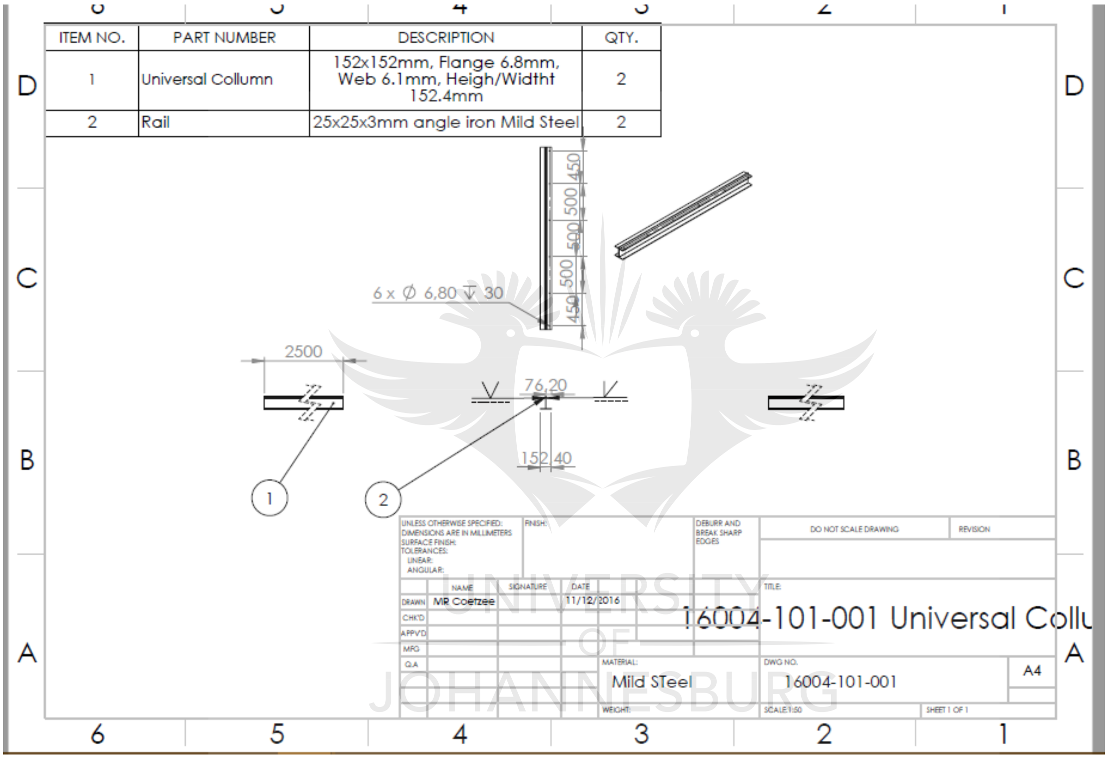
APPENDIX A: Mechanical Part List

a. Universal Column Beam
UNIVERSAL COLUMN SANS 1431 Grade 350WA H.E.B.

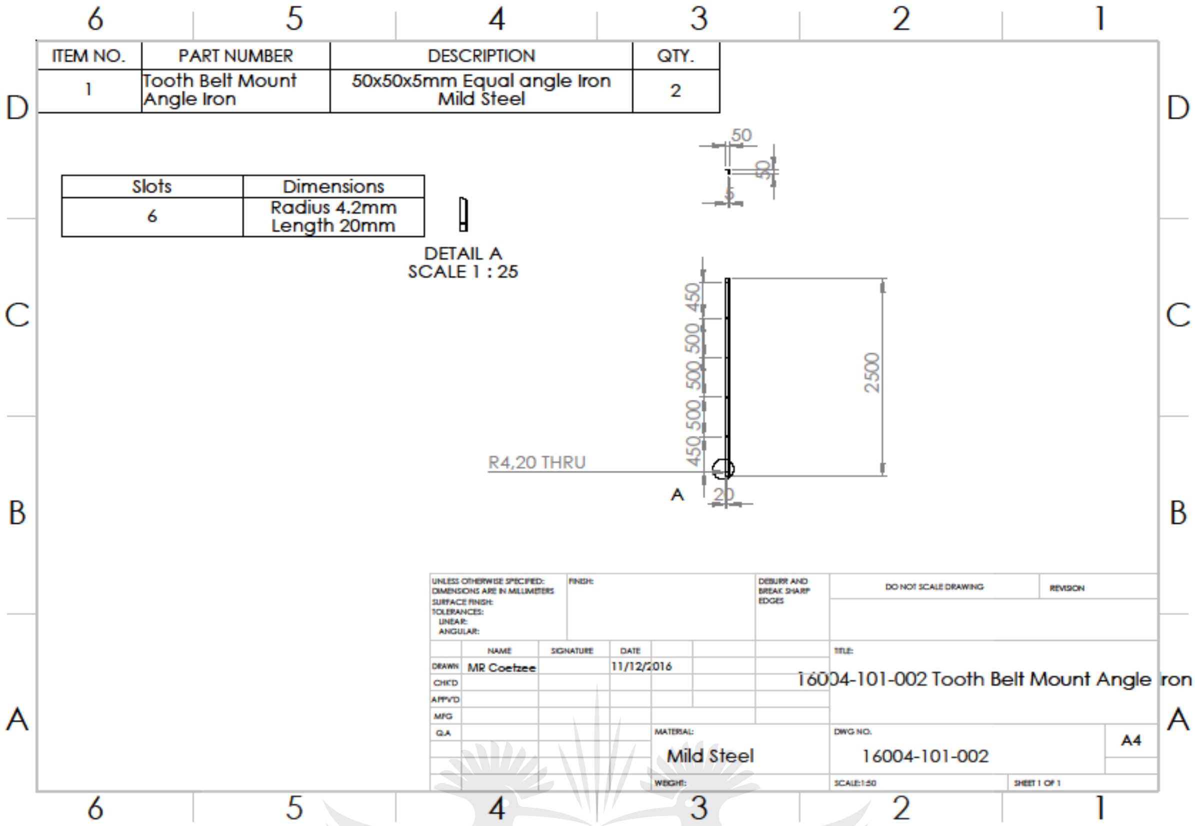
Macsteel Universal Column

Size	KG/M	Web	Flange	Height	Width
152 x 152	23.000	6.100	6.800	152.4	152.4

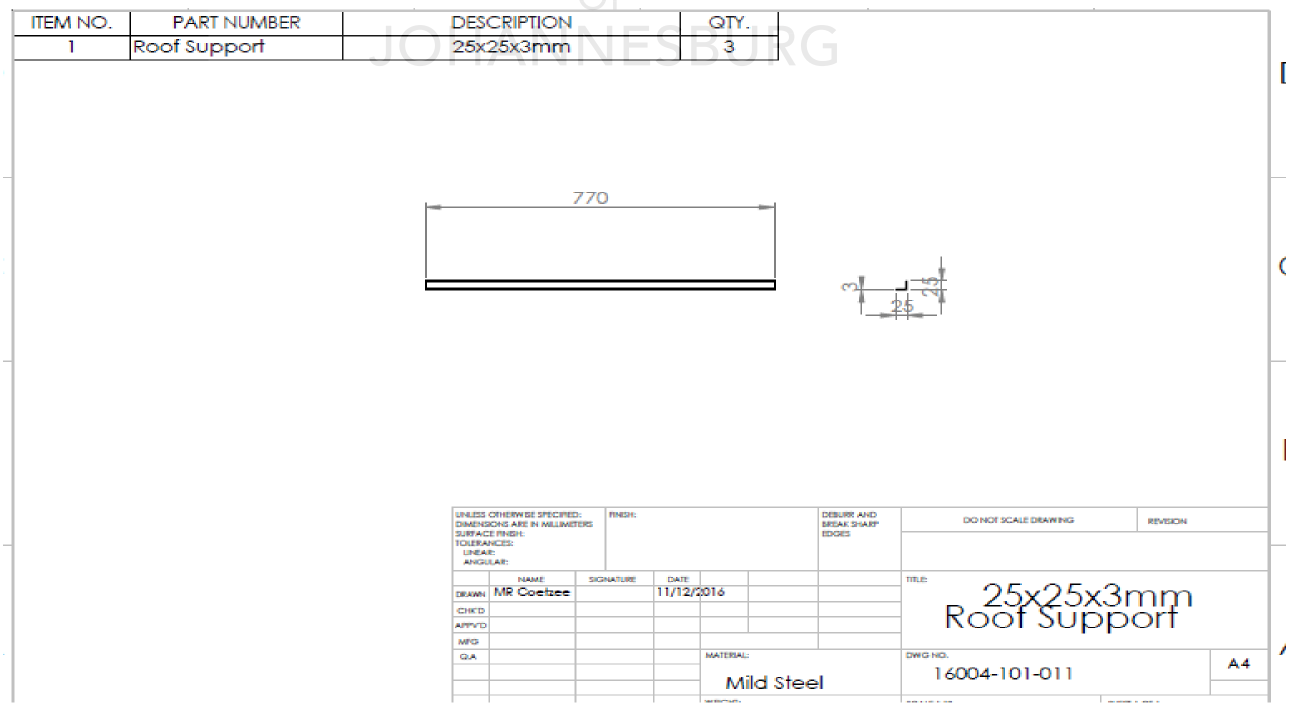
2500mm long (x2)



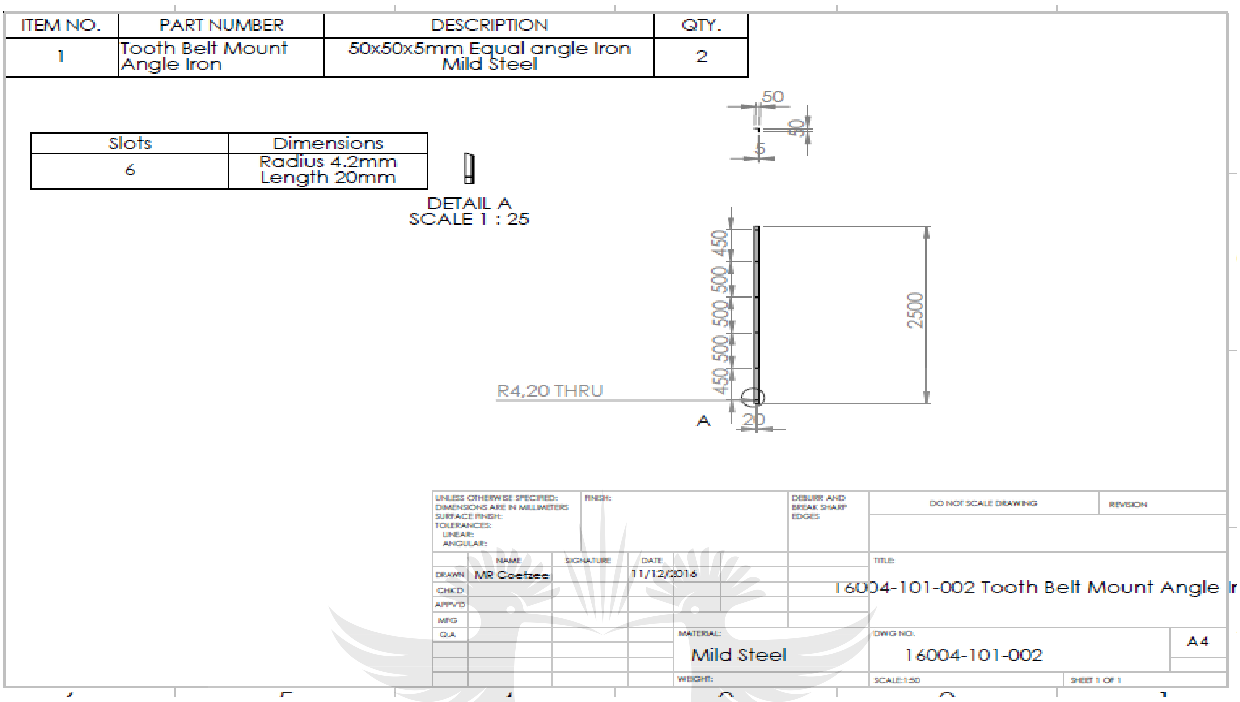
b. Base Mounts
EQUAL ANGLE MILD STEEL SANS 1431 Grade 350WA
150x150x10mm Equal Angle Iron 600mm long (x4)



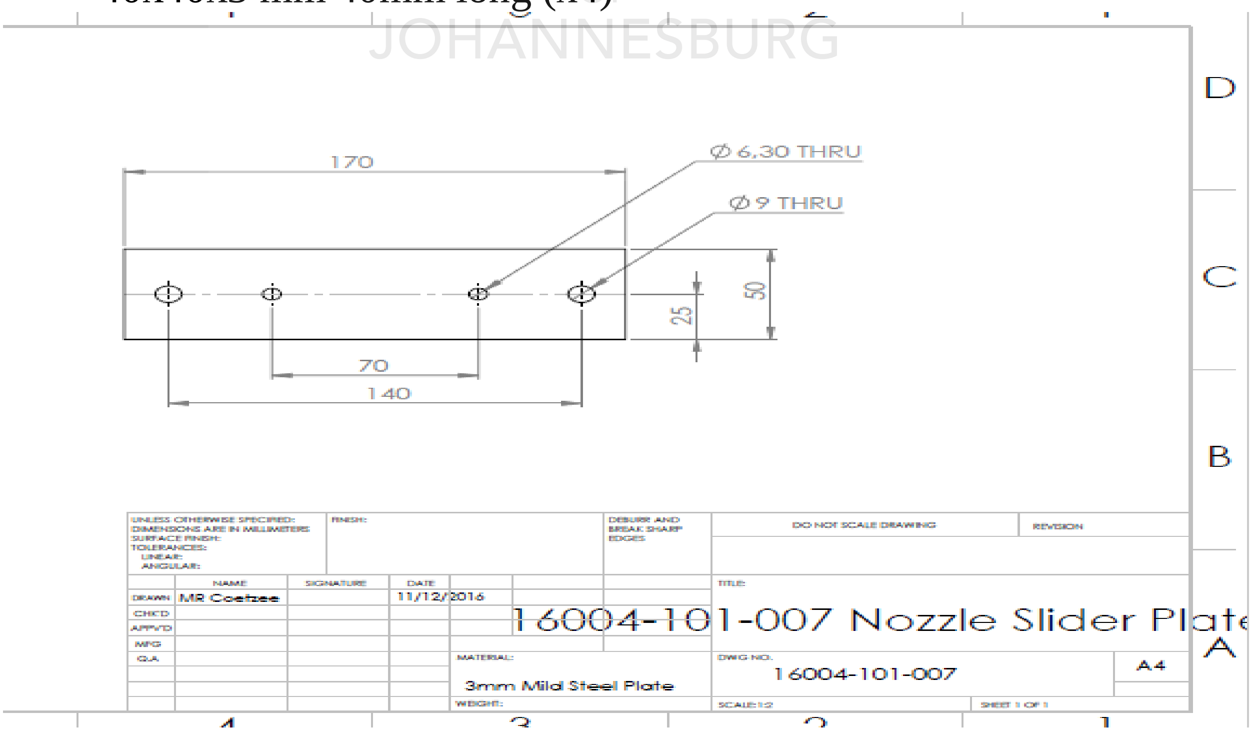
c. Roof Support:
(25x25x3 mm Angle Iron) 770mm long (x3)



d. Tooth Belt Mount
EQUAL ANGLE SANS 1431 Grade 350WA
50 X 50 x 3mm 2500mm long (x2)



e. Upright Horizontal Rail Support:
EQUAL ANGLE MILD STEEL
40x40x3 mm 40mm long (x4)



f. Shaft Support Block:
SKF: LSHS 20 x8