School of Mining Engineering

UNIVERSITY OF THE
WITWATERSRAND,
JOHANNESBURG

IDENTIFYING FACTORS CAUSING VARIATION IN STRENGTH TEST RESULTS OF THE BACKFILL MATERIAL AT SOUTH DEEP MINE

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A **dissertation** submitted to the Faculty of Engineering and the Built Environment,
University of the Witwatersrand, Johannesburg, in partial fulfilment of the requirements for
the degree of Master of Science in Engineering.

Johannesburg, 2021

DECLARATION

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ABSTRACT

Backfill plays a significant role in maintaining mine stability, improving safety and increasing the rate of extraction in deep underground mines. Backfill must be prepared such that it effectively and efficiently stabilises underground excavations for the short and long term. Factors causing variability of backfill strength affect the effectiveness of backfill to successfully stabilise underground excavations. Studies were conducted to determine the effect of factors such as preparation, mixing of tailing with the binder and curing on the strength of backfill material. The results indicated that the backfill strength is mostly affected by the mixing and curing procedures.

Inconsistency of the backfill strength results was caused by ineffective mixing before sampling is conducted and the curing environmental conditions. The change of sizes of the binder orifice affected the flow rate of the binder mixing with the tailings and the strength achieved after a certain curing period. The inconsistent curing temperature at different positions within the curing room affects the development of strength over the curing period. Identifying and understanding the effect of these factors can maintain consistency of backfill strength and reduce backfill operational cost. This thesis presents factors contributing to the variation of backfill strength test results at backfill operations and the effects of these factors on the strength of the backfill material.

DEDICATION

In loving memory of my brother

Thapelo Cornelius Madibeng

ACKNOWLEDGEMENTS

The work presented in this dissertation was carried out at South Deep Gold Mine in Johannesburg, South Africa. The work done in this dissertation was under the supervision of the School of Mining Engineering at the University of the Witwatersrand.

I would like to acknowledge the contributions of the following persons and express my sincere gratitude to them:

The Wits – Gold Fields International Partnership, for providing me with a research project and funding to cover all the acquired costs from the beginning till the end.

Professor R. Mitra for the supervision of this dissertation, the generous sharing of his vast experience and extensive knowledge in Rock Engineering empowered me to deliver internationally renowned research work.

The Rock Engineering supervisor at South Deep, Ms J. Graaf for her guidance and encouragement when I started with the project. Dr M. Du Plessis for his continued involvement and enthusiasm in the project encouraged me to put more effort into the project.

The Backfill department supervisor at South Deep, Mr M. Keetse for his selfless and invaluable assistance and extensive experience in backfill production and engineering. Ms R. Nekhavhambe for her assistance with the preparation and testing of the many backfill samples with unending patience and enthusiasm. Her assistance with compiling quality reports and presenting my work to the department is greatly appreciated.

The School of Mining at the University of the Witwatersrand for providing the facilities and support to conduct my research work productively. The support, advice and encouragement from the staff members and friends contributed directly to this work.

To my parents and my beloved daughter, Oreneile Matlou, who gave me the courage and motivation to finish this research.

To the Almighty God for giving me the wisdom and strength to see this through, I would like to dedicate this work.

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1 INTRODUCTION

1.1 Importance of Backfill in South African Deep-Level Mines

Rock bursts and rock-fall related incidents are still the major fatality contributing factors in South African deep-level mines. The future of underground mining in South Africa is dependent on the ability to mine safely at increasingly greater depths and obtain maximum ore recovery. Underground mining creates voids that need to be filled and supported to maintain mine stability. Backfill is a support method composed of waste material mixed with binding agents, cement or additives to form a strong solid material after curing for a certain period. Backfill in underground mines is an essential part of the overall mining operation and the design of backfill as a source of support is now regarded as an important part of the mine design process. The use of backfill to support underground mining voids has played an important role in overcoming some of the major problems associated with mining at greater depths. One of the main reasons for using backfill in South African deep-level gold mines is to provide local support in the stopes (Gurtunca & Clark, 1989).

The use of backfill in underground mines has increased over the past forty years due to its remarkable performance. Backfill serves five main functions when placed in deep-level underground mines:

- Improves local and regional stability of mining voids;
- Improves mine ventilation control;
- Allows increased ore recovery;
- Reduces the extent of waste disposal on the surface; and
- Reduces the extent of surface subsidence.

Backfill reduces the impact of strata control issues including seismicity. The use of different types of backfill, their specific purpose and engineering requirements are determined by the mine design. Mining with backfill provides a wide range of engineering solutions to the unique sets of problems to the mine and opportunities. It is very important to design a backfill system that is aligned with the mine design so that the stope support requirements are met and productivity in the mining operation is increased. Most deep-level mines use hydraulic backfill technology due to their ability to travel faster over greater depth and long distances. Hydraulic backfill compared to other technologies can achieve higher strength properties when placed underground which is beneficial when mining at greater depths. The main source of hydraulic backfill material in South Africa is the mill tailings and they are mixed with binder, cement and additives to achieve the required mechanical properties. Figure 1-1 shows the picture of an underground stope being filled with hydraulic fill material.

Figure 1-1: Filling an underground stope using hydraulic fill (Barrick Gold, 2020)

Two types of tailings used in hydraulic backfill are cyclone classified tailings (CCT) and full plant tailings (FPT). The CCT is obtained by classifying the mill tailings in a hydro-cyclone to the required particle size distribution to remove excess fines and FPT is produced by thickening the mill tailings to a desired relative density. The selection of the type of tailings is based on the availability and mechanical properties of the material when placed underground. Binder is used to enhance the mechanical properties of the fill material and contributes to a great portion of the costs of a backfill operation.

The backfill material is designed such that it can effectively and efficiently support the high-profile stope voids. The process flow of backfill production, distribution and placement must be managed to ensure the entire system is run holistically without hurdles. The quality of the backfill material is of great importance and should be monitored at all stages to ensure maximum performance in underground stopes. The main purpose of using backfill as primary support is to ensure the overall mine stability over the long term. Strict measures must be put in place to ensure that backfill quality is consistent throughout and the stopes underground are filled effectively. The mixture proportions of the backfill material affect its properties and must be monitored to ensure the desired backfill properties are achieved.

To obtain successful backfill performance underground, the quality of the backfill material placed must be prepared to the desired specifications. The quality of the backfill material is affected by the processes involved in preparation, thickening, mixing with binder or additives and distribution. Backfill material properties are altered during these processes and they should be monitored to ensure the final product meets the required properties. The relative density (RD), particle size distribution (PSD), permeability and strength are the main properties of hydraulic fill which determine the performance of backfill after placement. The main performance indicator is the uniaxial compressive strength (UCS), which determines the stability of the backfill material when subjected to stress underground. The relative density and particle size distribution affect the placement behaviour and *in situ* properties of the backfill (Streuders, 2011). Permeability affects the shrinkage and the ability of the fill to drain water after placement. Backfill with high ultra-fines (<10 μm) content has poor permeability, holds water for long and dries relatively slowly.

Sampling, curing and testing are part of the backfill quality control measures which are used in the backfill industry. Samples of the backfill material are collected and tested for different purposes such as RD, PSD, UCS and chemical analyses. These samples play a key role in ensuring that the backfill material produced is of the required quality. Samples collected for UCS are cast into cylindrical moulds, cured and tested after a certain period. The usual curing periods used in the industry are 7, 14, 28 and 56 or 60 days. Other backfill operations test for longer terms of 120 and 240 days. Rock mechanics standards and methods are used to test backfill for UCS. The American Society for Testing and Materials (ASTM) standards are used to test backfill. The test method for controlled low strength material is commonly used as a basis for testing backfill. Other ASTM methods are used for preparation, sampling and curing to ensure the backfill operations comply with international standards.

Consistent production of the required material properties helps achieve the desired performance of backfill. This can be achieved by implementing quality control measures that will ensure that the backfill system is run according to the required standards. Maintaining QC measures will enable the backfill plant to produce consistent backfill quality and reduce operational errors. Quality control is very important in backfill operations to ensure that a maximum strength of backfill is achieved and ensure consistent performance of backfill placed underground (Spearing & Wilson, 1988). Variation of the backfill quality affects the strength distribution of the fill within the stope. Inconsistent strength distribution affects the stability of the filled stope and the adjacent stopes. The inability of the fill to efficiently and effectively support the mining voids affects the overall mining stability and future mining plans.

This research discusses the factors causing variability of backfill strength results and their effect on the strength of backfill. Identifying these factors can help determine the possible backfill operational constraints and assist backfill operations in maintaining consistency of the backfill quality. Understanding the effect of these factors will help optimise the backfill system, increase the strength and performance of the backfill placed underground. Consistent backfill strength results can assist in reducing binder costs for the mine.

1.2 The Use of Backfill in Deep-Level Mines

Rockburst and fall of ground accidents are still major contributors to the total number of fatalities in South African mines. In 1985, a total of 311 rockburst and fall of ground related fatalities were recorded by the Department of Mineral Resources in South Africa. The number of overall fatalities in South African mines rose from 51 in 2019 to 58 in 2020 with FOG having contributed to most fatalities. A total of 20 fall-of-ground (FOG) related fatalities were recorded in 2019 contributing to 39% of the overall fatalities (Minerals Council South Africa, 2020). The increase in mining depth, increased temperatures, and seismicity, rockburst and rockfall hazards created a sense of urgency in the mining industry to design and adopt a support strategy that will allow safe and productive mining in these conditions. There was an urgent and immediate need to address the application of backfill in South African gold mines to address the impact of rock-bursts and fall of ground (Stewart, 1988). The anticipated benefits of backfill in other deep-level mines in North America and Australia and their advances in technology led to South African mines considering backfill to solve their current ground control problems.

The global increase in demand for metals caused an increase in commodity prices which led to mining companies increasing their production. The demand for increased ore production has led to mines creating larger stopes by increasing the volume of the stope voids while others have changed their mining methods. These led to the introduction of mechanisation and automation which allowed mining companies to produce higher mineral volumes, increase productivity and reduction in mining costs. The application of backfill in South African deep-level mines have reduced the impact of mining induced accidents, improved the stability of mined voids, allowed increased ore recovery and improved ventilation control underground. The technology behind mine fill and its application are quite extensive worldwide and research advances in Australian mines such as Mount Isa Mines in Queensland and Kidd Creek mine in Canada are ground-breaking (Potvin, 2005).

There is a variety of backfill technologies applied in different gold mines in South Africa and have different qualities based on the purpose they serve when placed underground. The effectiveness of backfill as a form of support depends on a range of factors including inherent properties of the material, and placement conditions. The inherent properties of the fill material determine the quality of backfill and its ability to ensure stability after curing. The placement properties determine the behaviour of backfill after it has been placed underground. This involves permeability properties, shrinkage and solid content after all the water is drained (Clark, 1988). These properties need to be studied and understood so that a suitable backfill quality that would effectively and efficiently support the mined-out stopes can be established.

Given the variety of mining methods applied in most deep-level mines, there is a need to develop a backfill strategy that will be able to supplement support in historic conventional voids and complement the backfill practice in high-profile mechanised voids. The current backfill technology used in the backfill industry has proved to provide great benefits to underground mine problems and there are extensive research enhancements of backfill mechanical properties with fewer costs. Quality control methods of monitoring backfill quality include effective sampling and testing of the backfill material at a different terminal.

Material properties such as relative density, particle size distribution and strength are constantly measured to monitor backfill quality. Material properties of hydraulic fill in gold mines have been studied extensively and their impact on the performance of backfill. However, the impact of operational factors on these properties haven’t been studied as much. Operational factors do contribute to the quality of backfill produced and its performance after placement. Inconsistency of mechanical properties of backfill causes unstable support conditions at the filled stopes which compromises stope stability.

This research was conducted at a gold mine in the Witwatersrand Basin, which is located northwest of the Witwatersrand in Gauteng Province, South Africa. The location of South Deep mine is shown on the map in Figure 1-2. The mine has previously deployed several mining methods and a number of these old voids are intersected by the mechanised long-hole stoping (LHS) operations. Historically destressing was either done using conventional handheld stoping or low profile stoping with crush pillars. Backfilling the old mining voids is challenging due to historic backfilling practices, degradation of old support, changing orebody geometries and pillars in the low profile cuts (Bradley & Matthysen, 2011).

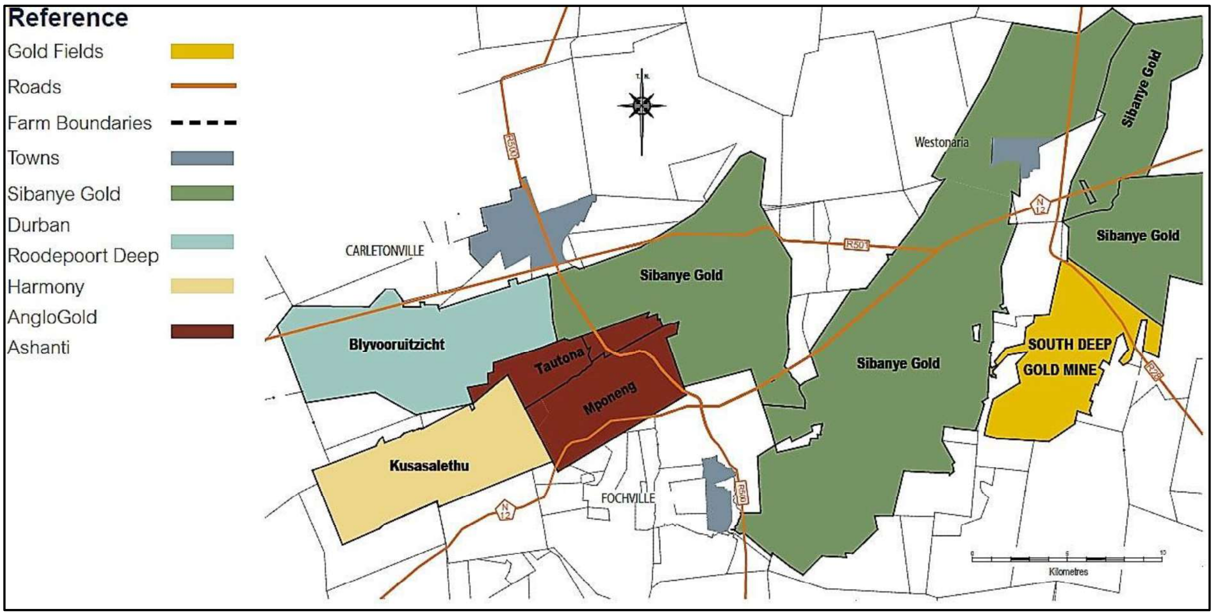

Figure 1-2: The location of South Deep relative to other gold mines in the Western-area region (Gold Fields, 2014)

1.3 Problem Statement

Predominant ground stress conditions such as compressive stresses exist in most underground mines and shear failure occur when the stresses exceed the strength of the rock supporting the hanging wall. The design of backfill material is based on the stresses which will act on backfill placed and the failure modes when subjected to higher stresses. It is important to understand these conditions so that the backfill material can be adequately assessed and optimised. The stress conditions at each mining section are different and so are the support strength requirements. The strength of the backfill required to fill all the mining sections should accommodate all mining sections as well as the engineering requirements.

Backfilling old mining voids has been a challenge at South Deep mine due to the introduction of new mining methods and mechanisation. The transition in the backfill practice from conventional low-profile stopes to high-profile mechanised stopes has been difficult. It has been identified that the process of mixing cement with the slurry is somehow erratic and is causing variability in the strength of the backfill material. Practical solutions that will take cognisance of the logistical backfill constraints at South Deep were required.

1.4 Research Motivation

Evolving technology and innovation in the mining industry has led to the rise of mechanisation and automation for mining operations worldwide. This was due to the quest for improvement in productivity and high ore extraction resulting in bulk mining methods. This led to the excavation of large stopes (high-profile) with increased advances (Masniyom, 2009). Due to large stope openings, the pressure to sufficiently and effectively support the large stopes significantly increased as well as the need for better structurally stable backfill design with good structural properties. High stiffness and sustainable long-term strength backfill are required to reduce convergence of the stopes and provide regional stability.

Backfill quality can be determined by its material and geotechnical characteristics. The ability of the backfill to maintain stability within the stope and limit shrinkage depends on its material composition and placement conditions. The relative density (RD), particle size distribution (PSD) and compressive strength are used to determine the quality of backfill. These parameters also determine the behaviour of backfill after placement in underground stopes. There is extensive research that was done on the material and geotechnical characteristics of backfill material. These have allowed engineers to optimise backfill designs that can obtain maximum quality and reduce costs for backfill operations (Masniyom, 2009). The quality of backfill material is affected by several factors which directly or indirectly contributes to the amount of strength developed by the backfill within a certain period.

There is a range of operational factors that affects the strength of backfill material beginning with the process of preparation, mixing with cement, adding additives, curing and testing. It is crucial to identify and understand the effect of these factors on the quality of backfill. These can assist the backfill operation to optimise the quality of backfill by improving the backfill strength, maintaining stability in underground stopes and saving costs for the mine. Failure to monitor these factors can lead to the variability of backfill strength obtained after placement. This causes inconsistency in the strength distribution within the filled stope and may cause ground instability. This research discusses the factors contributing to backfill strength variability and their effect on backfill strength.

1.5 Proposed Research Outcomes

The following outcomes of the research study were proposed and delivered:

- Understand the effects of parameters such as operator, day/night shift, cemented classified cyclone tailings (CCT) or full plant tailings (FPT) etc., on the backfill strength; and

- Develop improved backfill strategies and actions to deal with backfilling of historic voids and high profile mechanised long-hole stopes.

1.6 Contents of the Research Report

This research project report will consist of seven chapters which are to give the reader a plan of action which outlines the research actions that will be taken. The chapters are as follows:

- **Chapter 1: Introduction** – It establishes the scope, purpose, context and motivation of the backfill research to be conducted. It also gives a summary of the researcher's understanding and background of the research topic.
- **Chapter 2: Literature Review** – Evaluates previous studies that were done on backfill at South Deep Mine specifically and other studies on backfill tests in underground narrow, hard rock tabular mines which may contribute towards this research.
- **Chapter 3: Research Methodology –** Quantitative and qualitative data was collected and evaluated from the samples collected. A review of the current performance was conducted and possible factors causing variability were identified. The methodology helped determine the impact of each factor identified.
- **Chapter 4**: **Review and Analyses of Previous Results –** The review of previous backfill strength results and the analyses. The analyses of the results were used to investigate if there are evident factors that may cause variability in the backfill strength results.
- **Chapter 5: Factors causing backfill strength variability** – Results obtained from the tests and observations will be summarised and interpreted. The results obtained will be analysed and discussions on the obtained results will be made.
- **Chapter 6: Practical Solutions to maintain consistency of backfill quality –** Solutions to the current problems are provided and methods that could be used to maintain backfill quality consistency in the mine are discussed.
- **Chapter 7**: **Conclusions and Recommendations** – Conclusions on how different parameters contribute to the variability of tests results will be made. The contribution of different parameters on the strength of the backfill samples will be summarised.

Recommendations will be made to provide a practical solution taking note of the logistical constraints of the mine.

2 LITERATURE REVIEW

2.1 Introduction

Rankine (2007) describes backfill as any waste material that is placed into underground mining voids for either disposal or support purposes, or to perform some engineering function. Backfill material used to support the mined voids must have sufficient strength to ensure that regional and local stability is maintained during the excavation of stopes adjacent or beneath the filled stope. Waste material used to fill underground mining voids includes deslimed and full plant tailings, waste development rock, crushed and quarried aggregate, and alluvial sand. A small amount of cement or other pozzolans binders are added to the waste material to improve strength properties.

The backfill material can either be prepared underground or on the surface depending on the system and the type of waste material used. The backfill slurry prepared on the surface is transported underground using gravity base delivery methods while the more dense slurry is delivered by a pipeline system. Backfill strength required depends on the volume of the void to be filled and the stress it will experience. The addition of a binder content of 6% to the gold tailings can provide a UCS of 0.5 to 4 MPa. It is an essential requirement for the backfill to have a minimum cost of which the most contributing proportion of backfill cost is the use of binder (Grice, 1998).

2.2 Mining Conditions in South African Deep-level mines

Deep-level mines in the Witwatersrand Basin are presently mining at a depth of 3000 m below the surface. Future mining is expected to exceed the depth of 4500 m below the surface and major problems encountered at these depths are heat and high rock stresses. The nature of the orebody, mining methods and the depth of mining gave rise to different conditions in deep-level gold mines (Kamp, 1989). Mining at depths greater than 3000 m raises two most vital concerns which include rock-bursts and environmental conditions such as heat and toxic gases. These conditions affect the safety of employees working underground and the efficiency of machinery used. Backfill was introduced to help combat these problems. help improve productivity and mine safely at greater depths (Kamp, 1989).

Backfill has proved to be an important support medium in deep-level massive mine and offers characteristics that no other support medium. The steep dipping orebodies in the Witwatersrand basin and greater depth of mining below 4000 m presents challenges associated with providing a competent and effective support medium. There are extremely high stresses around tabular excavations which are mostly concentrated at the stope face. The stope support in these areas must be able to prevent a build-up of such high stresses and prevent severe fracturing of the stope face. Local and regional support must be provided to prevent the collapse of the hangingwall in working areas which can be caused by rock-burst or seismic trends (Lamos, 1993).

2.3 South Deep Gold Mine - Mining and Backfilling

South Deep is an underground mechanised mine, using backfill as a primary method of support. The orebody is accessed through de-stress and shadow development cuts to manage rock stress and seismic activity. Selective mining methods are employed at South Deep, and these include drifts and benches, and long-hole stoping (LHS) with backfill as the primary bulk mining method. The orebody at South Deep lies within the Central Rand Group of the Witwatersrand Supergroup and it is overlain by the Ventersdorp lavas (Watson, et al., 2014). The orebodies of economic importance are the Ventersdorp Contact Reef (VCR) and the Upper Elsburg reefs. The orebody diverges and thickens to about 120 m towards the eastern extremity of the mine boundary. Figure 2-1 shows the vertical geological section of the orebody from West to East.

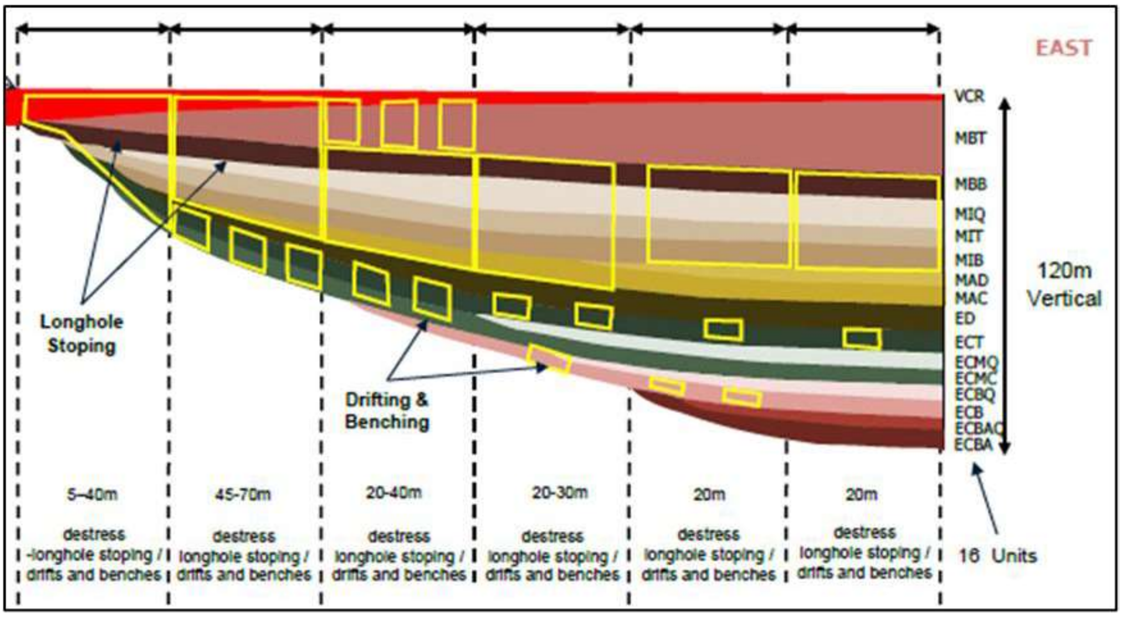

Figure 2-1: The vertical geological section of the orebody (Gold Fields, 2017)

The orebody dips to the south at between 10° and 14° which is too steep for mechanised equipment. The orebody is currently mined at depths of 3000 m below the surface and the virgin vertical stresses are high due to increased overburden depth. Figure *2-2* shows the cross-section of the orebody at South Deep and the reefs mined. The Upper Elsburg reefs contain conglomerates which are extremely strong and brittle rocks. Due to the high-stress environments, the rocks store strain energy which can be released violently as rock bursts. To destress the orebody, narrow tabular cuts can be made to allow normal massive mining techniques to be conducted above and below the cut.

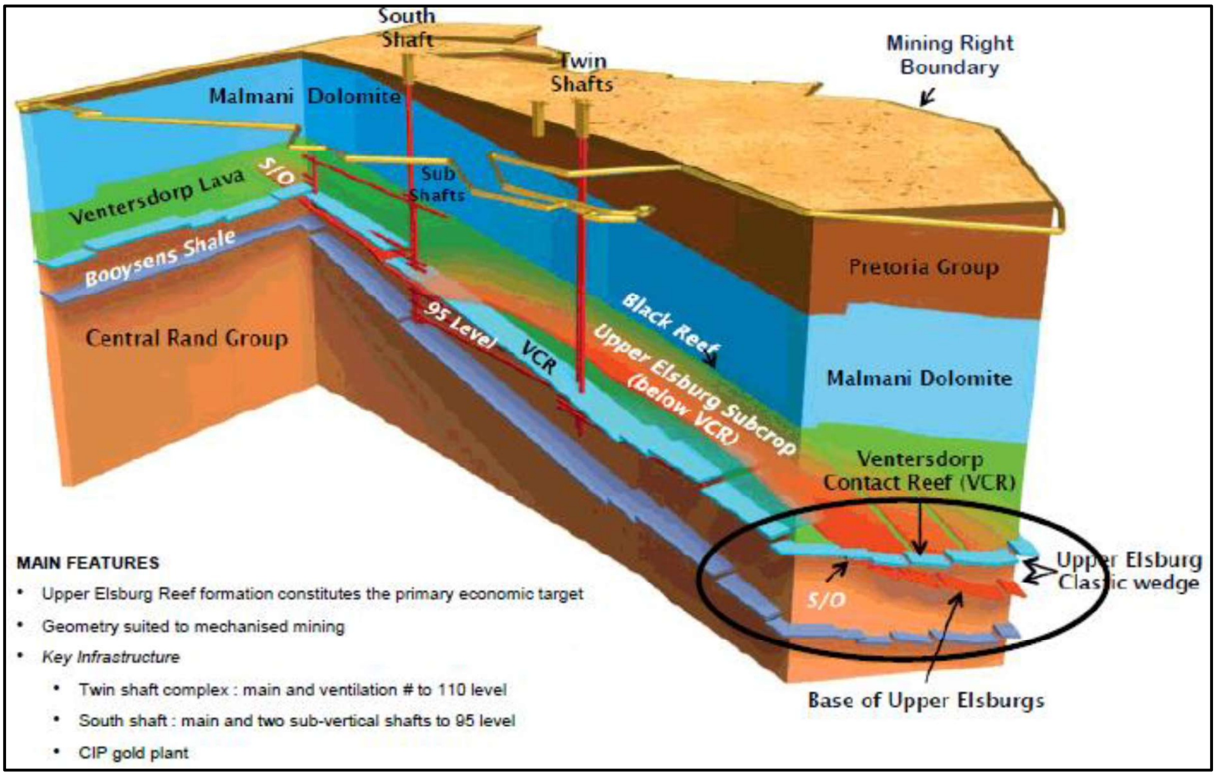

Figure 2-2: Cross-section of the orebody with the location of shafts and levels (Gold Fields, 2014)

As indicated in Figure *2-2*, the orebodies are accessed from the surface through two shaft systems, the Twin Shaft complex (main and ventilation shafts), of which the main shaft comprises a single drop to 110A – Level, at a depth of about 3000 m and the ventilation shaft to 110 level at a depth of 2,947m. The South Shaft complex is a sub-vertical system (three operating shafts) to 95-Level at a depth of 2,786m. The mine is divided into three main areas namely:

1. Current Mine (CM) – characterised by selective mining methods which are scattered over a large area and were originally exploited by conventional tabular mining methods. It is accessed from four active levels (90, 93 and 95) from both the South Shaft and Twin Shaft complexes
2. The North of Wrench (NoW) – is directly south and down-dip of Current Mine comprises six mining corridors separated by regional pillars that extend southwards to

the Wrench fault. A bulk non-selective mining method is applied, resulting in a higher Resources to Reserves conversion ratio.

3. The South of Wrench (SoW) – located on the east and west areas, situated south and down-dip of NoW and will be mined using a bulk mining method similar to NoW (Gold Fields, 2017).

The mine is currently exploiting NoW and Current Mine areas. The area is divided into 6 corridors which are separated by regional pillars which are 60 m wide. The corridors have a span of 180 m and the orebody is destressed using the rip pillar stoping layout with twin access. The tunnel profile of the destress stopes is 5.5 m high and the yield pillars are 6 m high. The yield pillars are 20 m long and 8 m wide and the mining sequences used to extract the orebody is sequential long-hole stoping. The long-hole stopes have 20 m high sidewalls and are 30 m long. The primary stopes are mined on both sides of the access, backfill support is installed and the primary stope next to the backfill is immediately extracted. The rib pillars are backfilled following mining progression (Gold Fields, 2017).

2.4 Importance of Using Backfill

Backfill provides ground support and regional stability in underground mining voids which allows the removal of ore from neighbouring stopes. An increase in the depth of mining operations increases problems in strata control and the occurrence and magnitude of seismic events. Backfill provides stability by reducing rock mass relaxation by allowing the rock to retain a load-bearing capacity and reducing the energy release rate (ERR) of crown pillars and abutments. Backfill in underground hard rock mines is used as ground support for pillars, walls and help prevent caving and roof falls, and enhance pillar recovery for improved productivity.

The use of backfill in narrow, hard-rock, tabular mines in the Witwatersrand Basin provides several advantages, which have been studied and proved while others might be realised in future. Backfill reduces damage caused in stopes by rock-bursts, reduces effective stoping width which improves stability at the stope face. Backfill has eliminated the necessity to leave wider stabilising pillars and reef pillars, and this increases the overall extraction ratio of the mine. Having a solid and freestanding backfill reduces the labour required to install stope support. Fire hazards associated with the use of timber in the stopes is eliminated and the heat from the virgin rock is reduced by sealing off most of the exposed rock (Blight & Spearing, 1996).

2.4.1 Energy release rate (ERR)

The energy release rate, *ERR*, is a concept introduced in the 1960s as an indicator of the proneness of mining excavations to rockburst and seismicity (School of Mining Engineering, 2018). The ERR is expressed in units of megajoules per square metre (MJ / m^2) and it is related to the extent of volumetric convergence taking place or allowed to take place in the back areas of the stope. The ERR is easy to calculate, particularly with the mining simulation computer programs, such as MINSIM, commonly used for stope layout planning and analysis in the gold and platinum industries. The energy release rate (ERR) is among the methods used to assess potential rock bursts in the mines together with other techniques (Cook, et al., 1966).

Rock bursts and fall-of-ground are still some of the contributing factors to mining accidents and fatalities in South African mines (Minerals Council South Africa, 2020). Rock bursts phenomena in deep-level hard rock mines are characterized by a sudden release of energy in a volume of highly stressed rock and causes local violent failure of the rock mass around the opening. The major motivation for placing backfill in deep-level mines together with stabilising pillars was to reduce the rate of mining-induced seismicity and the frequency of rock bursts. Stopes that have been backfilled survive the damage caused by rockburst and seismicity better than the conventionally supported stopes (Gay, et al., 1988). The recent backfill technology allows a large quantity of backfill to be placed underground to provide regional support and reduce the energy causing rock bursts (Piper & Ryder, 1988).

One of the criteria which could be used to determine the effectiveness of backfill is its impact on the face ERR and the average pillar stress (APS) levels and maximising ore extraction ratios (Piper & Ryder, 1988). A high-quality backfill material placed to cover more than 40% of the mined area can reduce the ERR level and enhance the mining depth. This could also allow mining to continue safely without leaving out pillars. The ability of the fill to reduce the ERR depends on the quality of the fill, the height and the width of the stope. High stoping areas in deep-level mines lead to enlarged ERR levels (Piper & Ryder, 1988). When using backfill in combination with stabilising pillars, Piper and Ryder (1988) showed that the ERR and the APS can be reduced by 30%. An ERR value of 40 MJ/m^2 can be achieved when a good quality backfill material is used to fill stopes at a mining depth of 3300 m and 80% of the mined area is filled.

According to the South African National Institute of Rock Engineering (SANIRE), a major purpose of all types of backfill is to accommodate the deformation of fill mass after placement and reduce stress levels throughout the mine whilst maintaining excavation stability. Backfill reduces the displacement of the rock mass by allowing the rock to retain a load-carrying capacity and distributing the load to crown pillars and abutments (SANIRE, 2015). Backfill reduces damage due to rock-bursts and minimises the energy release rate (ERR) which is a function of elastic closure and field stress. The most typical values of ERR in deep-level mines are from 20 MJ/m^2 to 40 MJ/m^2 (SANIRE, 2015).

2.4.2 Ventilation

When mining ultra-deep, narrow reef ore bodies in the Witwatersrand Basin, the ventilation and cooling systems within the stopes play a critical role due to high concentrations of active workers. The stope ventilation and cooling requirements are determined by the difference between the air temperature and virgin rock temperature. There has been extensive work done on the evaluation of ventilation and cooling requirements to maintain a wet-bulb temperature of 28°C. The impact of backfill in ventilation condition control is very significant and beyond the primary use as a mode of stope support or regional stability (Bluhm & Biffi, 2001). The benefits include:

- Reducing the heat from surrounding rock released into the air stream;
- Assisting in the control of airflow in the stope; and
- Reducing the use of timber thus minimizing the associated fire risk (Bluhm & Biffi, 2001).

The utilisation of backfill inhibits the spread of underground local fires by reducing the amount of timber used to support the stopes. Backfill seals off the back areas where most of the fires are likely to start.

When Impala platinum approved its 17th shaft project in 2008, the significant technical risk posed by the mining depth of 1000 −2500 m were identified although the project presented acceptable financial rewards. The mining environment in the Bushveld Complex has relatively high geothermal gradients and a high number of faults, potholes and geological structures associated with the ore body. The virgin rock temperature varied from 41°C at shallow levels to 62°C at a deeper level. The geothermal gradient in the Bushveld Complex is approximately 2.187°C per 100 m of depth and the reject temperature at the mine was 28.5°C (Zindi, 2008). The application of backfill at Impala assisted ventilation and cooling by:

- Reduced the refrigeration requirements;

- Allowed sufficient cooling to be distributed from upper to lower levels; and
- Reduced capital estimate for the refrigeration system by 25% compared to the costs of not using backfill (Zindi, 2008).

Backfill reduces the quantity of air required underground by reducing the area required to be ventilated. When backfill is placed in mining voids, it laminates the walls and reduces the amount of virgin rock temperature. This also reduces the intake air temperature supplied by the mine. The drainage water from the filled stopes reduces the dust generated by blasting and traffic on travelling ways which improve the quality of air in the stopes. The impact of backfill in deep-level mines was examined for different mining layouts and mining methods. The heat load per kt/ month in different mining configurations increase by 30% when backfill is not used. The use of backfill does not eliminate the need for in-stope cooling although it provides many benefits in ventilation and cooling (Bluhm & Biffi, 2001). The drainage of the backfill material has the potential to create a heat load if the slurry arrives hotter than the desired stope temperature. This effect can be simply reversed by cooling the backfill before placement (Bluhm & Biffi, 2001).

2.4.3 Ore recovery

The increase in the depth of mining increases strata control problems in underground mining operations which also increases the incidence and magnitude of seismic events. The severity of rockburst and seismicity can be reduced by designing mining layouts and systems that provide minimum volumetric convergence. Solid support, in the form of pillars of ore or waste rock, is very commonly used to provide stability in many mining methods (School of Mining Engineering, 2018). Underground mining operations that use room-and-pillar as a primary method of ore extraction leave behind significant quantities of valuable ore material as natural ground support. The pillars can exceed 50% or more of the total ore reserves which affect the overall ore recovery (Zur & Apel, 2004).

The utilization of backfill as a form of solid support eliminates the need to leave stabilising pillars, reduces the width to height ratio of pillars, allows pillar extraction to be applied safely and increases the overall extraction ratio of the mine. A good quality backfill material that meets the strength requirements of the underground mining voids would effectively support the hanging wall and provide local and regional stability. Remnant pillars are a substantial economic asset if they can be mined efficiently and safely. Mining these pillars would increase the mine production life, increase the labour requirements which would create jobs, and cash flow that would stimulate the local and regional economies (Zur & Apel, 2004).

2.5 Types of Backfill Technologies

There are different types of backfill technologies that are used in the industry and they are classified according to their application and nature of the material used. These include gravity backfill, mechanical backfill, pneumatic backfill, paste backfill, hand backfill and hydraulic backfill technologies. Gravity backfill is applied in orebodies that have a high dip angle which allows the material to roll into the stope. Mechanical backfill techniques require the use of a conveyor belt, slinger belt or dump truck to fill the mining voids with waste rock. Pneumatic backfill uses negative or positive pressure to transport bulk material through a pipeline into the mining voids. Paste backfill is most common in shallow mines and it consists of a high solid density mixture with a lot of fine materials, low permeability and very low post-placement shrinkage.

Hydraulic backfill is a technology that uses water as a transportation medium of the backfill solids underground. Hydraulic backfill uses a pump system to transport the backfill material through the pipes during preparation, mixing and distribution to underground stopes. Hydraulic backfill is commonly used in deep-level mines and uses a large quantity of cement to improve its mechanical properties. Hydraulic backfill is used in deep-level mines due to its ability to flow over long distances/depths without plugging. The availability of water allows it to flow freely without using more pressure on the pipes. These also allow the mine to save on energy used to pump the backfill over a long transportation distance.

Hydraulic backfill is mostly used in South African deep-level mines. The technology was adopted from massive base metal mines and was later introduced to narrow tabular mines. The main source of the backfill material is the mill tailings from the mines. The hydraulic backfill used is composed of mill tailings, cement, water and additives. The tailings used are either cyclone classified or full plant tailings. The selection of the type of tailings depends on the purpose of the backfill, the required or desired strength, design and operational constraints of the preparation plant, the distribution and placement system (Masniyom, 2009).

2.6 Backfill Material Composition

The major components of backfill are mill tailings, aggregate or rock, water, binder and pozzolans. Understanding the material properties of these components is essential in designing and constructing a backfill system. The properties of each component contribute towards the strength and performance of the material for both the short and long term. The physical and chemical properties of each component affect the preparation, transportation and placement of the backfill material. It is very important to study the properties of each component to achieve consistent and reliable results and performance of the backfill placed underground (Henderson & Revell, 2005).

2.6.1 Tailings

Tailings from the plant are produced from comminution and processing of mined ore at the metallurgical plant. When metal is separated from the impurities, the waste material forms the tailings which are mostly used as a backfill material. The tailings are made up of particles of different sizes and shapes which includes clay, silt and sand particles. Tailings are normally stored in a tailings storage facility but since backfill has been introduced in underground mines, tailings are now found to be useful in producing the backfill material which fills underground mining voids (Henderson & Revell, 2005).

Mill tailings produced from gold, copper and zinc mines contain a high sulphide content which originates from the pyrite minerals. When sulphide reacts with oxygen and water, the reaction form acid and sulphate which forms sulphate attack in the backfill material. Sulphate attack results in loss of mechanical stability of the backfill material and if a failure occurs, the placed backfill will collapse. These compromise the health and safety of mining personnel, equipment and loss in production.

Previous research conducted by Kesimal, et al. (2005) highlighted that physical and chemical characteristics of tailings affect the strength of the backfill material and these characteristics have to be studied and understood to optimise the backfill quality. Properties such as specific gravity, particle size distribution (PSD) and mineral composition affect the quality of the backfill produced. It was also identified that a higher content of silicate minerals in the tailings increases the water retention capacity of the fill after placement (Kesimal, et al., 2005).

2.6.2 Water

The water which is mixed with the tailings during preparation can also affect the properties of the fill material. The physical properties of water from different sources vary and this can affect the performance of the fill material during mixing. A study done by Wang and Villaescusa (2000) as quoted in Henderson and Revell (2005) showed that a higher pH of the water affects the strength of the backfill.

2.6.3 Binder

The most commonly used binder in the backfill industry is the Ordinary Portland Cement (OPC) which is hydraulic. The cement is mixed with water and develops strength after hydration over time. The chemical composition of cement includes calcium, silicon, aluminium and iron. Some of the chemicals included in the binder composition provide resistance against "sulphate attack", which is a chemical reaction whereby sulphate ions attack cement components and causes a deterioration mechanism in concrete. Sulphate attack causes either softening and decay of the concrete matrix or expansive cracking of the hardened concrete. Ions responsible for the deterioration mechanism in cement include calcium, magnesium, sodium and potassium (Mishra, 2019). These chemicals delay the strength development of the fill material.

The type of binder and binder content added to the tailings affect the mechanical properties of backfill material. The cost of cement contributes to 75% of the total backfill operating costs and the binder content added to tailings contribute towards the strength of the backfill material. Cement improves the mechanical stability of the backfill material and yields better backfill performance over a long period. The graph presented in Figure 2-3 shows the effect of binder on the yield stress of tailings at different slurry densities.

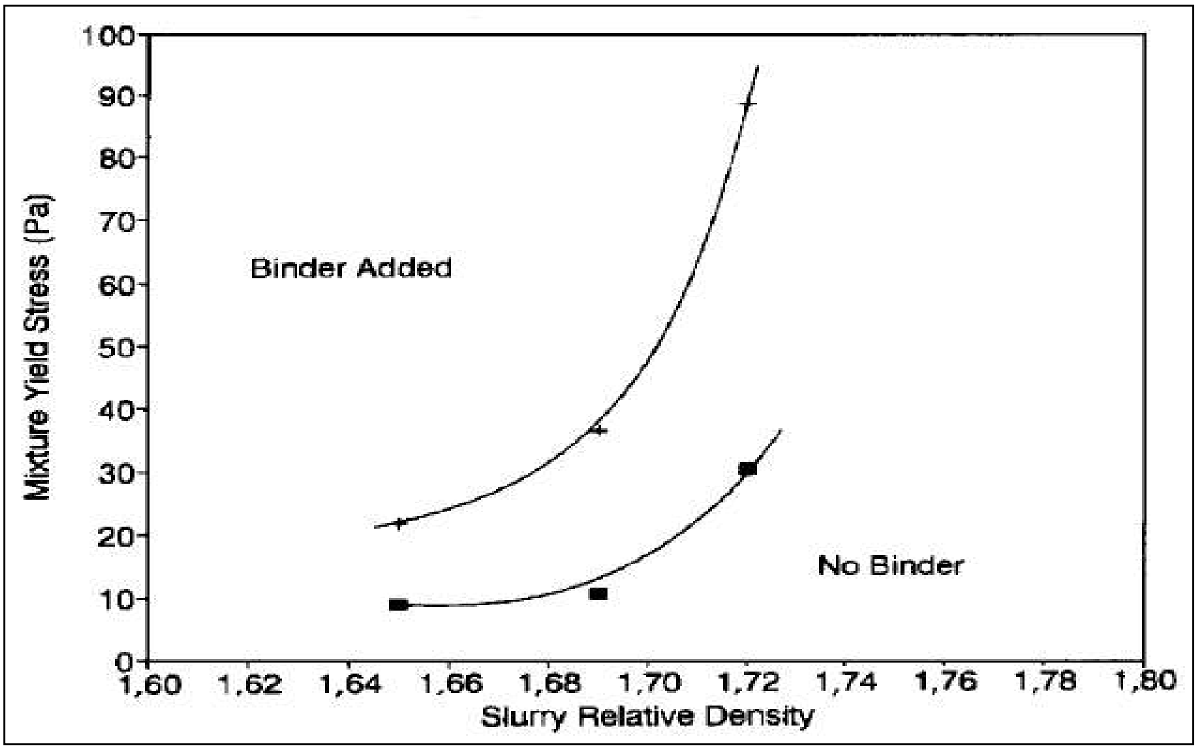

Figure 2-3: Slurry density versus the mixture yield stress (Pa) (Spearing & Cooke, 1993)

Like other components, the physical and chemical properties of the binder plays an important role in the mechanical performance of the backfill material. Chemicals such as normal silicates, soluble silicates, insoluble residue and calcium oxide improve the strength of backfill. In research conducted by Kesimal, et al. (2005) in Turkey, it was determined that a binder containing a high content of soluble silicates, low content of insoluble residue and normal silicates achieves higher strengths. A binder containing a higher proportion of calcium oxide achieves higher strengths.

In hydraulic fill operations, the binder is mixed with water before it is added to the tailings. The cement to water ratio affects the strength that the binder provides to the backfill material. When the cement to water ratio is high, the backfill material achieved higher strength. Some operations add dry cement to the tailings and agitate the mix until it is well blended. This method saves the water and time required to make the cement slurry (Grice, 1998).

2.6.4 Pozzolans

Pozzolans are products that have cementitious properties but are not cement. These include fly ash, slag, gypsum and other additives. Due to the higher cost of cement, pozzolans are mixed with a very low amount of cement to yield the required strength. Pozzolans are cheaper and available to many mine operations. These have enabled them to partially replace the sole use of cement. The addition of natural and artificial pozzolanic additives with cement increases the resistance of binders to “sulphate attack” but they also cause a delay in strength development as compared to using cement without additives (Kesimal, et al., 2005). The impact of adding pozzolans to the backfill material is indicated in Figure 2-4. The addition of fly ash with cement to the backfill material increases the UCS of backfill over time. The rate of increase of UCS is relatively higher when using fly ash as an additive to the backfill material.

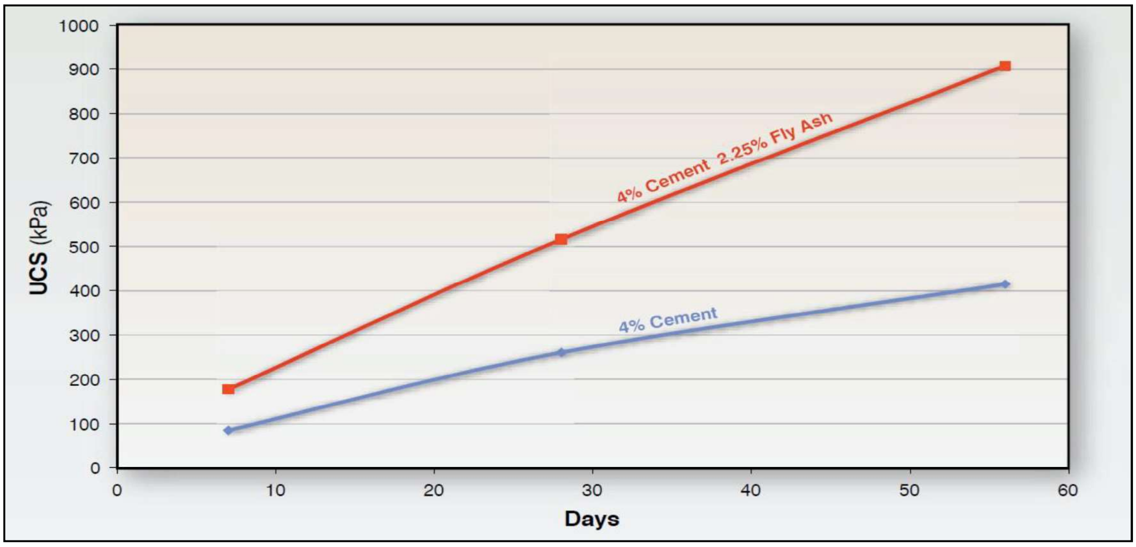

Figure 2-4: The effect of pozzolans on the strength of the backfill material (Henderson & Revell, 2005)

2.7 Geomechanics of Backfill

Geotechnical characteristics are features that determine the physical/mechanical and chemical properties of soil or rocks. The characteristics are used to evaluate the stability of rocks/soils deposits when exposed to different environmental conditions. Different types of material can be used to make up backfill for support purposes and these include sand, gravel, crushed waste rock, total mill tailings or classified tailings. Chemical additives or binders (cement) are used to improve the mechanical, placement and transportation properties of the backfill material. In terms of hydraulic fill, the material is made up of water, solid particles and air. The geomechanical properties of backfill are discussed in the following subsections.

2.7.1 Strength of material

The strength of a rock is determined by its behaviour when it is loaded to exceed its maximum load-bearing capacity. This principle also applies to backfill masses placed underground as a mode of support. The mechanical properties of backfill that are studied include the axial compression of a circular cylinder with a height to diameter ratio of 2.5 or 3. Stress-strain curves are used to determine the elasticity of the backfill material when stress is increasingly applied to the backfill specimen. Backfill material has been tested to be brittle material since its ability to resist load decreases with increasing deformation. The mode of deformation or failure under confining pressure for brittle material such as cemented backfills is normally inclined at an angle less than 45° in the direction of the principal stress. This type of failure is referred to as shear failure since a shearing displacement occurs along the surface of the two places (School of Mining Engineering, 2019).

2.7.1.1 Uniaxial compressive strength (UCS)

The uniaxial compressive strength (UCS) is the maximum axial stress which a rock specimen can carry before it starts failing. The process of failure occurs progressively throughout the loading period and the rock steadily deteriorates. The test is intended for determining the stress-strain relationship, the Elastic modulus (E), and Poisson's ratio (v) for a given rock type. UCS tests for backfill material are conducted in a laboratory using a large-scale static testing machine. The compressive strength in the test specimen (σ) is calculated by dividing the compressive load (P) on the specimen by the initial cross-sectional area (A_0) which is presented in equation (2-1).

$$\sigma = \frac{P}{A_0} \qquad (2\text{-}1)$$

An example of a conventional UCS test machine and a backfill specimen is shown in Figure 2-5.

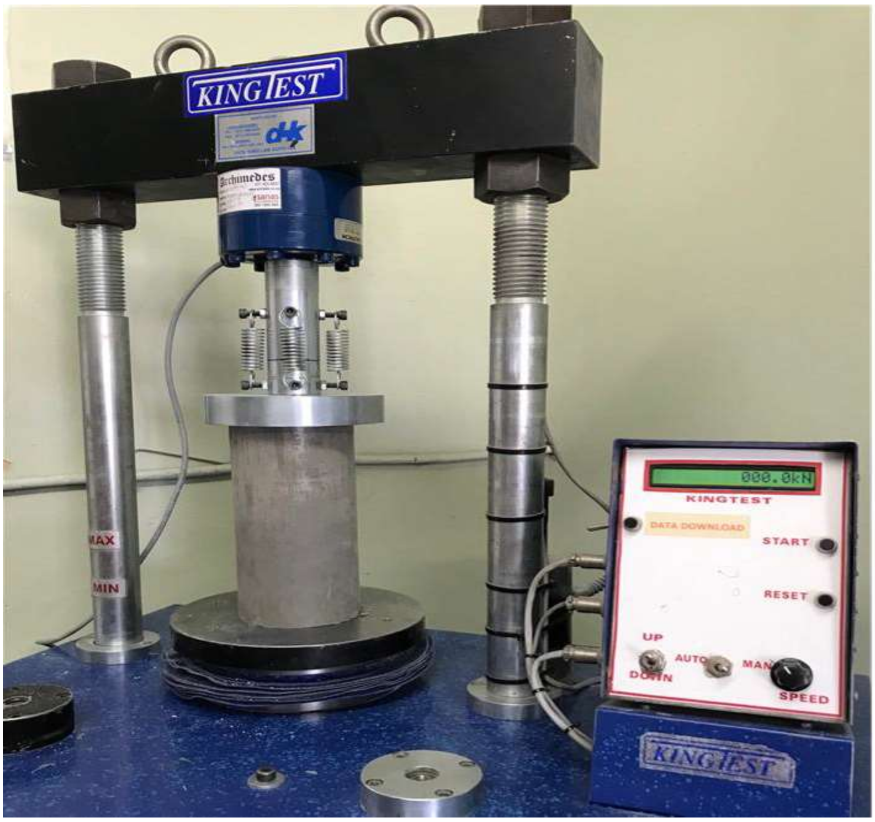

Figure 2-5: UCS test on a backfill specimen with the load cell

Modern compression test machines can record parameters such as the compressive strength (σ), axial strain (ε_a) and stiffness (k) from the strain gauges attached to the specimen during testing. Extensometers are also used to determine the lateral strain on the specimen.

a) Backfill Stiffness (k)

Deformations occurring during uniaxial compression on a backfill specimen include axial strain and lateral strain. Determining the deformation occurring during the test help determine the stiffness (k) of the backfill specimen. Stiffness is defined as the material's resistance to deformation by compression or tension measured in Newtons per meter (N/m). The stiffness of backfill mass and the rock mass being supported is of vital importance since it affects the ability of the backfill mass to withstand the load. The stiffness of a backfill specimen is expressed in terms of load resistance per unit of deformation as given in equation (*2-2*):

$$k = \frac{P}{\Delta L} \tag{2-2}$$

where ΔL is the deformation induced by the applied force(m) and P is the applied force (N).

The stiff testing machines applies stress to the specimen in a more confined space and the maximum load before failure is greater than when using conventional testing machines (School of Mining Engineering, 2019). Figure 2-6 illustrates the behaviour of a specimen loaded by a soft and stiff testing machine. The machine and the specimen are acting like a spring that is loaded in parallel. When a specimen is at its peak strength and it is further compressed by a small amount of load, Δs, to accommodate the displacement made, the load on the specimen must be reduced from the peak (A) to point B where the energy given by the machine is absorbed by the specimen.

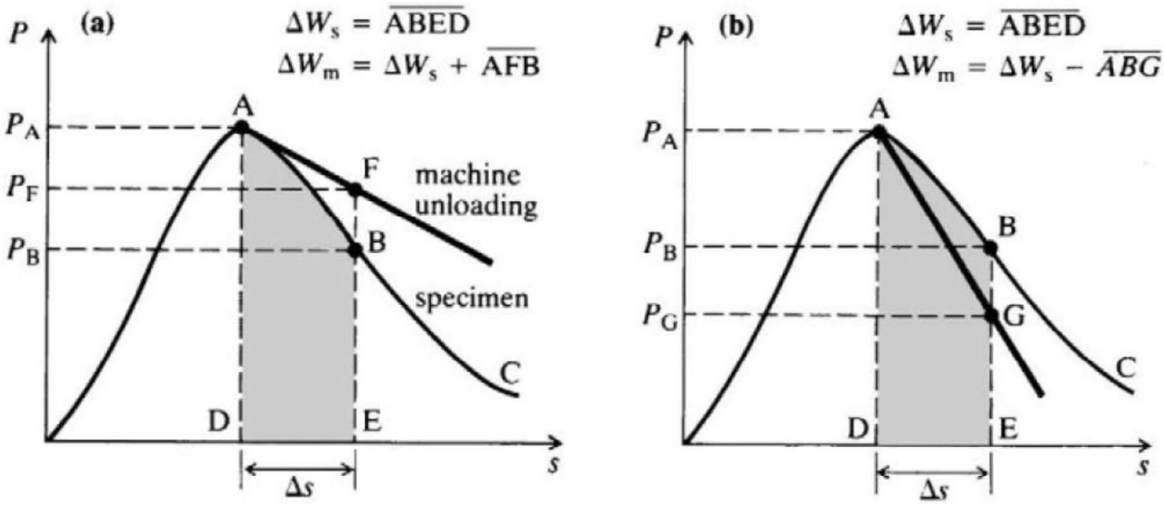

Figure 2-6: The behaviour of the specimen loaded by a soft (a) and a stiff (b) compressive test machine (Brady & Brown, 2006)

A soft machine at point A unloads, releases the stored strain energy and a sudden failure is experienced. This happens because the energy released by the machine during unloading is greater than the energy absorbed by the specimen after reaching its peak strength (A to B). A stiff machine at the post-peak region (A to B) releases less stored strain energy than the energy absorbed by the machine and more energy is required to deform the specimen post its peak strength region (ABC).

The axial strain measures the deformability of the material when stress is applied to the material and it determines the resistance of backfill material to deformation or compression. The axial strain (ε) is expressed as the deformation per unit length and it is calculated using equation (*2-3*).

$$\varepsilon = \frac{\Delta L}{L} \tag{2-3}$$

where ΔL is the deformation(m) and L is the unit length (m).

The relationship between stress and strain can be related by the expression in equation (*2-4*).

$$\sigma = \varepsilon E \tag{2-4}$$

where σ is the axial compressive stress (MPa) and E is the Modulus of Elasticity (Young's Modulus) (MPa).

Backfill is the only known support that can limit stope convergence besides pillars. Although it is relatively soft, it allows 40% deformation before generating sufficient load to limit convergence. The addition of a binder to the backfill tailings increases stiffness which makes the material to be more brittle. A brittle material is prone to cracking under blast loading and rupturing under local rock deformation (Masniyom, 2009). The addition of a binder improves the strength of backfill but it must be limited such that the material is not too brittle. Other methods used to increase the stiffness of backfill include the installation of steel mesh inside the backfill material. This method was developed in Tautona and Moab Kgotsong Mine in South Africa. The method was adopted to eliminate timber stocks on gully shoulders (Scheepers & Murphy, 2011).

The role of backfill stiffness on lateral wall loads and convergence is quite significant such that backfill placed in underground stopes reduces the load on lateral walls and limits the rate of convergence. Numerical model methods have been used to study the role of backfill stiffness on underground stopes walls. In a study conducted by Aubertin et.al, data was collected from 3.6 m and 6 m high test walls in an underground mine to study their response when using different backfill materials as primary support. Backfill material with granular particles, low friction angle and significant fines content were used in the numerical simulations to study the behaviour of stope walls. The results demonstrated that granular backfill material with a small amount of soil cohesion can significantly reduce lateral wall displacements provided that the relative displacements between reinforcement and backfill are small. The addition of cohesion or binding element to the backfill soil has a significant influence on the shape of the deformed wall face and the distribution of reinforcement loads at the connections and within the reinforced soil zones (Aubertin, et al., 2003).

2.7.1.2 Triaxial strength

Triaxial compressive tests are conducted to determine the behaviour of the backfill material when it is axially loaded to failure in three directions while the confining pressure is constantly applied. The backfill material placed in between two stopes experiences stresses from the sidewalls and the hangingwall. Triaxial compressive testing is therefore very important in studying the behaviour of backfill placed underground. Principal stresses are maximum and minimum normal stresses acting on a plane at which the shear stress is zero. When principal stresses act on a 3-dimensional object such as a cylindrical specimen, the maximum stress acts in the vertical direction and is represented as σ1. The intermediate stresses act on the sides in a horizontal direction and are represented as σ2 and σ3. The principal stresses acting on the backfill material are different in real life but in the case of laboratory tests, the intermediate stress (σ2 and σ3) acting on the side of the specimen are treated as being equal. With the current technology used to conduct a triaxial test, applying different principal stress on a specimen is challenging and that is one of the reasons why it is not widely used. Since the effect of intermediate stresses on the specimen are minor, assuming them as being equal has minimal impact on the behaviour of the specimen (International Society for Rock Mechanics and Rock Engineering (ISRM), 1983).

Figure 2-7 presents an example of a backfill specimen under triaxial compression with the three principal stresses and the resultant stress condition on a shear plane surface.

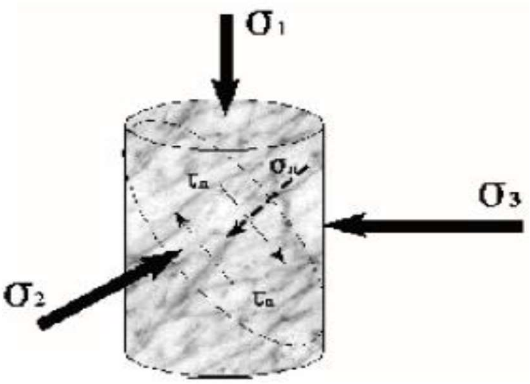

Figure 2-7: Principal stresses (σ_1, σ_2 and σ_3) acting on a backfill cylinder and the resultant stress condition on a shear plane surface (τ_n) (Masniyom, 2009)

The strength of a rock specimen under triaxial loading with confining pressure increases with confining pressure. This behaviour was observed when a series of triaxial tests were conducted over a range of confining pressures. The results obtained by Mohr and Coulomb shows this behaviour in Figure 2-8.

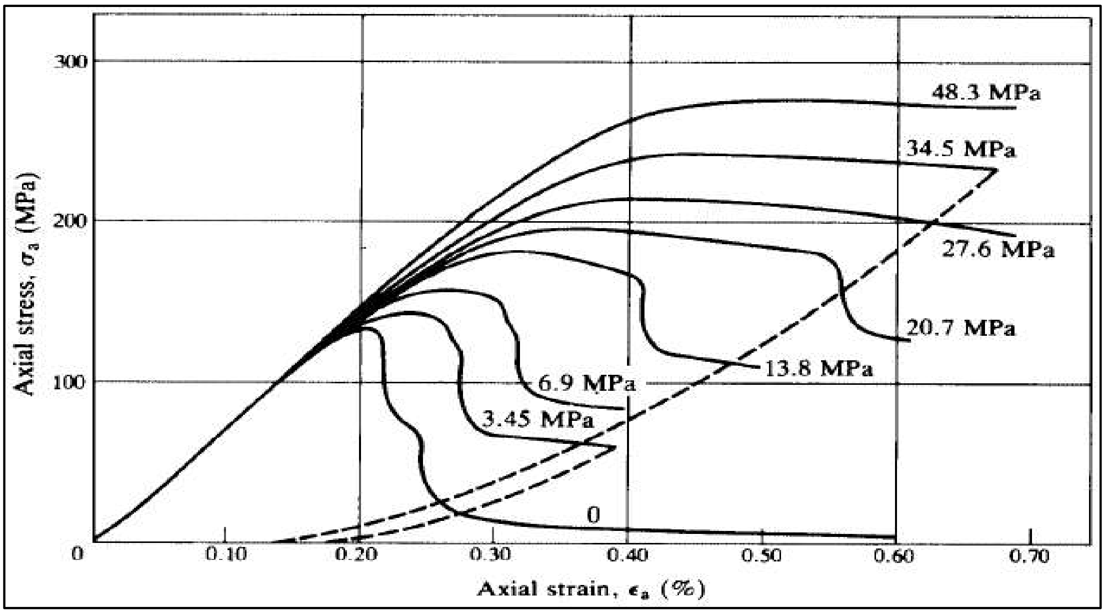

Figure 2-8: Axial stress-strain curves obtained in triaxial compression tests (Brady & Brown, 2006)

2.7.1.3 Mohr-Coulomb failure criterion

Mine backfill is composed of granular solid material which was milled and has inter-particle pore spaces. The pore spaces in the backfill material are filled with air and water which make up the backfill volume. When a backfill material is subjected to normal compressive stress, part of the stress is carried by the solid particles while the other is carried by the pore water. Backfill develops shear resistance through the frictional resistance, interlocking and cohesion or any cementing of fill particles at the surface (Kuganathan, 2005). The Mohr-Coulomb failure criterion is one of the empirical theories generally accepted to be the most applicable means of strength analysis for rock material. This theory is also used to analyse the mechanical behaviour of backfill material. Figure 2-9 shows the shear behaviour on a plane that was loaded under triaxial compression.

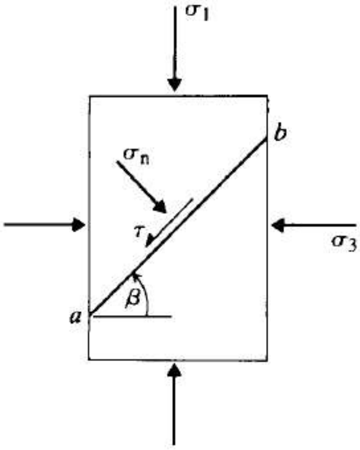

Figure 2-9: Shear failure of a rock specimen on plane ab (Brady & Brown, 2006)

The shear strength of the backfill material is calculated in terms of total stress since the pore water pressure is taken into account. The Mohr-Coulomb failure strength equation is also used to calculate the total shear resistance of the backfill. The equations for the Mohr-Coulomb failure strength in terms of total stresses is presented in equation (2-5).

$$|\tau| = \sigma_n \tan\phi + c \quad (2\text{-}5)$$

where σ_n is the normal stress, *c* is the cohesion and ϕ angle of internal friction.

The Mohr-Coulomb strength envelope is presented in Figure 2-10 where the shear, normal and principal stresses are illustrated on the graph. The curve drawn tangential to the Mohr circle represents the state of stress failure of the specimen.

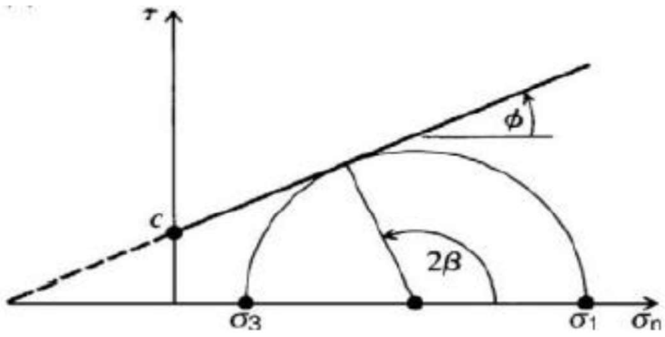

Figure 2-10: The Mohr-Coulomb strength envelope (Brady & Brown, 2006)

The strength of backfill material is dependent on factors such as material properties, curing properties and placement properties. The ability of a backfill mass to maintain stability in a highly stressed mining void depends on its strength after placement. The shear and compressive strength of backfill can be determined using the above-mentioned methods. These methods determine the behaviour and strength of backfill after placement and its ability to maintain stability within the stope.

2.7.2 Components of backfill

The backfill material is generally composed of tailings solid particles, water and air within the pores or void spaces between the solid particles. The properties of the fill composition affect the mechanical, placement and engineering properties. Properties such as void ratio, porosity, water to solids ratio and unit weight of the backfill material affect the placement and mechanical properties of the fill. Figure 2-11 shows a backfill phase relationship between the solid particles, water and air in terms of volumes and weights.

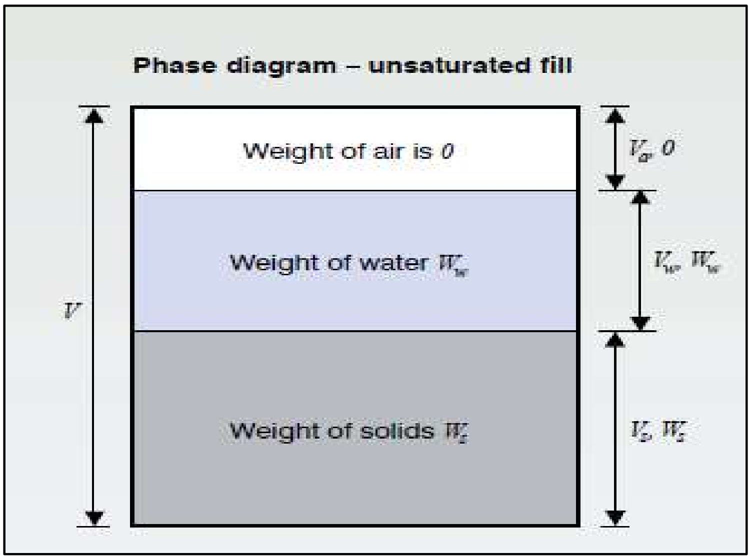

Figure 2-11: Phase relationships for backfills (Kuganathan, 2005)

The ratio of the volume of all space between the mineral grains to the volume of all the mineral grains is called the void ratio (e) and is a very useful measure that indicates the amount of space between the solid particles and their proximity. The equation for the void ratio is calculated using equation (2-6).

$$Void\ ratio\ (e) = \frac{\text{Void volume } (\text{V}_\text{V})}{\text{Void Solids volume } (\text{V}_\text{s})} \tag{2-6}$$

The void ratio measures the packing density of the backfill material. Ideally packed backfill material has a void ratio of more than 80%. This ratio is considered to be a good density since the backfill material would require less binder to fill the voids and allows more of the binder added to coat the tailings and enhance the cohesion of the backfill material.

Porosity is also a useful property that determines the volume of voids to the total volume of backfill solid particles. The porosity of a backfill material must be kept at an acceptably low ratio to reduce the amount of air within the backfill material that would increase the binder content of the fill. Less porosity allows the solid particles to be efficiently coated with the binder and provides good cohesive properties. Equation (2-7) shows the calculation for porosity using volumes.

$$Porosity\ (n) = \frac{\text{Volume of voids } (\text{V}_\text{S})}{\text{Total volume of fill } (\text{V})} \tag{2-7}$$

The water to solids ratio determines the amount of water within the backfill material. This measurement is important in determining the amount of water used in the backfill production and the amount of water to be handled after placement. The water to solids ratio affects the moisture content of the backfill material after placement and the curing process. This factor also contributes to the strength obtained by the backfill material after placement. Equation (2-8) shows the calculation for the water to solids ratio.

$$Water\ to\ Solids\ ratio = \frac{\text{Mass of water } (\text{W}_\text{w})}{\text{Mass of solids } (\text{W}_\text{s})} \tag{2-8}$$

The parameters discussed in this section are very important in the evaluation of the behaviour of backfill after placement more especially its stability. Understanding these properties can help improve backfill quality, reduce binder content and provide maximum strength to the backfill material.

2.7.3 Particle Shape and Angle

The source of tailings used to make backfill is mostly mill tailings which have been ground during the metallurgical processes in the mine. The shape of the solid particles greatly influences the mechanical properties of the fill. Most backfill particles are very angular and have rough surfaces. The particle shape affects the size of the voids and the connectivity of the paths available for transporting water within the backfill material (Masniyom, 2009). The friction angle of the particles is affected by the particle shape and packing density. The particle shape and the grade of the backfill material determine the friction angle of the particles. Angular and uniformly graded material provides friction angles of $35 - 43°$ while a well-graded material provided friction angles of $39 - 45°$ (Masniyom, 2009).

2.7.4 Particle size distribution and size grading

Particle size distribution (PSD) is a mathematical function that determines the relative amount of particles present in a solid material according to their sizes. A higher amount of fines in the tailings reduces the strength of the backfill material while fewer fines reduce the binder required and thus improve the strength. Size gradation is the classification of the size distribution of a material according to different grades. The material can be classified as well-graded, poorly graded or graded. A well-graded material has an even proportion of different particle sizes while a poorly graded material has a large proportion of one particle size than the other. The gap-grade includes an equal proportion of fine material and coarse material which forms gaps in the material. Figure 2-12 shows a typical PSD graph of paste and hydraulic fill for different tailings.

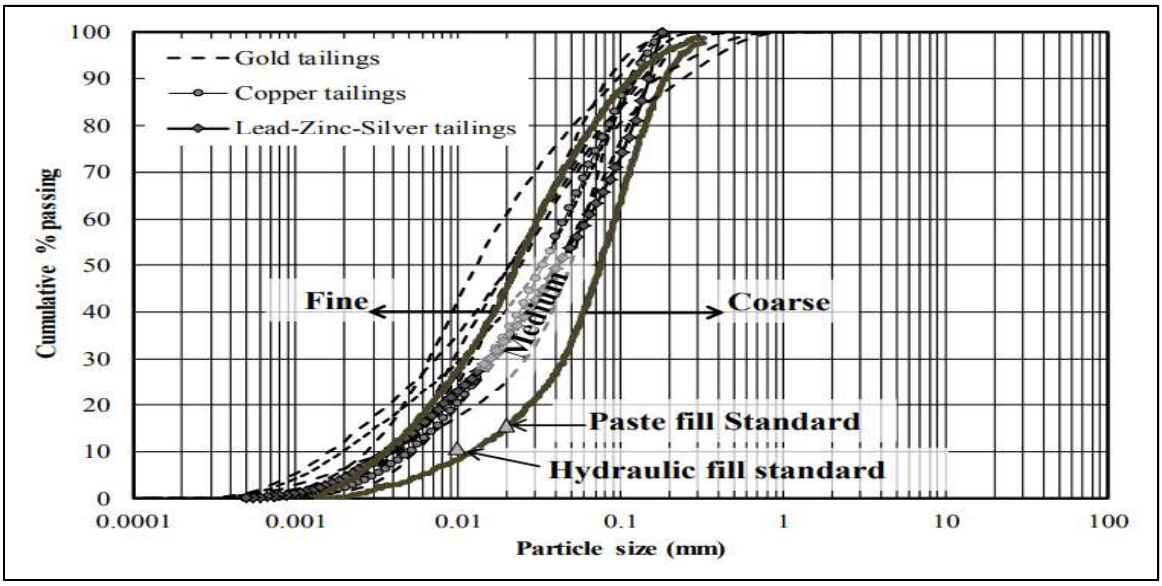

Figure 2-12: Particle size distribution of different tailings (Saw & Villaescusa, 2013)

2.7.5 Relative density and specific gravity

The relative density is the mass per unit volume of a substance relative to water. It is one of the most important parameters of the backfill material. When a backfill material is too dense, the void ratio will be minimal while the fill is loose, the void ratio will be at its maximum. When the relative density of the fill is too loose (0 – 30), it is prone to liquefy during saturation. This can be avoided by adding a binder to the material or thickening it to a higher density (Kuganathan, 2005). Higher slurry densities reduce permeability and improve the water to cement ratio. This reduces the amount of binder required to mix with the tailings.

The specific gravity of the fill is the ratio of the weight of solid particles of a substance relative to the weight of water. The specific gravity also determines the porosity void ratio, solids content and density of the fill. The target density of backfill depends on the particle specific gravity and the percentage of solids by volume in the slurry. This parameter also controls the amount of drainage water released after placing and transportation requirements.

2.7.6 Compaction and Consolidation

Compaction is defined as a process in which unsaturated fill particles are forced to move closer to each other by mechanical energy. When the backfill particles are forced to move closer to each other, air escapes making the material denser. The compaction characteristics of a hydraulic or cemented hydraulic fill can be studied by performing standard compaction or Proctor compaction tests on the material. This test is used to determine the maximum dry density of the fill material at a given water content. Consolidation is a process in which the volume of saturated soil decreases due to applied stress. Solid particles are forced closer by gravity-related static forces and as a results pore water pressure escapes from the fill. The inability of the pore water pressure to escape will prevent consolidation to occur. Backfill slurries undergo consolidation during placement and the process occurs instantly due to the high permeability of the fill material. Consolidation tests are conducted using an oedometer or triaxial chamber whereby the volume change and applied pressure on the filled sample are recorded (Kuganathan, 2005). Compaction and consolidation tests were not conducted on the studied backfill material.

2.7.7 Permeability and percolation rate

Permeability is a measure of the ability of a material such as soils or rocks to transmit fluids. It measures the ease of flow of fluids such as water through porous solids. Permeability is determined by applying a head and determining the depth of penetration or the amount of liquid or gas passing through the sample. Permeability of soils varies with void ratio and grading. Porosity and permeability are related properties for any rock material or solid particles. A backfill material with minimum porosity (fewer voids spaces), tightly packed with a higher density has less permeability since the material does not allow fluids to pass through easily. The consolidation of any backfill material is closely related to its permeability. A highly permeable material provides rapid consolidation and less shrinkage during placement (Barrett, et al., 1988). Permeability of cemented tailings fill is relatively lower due to the cementing reaction which can result in poor drainage characteristics in the early stages after placement (Clark, 1988).

Darcy's Law is used to define the permeability of material and it is calculated using equation (2-9).

$$K = \frac{QL\eta}{hA\gamma^2} \tag{2-9}$$

$$Q = q\gamma \tag{2-10}$$

where,

K = permeability of a porous medium, m^2

Q = quantity rate of flow of fluid through a porous medium, N/s

L = length of a porous medium, in direction of flow, m

H = static pressure differential across a porous medium, m

A = cross-sectional area of a porous medium, normal to the direction of flow, m^2

η = absolute viscosity of fluid flowing, Ns/m^2

γ = unit weight of fluid flowing, N/m^3

For hydraulic backfill, the most important design criterion is the percolation rate. Percolation rate determines how quickly water passes through a porous medium such as tailings or soil. Percolation rate helps evaluate the ability of tailings solids to absorb water and drainage after placement. The percolation rate of tailings particles is primarily due to gravity pulling the water vertically downwards during placement. This parameter is controlled by the particle size distribution, cement content and friction between tailings particles. A minimum percolation rate of 10 cm /hour is acceptable in many mines and this rate provides good drainage properties for the fill while minimising the liquefaction potential. A relatively slow percolation rate delays drainage and creates high pressure on bulkheads which could cause failure if not controlled. The percolation rate of backfill material is calculated using equation (2-11).

$$V_p = \frac{q}{A} \tag{2-11}$$

where,

V_p = percolation rate, m/s

q = quantity rate of flow, m^3/s

A = cross-sectional area of sample normal to flow direction, m^2

Permeability and percolation rate are important characteristics in mine backfill. Effective permeability is required to ensure that excess water used to transport backfill into the stopes is drained rapidly to increase the rate of placement and curing. The particle size distribution affects the permeability and percolation rate which is the reason why most mines have to deslime the tailings material (Masniyom, 2009).

2.7.8 Yield shear stress and slump test

A slump test is a method used to measure the consistency of fill material before settling. It is used to determine the workability and flowability of a slurry. The slump tests are usually conducted on a paste fill material. The slump test is conducted using a 300 mm cone and provides only an index relationship since the results are influenced by the relative density of the paste in addition to the yield shear stress. The cone slump test is dependent on both yield shear stress and density, which can vary with changes in solids specific gravity, particle-size distribution and chemical composition. Therefore, it is recommended that the yield shear stress rather than the empirical slump height should be used as the variable to monitor paste consistency. For increasing solids concentration, there is an exponential increase in yield shear stress, so control of the pulp density is extremely important.

Pashias et al. (1996) have determined a solution for a cylindrical slump test from which yield shear stress can be calculated directly. This is a simple procedure conducted in almost the same way as the cone test, but instead, using a cylinder with equal height and diameter dimensions (Pashias, et al., 1996). In practice, a 200 mm diameter cylinder can be used for routine paste fill work. Figure *2-13* shows a cylinder slump test using a 200 mm cylinder at a paste preparation plant.

Figure 2-13: Cylindrical Slump Test (Grice, 2005)

Pashias et al. (1996) state that the cylinder model equation relating yield shear stress and slump height can be determined from:

$$s' = 1 - 2\tau 0'(1 - \ln(2\tau y')) \qquad (2\text{-}1)$$

where: s' = s/H = dimensionless slump height

$\tau 0'$ = $\tau y/(\rho g H)$ = dimensionless yield shear stress

ρ = density (kg/m3)

g = gravity (m/s2)

H = cylinder height (and diameter) (m)

s = slump height (m)

The dimensionless slump height is the ratio between the actual slump and the height of the cylinder in metres. Using the above relationship, the variation of a slump as a function of yield shear stress can be plotted as shown in Figure 2-14. Note that, for the graph, the values are only valid for a cylinder of 200 mm height and 200 mm diameter and a pulp density of 2.1 t/m3. Using cylinders of different dimensions and changes in bulk density will require the graph and table to be recalculated (Grice, 2005).

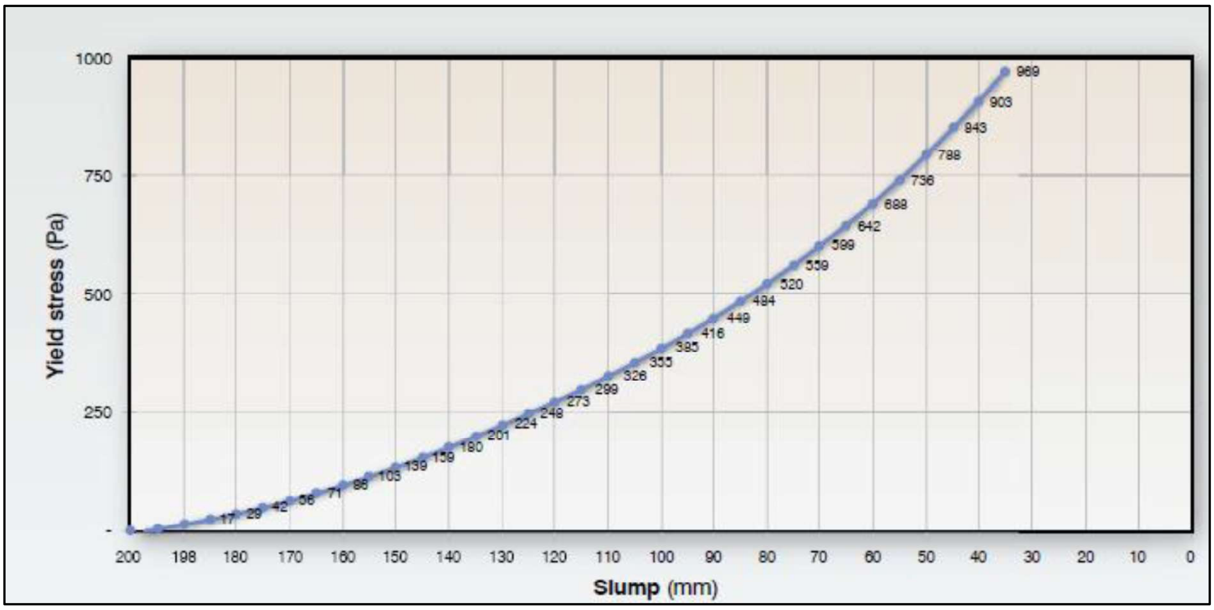

Figure 2-14: Yield shear stress as a function of cylinder slump for 200 mm cylinder, 2.1 t/m^3

2.7.9 Flowability

Flowability is the capacity of a fluid or loose particulate solid material to move by the flow. The flow spread of fill materials decreases with the increasing solid content. In cemented fill materials, water can cover the surface of binder and tailings particles as a water film, playing a role in lubrication during the flow of the backfill slurry. The increase in the solid content can enhance the inter-particle contact, which will increase the force of friction between particles and decrease the lubrication effect of water and then hinder the flowability. On the other hand, contrary to the influence of the solid content, rising the binder dosage seems to be beneficial to the workability of cemented backfill slurries. One of the critical factors affecting the workability of a cemented backfill slurry is the reaction of the binders, where the dissolution of binders particles into solution and formation of reaction products in the binders particles surface and solution. This can lead to the changing of the inter-particle force through the formation of new bonds and then the workability (Qiu, et al., 2019)

A study done by Qui et.al in 2019, demonstrated the behaviour of cemented paste backfill (CPB) which included flowability. The results of the study conducted showed that the flow spread also supported increasing in yield stress of the CPB slurry. A decrease of 67% flow spread was observed when solid content increased from 70% to 80% at the 12% binder dosage. With the same solid content, the yield stress decreased when increasing the binder dosage. The rheological properties of a CPB sample determine not only the solid content but also the binder dosage (Qiu, et al., 2019).

2.8 Basic Mine Fill Materials

Different types of backfill material are used to fill mining voids and they include rock, aggregate, paste, and hydraulic fill. The types of backfill material can either be cemented or uncemented. Cemented backfill includes the use of waste material which is mixed with a binder product to improve the strength while the uncemented backfill does not use any binder.

2.8.1 Rocks and aggregate fill (cemented or uncemented)

Rockfill is made of crushed waste rock excavated from underground development with particle sizes ranging from 25 - 300mm. Rockfill is alternatively mixed with hydraulic backfill slurry and a very small amount of binder to improve its mechanical properties. Aggregate fill is made of finer particles that were excluded from the crushed rock. The particle sizes of aggregate fill are less than 25mm. The sources of rock and aggregate fill are normally waste rock from open-pit operations, waste rock from underground development mining, quarried rocks and coarse gravels (Henderson & Revell, 2005).

Rocks and aggregates sourced from quarried rock require extra rehabilitation at the end of the life of the mine. Alluvial sands can also be used especially if they are not fetched far from the mine proximity. Severe ecological damage can be caused to the rivers where the alluvial sands are collected so the process should be done under strict control measures. The type of aggregates used must be consistent since the change in the aggregate material will have different material properties which can affect the mechanical properties of the fill. The amount of clay in the aggregate material must be highly monitored since it affects the porosity and drainage properties of the fill.

Other forms of rockfill involve modification of the rock particles to suit the mining requirements. This is done by optimising particle size by adding fines or blending different rock particles and adding binders such as cement (Kuganathan, 2005). The composition of the modified rock fill can be composed of different materials such as:

- Cement slurry rock fill – no fines added;
- Well-graded rock fill – no cement added;
- Cemented tailings slurry rock fill – binder is added and
- Tailings paste rock fill (PRF).

The above-mentioned types of rockfill have different final placed porosities. The lower porosity of the rock fill material increases the strength of the fill to the same level when the binder is added. Rockfill has a common problem of material segregation when blended with hydraulic fill or cement slurry. When the cement slurry rockfill is placed in the stope, the high rock particles are piled in the middle and the slurry surrounds the pile (Kuganathan, 2005).

2.8.2 Paste Fill

Paste fill was developed in the late seventies at Bad Grund Mine in Germany. Paste fill is a high-density slurry that has been thickened to an unsettling state and has a solid content of 70 to 80% by mass. Paste uses full plant tailings with about 15% of the particles less than 20 µm. The final density of a paste fill is higher than hydraulic fill density and there is less water drained after placement. Less water is used during the preparation of paste fill and its high solid percentage reduces shrinkage at the stope. Due to a higher amount of fines, paste fill material has lower permeability and retains water post-placement (Grice, 2005).

Paste fill was only accepted as viable to hydraulic fill in 1990 in Canada and Australia. The correct definition of paste fill has been debated since the 1980s due to its concentration characteristics falling within thickened and paste. Paste fill is defined according to the physical and material characteristics of the tailings material. The rheology of paste fill conforms to the Bingham plastic flow model which has a non-Newtonian fluid behaviour. Minimum yield stress is required to overcome static friction before paste fill movement commences (Rankine, et al., 2007).

The key rheological property of paste fill is the yield stress and it is directly proportional to the density of the solids of the mix before the cement is added to the tailings slurry. Paste fill can be placed at relative densities of 75 to 80% solids by weight. When paste fill is transported by a gravity-operated distribution system, only potential energy at the driving head can be used to pump the material down the shaft. At a controlled density, flow occurs when the driving head is greater than the pipe wall shear stress and if the density of the paste is too high, a blockage can occur.

2.8.2.1 Paste fill material properties

A paste can be described as a non-segregating slurry that has low water content when placed and it can maintain a single homogeneous phase from preparation till it is placed underground (Coxon, et al., 2005). Some of the material properties of paste fill are described below.

a) **PSD** – The material has relatively more fines at 15% with the stream having a minimum size of 20 µm.
b) **Relative density** – The density of the material is about 75 – 85% solids by weight in underground mines. The higher slurry densities reduce permeability

and improve water to cement ratios. The quantity of cement required to achieve comparable strength to hydraulic fill is less when using paste fill.

c) **Flowability/line velocity** – The material has no critical flow velocity since the paste material does not settle in the pipes. There are high friction factors generated when the paste is transported which require pressure pipes of more than 5 MPa to be used. Where the reticulation geometry of the paste system is favourable, gravity methods may be used to transport the paste underground (Grice, 1998).

d) **Yield stress** – Has minimum yield stress ranging from 150 – 650 Pa at a pulp density of 70 – 80%.

e) **Preparation -** Can be prepared using filters.

f) **Drainage from stope** – Minimum or insignificant drainage occurs after placement in the stope due to slime fractions and the non-draining nature of the fill.

g) **Final Density** – The final density of paste fill is high as compared with hydraulic fill.

h) **Permeability** – There is very low permeability in paste fills since they contain a high amount of fines.

i) **Water content** – There is less amount of water in the paste material as compared to hydraulic fill. Paste fill is composed of mostly solid particles of which they include a fair amount of slime fraction.

j) **Solid Content** - Paste has a high percentage of solids which ranges from 75 – 85%.

k) **Binder Usage –** Paste fill uses low binder content compared to hydraulic fill. The typical binder content added to the paste fill ranges from 4.5 to 5% by weight. In special cases, some paste fill operations add a minimum binder of 1.5% provided that the paste tailings have a higher density (Grice, 1998).

2.8.2.2 Geotechnical considerations in paste fill

Mechanical properties such as UCS and shear strength of paste fill are influenced by cohesion, internal friction angle and pore water pressure. These factors are bound to change due to the change in paste fill material properties. Factors affecting the UCS of the paste fill include the binder content, heat load due to hydration or geothermal gradient, hydraulic conductivity, curing time and surcharge load. Paste fill placed in underground stopes is exposed to different environmental and geotechnical conditions which affect its performance. Chemical, thermal and hydraulic properties play a key role in improving the mechanical strength and stiffness of the paste fill material. Sheshpari (2015) highlighted that the arching effect of the paste-fill after being placed also plays an important role in strength improvement.

Previous research proved that the UCS of the paste fill increases with the increase in the amount of binder content mixed with tailing and it improves with a decrease in the void ratio of the material. Sheshpari (2015) highlighted in the laboratory study conducted by Ghirian and Fall in 2013 and 2014 that an increased hydraulic conductivity of water mixed with tailings reduces the UCS of the paste fill. The Elastic Modulus (E) and UCS of the paste fill increase with the increase in curing time and cement hydration. The values of paste fill cohesion tests are approximately half of the UCS values and the friction angle (φ) of the fill at different heights remains the same. The development of the shear strength of the paste fill is directly related to the increase in cohesion of the paste fill which is caused by cement hydration and bonds formed between tailings grains during curing (Sheshpari, 2015).

Paste fill is considered a non-segregating slurry, meaning that it has very low amounts of excess water when it is stationery. The flow characteristics of paste fill remain the same even when it comes to rest and the flow can be continued after some time. Paste has no critical flow velocity and can remain idle in the pipeline system for different periods without plugging. To remobilise paste which is stationery requires sufficient shear yield stress to make it flow (Henderson, et al., 2005). The advantages and disadvantages of using paste fill are presented in Table 2-1.

Table 2-1: Advantages and disadvantages of using paste backfill (Lang, 2009)

Advantages	**Disadvantages**
Higher strengths can be achieved with equivalent cement content.	Paste backfill systems typically have higher capital costs compared to conventional hydraulic backfill plans.
The drainage of water and slimes from the fill is minimized, reducing the need for bulkhead construction and extensive drainage works. This feature also reduces maintenance on sumps and mine de-watering pumps.	The pumpability of a paste is very sensitive to small changes in water content and grain size distribution.
In some cases, unclassified tailings can be used to make paste rather than just the coarse fraction as is the case for hydraulic backfill.	The distribution network in the mine requires a greater level of engineering design to control pipeline pressures.
Shorter stope cycle times can be achieved because an equivalent strength can be achieved in a shorter time with paste backfill.	

Paste backfill systems achieve lower porosities than conventional fill thereby increasing the tonnage of the material that can be disposed of underground.	
Since paste backfill is deposited as a non-segregated mass of backfill (because cement particles are not displaced by the internal movements of the draining water), more predictable strength properties for the fill can be achieved.	

2.8.3 Hydraulic Fill

Hydraulic fill is a common type of backfill made of mine tailings which are discarded after ore has been recovered from the run of mine. Hyrocyclones are used to remove fines in the tailings during desliming. The tailings used in hydraulic fill have a larger particle size distribution with more particle sizes greater than 420 µm. Hydraulic fill is designed to be placed such that the excess transport water drains out, leaving a porous fill mass with residual moisture content. Internal stresses in the fill are developed by the self-weight of the backfill particles. The fill is confined by stope walls, the inter-particle friction resists internal stresses which are less than geostatic values because of arching. Hydraulic fill is also used as a component in other types of fill containing an aggregate material. Mount Isa Mines uses aggregate material of 65 mm maximum size and cemented hydraulic to fill its mining voids underground (Grice, 2005).

The use of a binder with hydraulic fill is not required if the fill will not be exposed by future mining activities or be resaturated by water ingress. The addition of cement binders is required when the fill will be exposed from the pillar and when the hydraulic fill material properties pose a risk of liquefaction or resaturation after placement. The addition of cement binder in hydraulic fill is required in these cases since they provide additional shear and cohesive strength to maintain stability once the fill is exposed.

2.8.3.1 Material properties of hydraulic fill

The following material properties are considered when designing a hydraulic fill system and affect the mechanical, transportation and placement properties of the backfill material. The following properties describe the nature of the hydraulic fill.

i. **PSD** – The material has a narrow band of particle size distribution and is well graded. The PSD has a minimum of 10% of particles that are below 10 µm in size and has a large fraction of coarse particles. A suitable PSD gives good drainage properties by ensuring acceptable permeability of the placed fill.

ii. **Relative density** – The density of the material is about 60 – 72% solids by weight. At a high density, the drainage of transport water is reduced.

iii. **Particle shape** – Tailings have sharp and angular particles which cause high friction than natural soils.

iv. **Flowability/ line velocity** – The material has a critical flow velocity which must be above 2m/s; if it is less, settling occurs.

v. **Yield stress** - Slurries do not have minimum yield stress.

vi. **Preparation** - Can be prepared using cyclones or thickeners.

vii. **Probability of segregation in the stope** – There is a high chance of segregation in hydraulic fill.

viii. **Drainage from stope** – Drainage occurs as soon as placement starts and continues till placement finishes. Good drainage properties reduce the pore water pressure and the probability of liquefaction. Decant water of the hydraulic fill must be removed quickly to prevent liquefaction. The rate of drainage is dependent on the driving head and the permeability of the backfill slurry. The quantity of water drained relies on the initial slurry density and the moisture content of the backfill after placement. Hydraulic fill must have a porosity of around 50% to allow free draining of the water in the placed slurry.

ix. **Final Density** – The final density of the hydraulic fill is low at placement as compared to the density after preparation at the backfill plant.

x. **Supernatant water** – There is more decant water after placing which is drained out of the slurry. The water content in a hydraulic fill can be at a range of 33 – 54% of the total mass of the slurry while the solid content ranges at 65 – 75%.

xi. **Post-placement shrinkage** – Immediately when backfill is placed, decant water is drained and the solid particles settle, the backfill material shrinks.

xii. **Permeability** – There is medium to low permeability in hydraulic fills since they contain an even distribution of particle sizes. Placed hydraulic fill has a porosity typically around 50%, although values as low as 30% have been recorded.

Hydraulic fill can be placed with or without cement. Uncemented hydraulic fill is one of the cheapest bulk-fill materials available, however, to ensure safe operation, strict controls must be implemented to monitor the material properties such as drainage, design and construction of retaining barricades and permeability. When these parameters are not monitored, inrush accidents are bound to happen due to liquefaction failure. There is an increasing trend to replace the hydraulic fill with paste fill. This is due to the availability of a high proportion of finely ground tailings and the need to add cement to the fill material. In some cases, there is a high proportion of coarse material to produce paste fill and hydraulic fill is the only available material (Grice, 2005). The advantages and disadvantages of using hydraulic fill are presented in Table 2-2.

Table 2-2: Advantages and disadvantages of using hydraulic fill (Grice, 2005)

Advantages	**Disadvantages**
The surface processing plant is relatively simple and low capital cost but requires effective instrumentation and quality control systems.	The risk of inrush and its consequences can be higher in uncemented hydraulic fill compared to cemented hydraulic and paste fill operations if badly designed and/or operated;
Hydraulic fill can be produced very cheaply but it is not easy to produce hydraulic fill that is out of specification.	Inadequate collection of drainage water can result in poor roadway conditions, damage to vehicles and have a major impact on the ventilation systems;
A cement binder is not required in many situations where future exposure is not required (e.g. cut-and-fill stopes and remnant pillars). This substantially reduces the cost compared to paste fill. Where a large percentage of fill must be cemented, this advantage disappears.	The fill placement rate is constrained by drainage rate and account must always be taken of pouring and resting times and the establishment of unsaturated filling conditions.
The preparation and delivery costs are relatively low since the dewatering and desliming functions can be carried out using simple hydrocyclone technology.	The desliming process reduces the available tonnage of fill material to be placed underground. The corollary to this issue is that while the fill plant is operating, the finest tailings sizes are rejected to the surface storage facility. These have, in general, poorer geotechnical performance in these storage areas.

2.8.3.2 Cemented hydraulic backfill

The addition of cement into hydraulic tailings improves the mechanical and physical properties of the backfill material. A typical cement content of 6% is added to the tailings and yields a uniaxial compressive strength (UCS) of around 750 kPa within 28 days. Portland cement is the most commonly used binder and it achieves higher strengths and quick curing when more than 6% binder content is added to the tailings slurry. Cement can either be added as a slurry or as powder depending on the engineering constraints of the backfill system.

The amount of cement content added to the hydraulic backfill varies in different mines depending on their strength requirements. As mentioned before, binder costs in a backfill plant contribute to about 70% of the backfill operating costs. Most operations are trying to reduce the amount of binder used by substituting it with additives such as fly ash, ground furnace slags and other additives to obtain the same strength as the one obtained when cement is used.

2.9 Hydraulic Fills at South Deep (CCT and FPT)

South Deep Mine uses hydraulic fill material to fill the underground long-hole stopes. The hydraulic fill is produced from the tailings at the gold plant which produces Full Plant Tailings (FPT) and Cyclone Classified Tailings (CCT). The preparation of tailings is different for both CCT and FPT. With CCT, mill tailings are fed to multiple cyclones of different sizes to remove the excess fines and obtain the desired particle size distribution. The cyclones take the underflow to the next stage of classification while the overflow is taken to the thickeners for processing. The underflow is then transferred to the CCT storage tank where it is kept to the correct relative density until it is mixed with the cement and additives.

FPT is produced by thickening the mill tailings to a desired relative density. The mill tailings are directly transferred to the FPT plant where they are thickened to the required density. The FPT is then sent to the FPT storage tank where they are kept at the required density until they are sent to the mixing tanks where cement and other additives are added. The addition of a binder to the tailings is done differently for different operations. Some operations mix the cement with water to make it a slurry before it gets mixed with the tailings while others add dry cement into the tailings. There are different methods used to mix tailings with a binder in the backfill industry which includes compressed air and mechanical agitation method. The mixing process is mostly done on the surface but in some operations, the cement is sent underground and mixing is done at the underground dams.

The backfill system used in South African mines consists of more or less than five processes which include:

- Backfill preparation plant;
- Shaft storage and distribution plant;
- Underground storage dams;
- Underground backfill distribution piping;

- In-stope backfill placement (Streuders, 2011)

The backfill preparation plant produces tailings with the required PSD, relative density and moisture. When using cemented hydraulic fills, cement is also prepared by mixing it with water to achieve the required relative density before mixing with the tailings on surface. Mixing in most backfill operations is conducted on surface and the final product is stored in the shaft storage tanks where it is continuously agitated. Cleaning of pipelines is conducted before distribution can start. This is conducted before and after pumping the backfill slurry underground.

Backfill distribution is done on the surface where either the cemented or uncemented tailings are sent underground through a borehole system. The backfill product is sent underground to the dams where they are stored, agitated, and then pumped through the pipeline system to the stopes. The in-stope placement preparation is done by construction paddocks with wire mesh and geotextile bags which are secured by the pre-stressed elongates. The paddocks are constructed based on the stope dimensions and the type of backfill to be placed. These are done to prevent leakage and allow enough draining of the hydraulic fill.

Backfill placement is conducted by pumping backfill from the storage dams underground to the stope. This process continues throughout the shift, stops when the shift is over and continues again when another shift starts pumping backfill. Before distribution of backfill from the surface distribution plant, flushing is done using water and when the lines are clear, backfill pumping commences. Flushing of water through the pipes is also done after the backfill pumping shift ends. This is done to prevent backfill accumulation on the lines which cause blockages and can lead to pipe replacements which causes delays during the shift (Streuders, 2011).

2.10 Sampling

Sampling is described as a process of selecting a subset of individuals to make statistical conclusions and estimate the characteristics of the whole population. Sampling is used to define resources, optimise resource utilisation, maximise profitability and for process control (Heath and Sherwood, 2000). To obtain accurate results, the samples taken must be representative, if not, the conclusions made on the analyses of results can negatively impact the operation at which the samples were taken. Pierre Gy's sampling theory defines correct sampling as a sampling scenario in which all parts of the population have an equal probability of being included in the sample (Pitard, 1993).

The primary objectives of sampling are to collect a sample that is representative and to ensure that there are no changes in the environment or procedure during collection and analyses. The secondary objective is to record any variability occurring during collection and analyses. Understanding the purpose of collecting the sample, sampling error, sample selection method, sampling procedure, and sample size to be collected is important. These parameters help obtain representative samples, accurate estimation of characteristics and conclusions about a population. For this research, the above-mentioned parameters are described below:

2.10.1 Purpose of sampling backfill material

Backfill material at the mine is prepared on the surface and transported underground through pipelines to the long-hole stopes. Sampling backfill material on the surface helps determine the characteristics of the fill material sent underground. It also determines the quality and the performance of the fill material as compared to the strength requirements underground. Samples collected at the backfill plant must represent the bulk fill material placed underground. The characteristics of the sample must match that of the placed material in underground stopes. The sampling of backfill material is also carried out to monitor the process from preparation to distribution.

2.10.2 Sampling error

A sample must represent the population from which it comes although the precise representation of the population is not guaranteed. Sampling error can cause the sample collected to be unrepresentative of the population and these may lead to wrong conclusions being made. It is important to understand the errors that may cause the sample to lose its credibility in representing the population. Some of the units in a population may be unusual or carry characteristics way different from the majority of the population. This factor cannot be avoided but collecting a large enough sample will reduce the chances of collecting more unusual samples (Pitard, 1993).

The tendency of favouring the selection of particles of particular characteristics can cause errors in sampling. These sampling errors are referred to as sampling bias. Sampling bias limits or restrict other particles from being included in the sample, which is against Gy’s law. Sampling bias can be caused by selecting the wrong population or poor study design. Measurement errors are not sampling errors because they only result from instrument failures or poor procedures (Pitard, 1993).

2.10.3 Sampling procedure

The sample taken should be as large as possible to avoid sampling errors. Effective and efficient sampling procedures must be implemented to reduce the risk of incurring sampling errors during the sample study. The procedure which is carried out during the collection of backfill material includes sample collection, preparation, curing, and testing.

2.10.4 Sample selection method

The sample selection method depends on the purpose and type of sample to be collected. Different types of samples can be studied from a population. The sample can be selected out of convenience, purpose, and judgment or random. For this research, systematic random samples will be collected.

2.10.5 Sample size

Although collecting a large sample reduce the chances of incurring sampling errors during a sample study, it is important to define the study population before selecting an optimum size of the sample. These will help include or exclude a certain group of subsets that are not representative of the population study. Two of the limitations of deciding on how large the sample may be are time and funding. The sample size depends on the type of analyses to be performed, the number of comparisons and variables to be studied, and the precision of the estimates to be achieved at the end of the study.

2.11 Operational Factors that Affect the Strength of Backfill Material

The literature review explained geotechnical factors which affect the strength of the backfill material. These factors affect the stability of the backfill material either mechanically or chemically. Although these factors have been studied and proven to affect the strength of the backfill material, the operational and design factors can also affect the stability of the backfill material. Operational and design factors affect the end product produced at the backfill plant since they are responsible for the preparation, mixing, distribution and sampling of the backfill material being sent underground. Operational factors need to be studied to ensure that the product being prepared meets the strength requirements. Geotechnical parameters of the backfill material are affected during preparation, mixing, distribution, curing and sampling. Some of the operational parameters which were studied include preparation, mixing, curing and testing.

Inconsistency in the quality of backfill can be determined from the early stages of preparation till the transfer point to the underground workings. The main parameters used to monitor hydraulic backfill quality include relative density (RD), particle size distribution (PSD), permeability and strength. The strength of the backfill is normally tested from samples collected at the points transferring underground. The RD, PSD and permeability can be measured instantly at different points in the preparation plant. Inconsistent backfill quality results obtained on the surface provides inconsistent backfill performance underground and affects the stability of the filled stopes underground and contributes to the stability of the entire mine. Operational factors must be identified and studied to understand their impact on the strength of backfill and the performance of backfill underground.

Factors such as day and night shift work, mixing of cement with tailings, backfill curing conditions, sampling backfill underground and quality control procedures can be studied to help maintain consistency of the backfill quality and improve backfill performance at the mine.

2.11.1 Day or Night Shift Work

Shift work was introduced in many industries to reduce the workload of employees and restrict them to finishing work before the end of the day. The inconsistency of working hours of employees, low utilisation of equipment and the cost of overtime wages made companies consider working around the clock. Shift work was introduced for economic reasons and to maximise the utilisation of equipment which was expensive. The health and well-being of employees were also considered when designing shift work schedules. The working hours, the number of days in and off work were also designed to suit the health and well-being of workers (Folkard & Tucker, 2003).

Although the productivity of employees varies across different shifts, factors such as the nature of work being carried out and the number of people present to carry out the job also play an important role in determining the productivity of employees during each shift. Research has shown that during the night shift there is less supervision of work as compared to the day shift. Even if the human body can adjust to working at night, research has shown that at certain hours of the night, the efficiency of employees is reduced due to their bodies reaching a resting mode (Folkard & Tucker, 2003).

One of the researches done on shift work measured productivity using speed and accuracy of work carried out over 24 hours in a day. The study showed that from 23:00 h, efficiency starts dropping below average and increases after 03:00 h in the early morning. During the day shift, efficiency starts increasing above average from 07:00 h to 19:00 h. The trend of the data shows a decline in efficiency just before lunchtime (noon) and it increases again at 15:00 h in the afternoon. A decline in efficiency below average occurred after 19:00 h. This proves that a day shift is more productive than a night shift (Folkard & Tucker, 2003).

A backfill plant runs on a 24 hour day and has a shift work schedule. The process of preparation, make-up, mixing, distributing and sampling occurs both during the day and night. The variety of sample test results taken during the day and night is possible. Factors such as visibility, less supervision, fewer people working on night shifts may also impact the quality of work carried out at night.

2.11.2 Mixing Cement with Tailings

Mixing tailings with a binder to form a higher strength backfill is a challenge that many backfill operations experience. Blending the two to form a homogenous material is difficult to achieve at the backfill plant. Gold plant tailings have a higher proportion of fines than other metal plants. Gold plant tailings relatively have higher specific gravity, higher viscosity and settle faster than other tailings. Binder is mixed with the tailings either in a slurry state or dry. The measurement of the percentage of binder solids and tailings are important as they enable the plant to determine the percentage of binder required to achieve a certain strength.

Using a dry binder is easy to weigh and quantify against the amount of tailing used whereas when the binder is in a slurry state it makes it difficult to measure the percentage of binder solids added to tailings solids. A study conducted by Baguley (1988) showed that there is a large amount of air within the binder powder and can cause cavities on the impeller system that mixes the two products. Since the tailings are denser, a dry binder will float and be attached to the sides of the mixing tank. This makes mixing difficult as the binder accumulates on the sides and forms granules (Baguley, 1988).

In some operations, the binder is mixed with water to form a slurry that can easily mix with the tailings slurry and produce higher strength backfill. This method is most common in hydraulic backfill operations and it consumes a lot of water which increases the amount of water to handle underground. A wet binder is mostly preferred and produces a more blended backfill product (Baguley, 1988).

The shape of the mixing tank plays a key role in ensuring that the binder is blended efficiently with the tailings. The selection of the shape of the mixing tank depends on the quantity, nature and mechanical properties of the backfill material. Round tanks are mostly used when mixing gold tailings with the binder. Round shape tanks can handle high settling slurries and can produce a homogeneous slurry. Deslimed gold plant tailing requires a simpler mixing method since they have particles which a lot finer and settles faster relative to the ordinary slime slurries (Baguley, 1988).

2.11.3 Backfill Curing Conditions

Curing is the process of maintaining continued hydration by maintaining satisfactory moisture content and temperature within the concrete material for a sufficient period. Hydration takes place as soon as the concrete is placed. Curing significantly improves the properties of backfill material such as strength, abrasion resistance, durability, volume stability and water-tightness (Akinwumi & Gbadamosi, 2014). Kosmatka and Wilson (2011) emphasised that the most effective concrete curing methods are dependent on the materials used, construction method, and the intended use of the hardened concrete. These imply that concrete products are effectively cured based on the nature of the material, the purpose they serve and the method by which they are constructed. Different curing methods are used to cure backfill based on these key factors. Curing conditions are also dependent on these key factors and they are designed to simulate real-world situations.

Curing methods used in cemented hydraulic backfill are mostly guided by the concrete industry methods. Curing in the concrete industry can be completed by preventing the loss of moisture from the concrete and keeping the exposed surface continuously wet. There are different methods and mechanisms used to maintain the conditions listed above. Since backfill is placed underground and left to drain by itself over the curing period, the decant water keeps the surface hydrated. The moisture loss was reduced by enclosing the backfill with the barricades and stope walls. Backfill samples collected for strength tests in the laboratory are placed in PVC moulds and enclosed with containers to prevent moisture loss. The backfill samples are placed in a curing room at a constant temperature and humidity.

Backfill material at South Deep is mixed with cement to improve its mechanical properties. Desired mechanical properties of backfill are achieved when the cement is sufficiently hydrated. The extent to which the hydration of cement in the backfill material is completed influences the strength developed and the durability of the backfill placed. To achieve more desirable, valuable backfill properties, curing conditions must be effectively controlled (Kosmatka & Wilson, 2011). Backfill curing conditions include the extent of the hydration process, curing climate, temperature, relative humidity, air circulation and curing room design.

The sample results obtained during testing are also affected by the curing conditions since they affect strength development and other physical properties (Kraft, 2016). The processes involved in curing backfill samples in the laboratory must be maintained and monitored frequently to note any change or deviation from the standard curing procedure. Understanding the effects of curing conditions on backfill sample test results improves the knowledge of the backfill personnel on what results are expected when there is a certain change in the process. It also increases confidence in the backfill material that is placed underground.

2.11.3.1 Hydration

Hydration in the concrete industry is defined as a hydraulic chemical reaction whereby cement is mixed with water and form strong bonds which give the product strength. The extent or duration of the hydration process influences the strength development of the mixture. The right period of hydration differs for each material that is mixed with the cement slurry. For normal concrete mixtures, longer hydration periods yields higher strength. The period of complete hydration also differs with the type of material being used. The ratio of cement to water in the mixture affect the hydration process. The cement acts as a glue that binds the backfill material together to form a hardened backfill structure.

In most hydraulic backfill operations, a binder (cement) slurry is first prepared before it mixes with the tailings. This process is referred to as binder make-up in metallurgy. The hydration process starts immediately when the binder is mixed with water and if the binder is left uncirculated for some time, it hardens. At the binder make-up, the right water to cement ratio is determined and the right volume of cement and water are mixed. The hydration process continues from mixing with tailings to placement, curing until all the water is removed from the backfill slab. The hydration process is affected by air temperature, moisture content and the ratio of cement to water.

2.11.3.2 Curing Climate

The climate in which backfill is cured influences the quality of hydration and strength development. The ambient temperature and moisture level in the air affect the rate and quality of hydration. Inconsistent temperature and moisture content cause variation in the quality of backfill material.

a) Temperature

In high-temperature environments, the warm air heats the backfill material and increases the rate of hydration and the backfill material gains strength at an increased speed. When hydration is completed within a short period, the backfill material also becomes hardened relatively quicker. The backfill samples cured at high temperatures have higher strength at 7 days and the strength may even be more than the 28 days required strength.

Change of season also plays a huge role in the curing conditions. Air temperature is lower in winter than in summer. In winter, the hydration process is slower than in summer and strength is developed at a low speed. The air temperature in curing chambers must be monitored so that the air temperature is kept constant through all seasons. The readings on the thermometers must be regularly calibrated and monitored to ensure the correct temperature readings are recorded.

Although high ambient temperatures increase the speed of hydration and strength development, the air temperature must not be too high to eliminate external moisture in the air. The moisture content in the air also play an important role in curing backfill therefore, ambient temperature levels must be balanced with the moisture levels in the curing chamber. If the temperature is increased, more moisture must be added to the room (Kraft, 2016).

b) Relative Humidity/ Moisture Content

Moisture content is very important in the curing process and affects the hydration process. The minimum moisture content allowed to cure concrete products is 90%. Below this value, the hydration process is compromised. Lack of moisture in the air leads to incomplete hydration and weak backfill material which compromises stope stability. Controlling the moisture content during the curing process reduces the level of evaporation and thus the amount of cement required to provide the desired strength to the backfill material (Kraft, 2016).

When curing backfill samples, sealable moulds are used to contain the sample and keep the moisture in the sample constant. However, external moisture is also very important. The curing chamber must have a correct level of moisture and temperature when curing backfill samples. The external source of moisture can help prevent moisture loss in the chamber. Evaporation of moisture from the moulds critically influences the strength of the samples at the corners and on the surface causing them to be weaker (Kraft, 2016).

c) Air Circulation

Air circulation within the curing environment plays a key role in curing backfill material to control the velocity of air circulated within the chamber. Air circulation at all sections of the room must be controlled to ensure that the right speed, temperature and moisture is circulated throughout the room. The air velocity within the chamber affects moisture evaporation from the surface of the backfill material. When the air circulation is not controlled, there would be an increase of heat with elevation within the room which causes the bottom shelves of the curing chamber to be colder and top shelves to be hot. Uncontrolled air circulation can create cold and hot areas within the room and inconsistent levels of moisture and temperature. At higher air velocities, there is increased evaporation of moisture affecting the quality of backfill material.

2.11.3.3 Curing Room Design

The design of the curing room must be constructed such that the conditions within the room are maintained all the time and that the change in the external environment does not affect the internal environment. Changes in climate conditions like, temperature (summer or winter), moisture, air velocity (spring) should not affect or change the conditions in the curing room. The construction of the room must be laminated and sealed to prevent this to occur. The curing room must be assessed often to notice any change in the climate conditions and the conditions must be maintained all the time.

The curing chamber must have enough space to allow good air circulation and to give enough room for samples to receive the required temperature, moisture and air velocity. Good curing room design improves the quality of backfill samples and reduces costs associated with an adjustment that is made to ensure a better quality of results are obtained from the samples. This also reduces binder cost as it provides optimum quality of backfill samples collected at the backfill plant. A well-designed and maintained curing room help provide consistent sample test results (Kraft, 2016).

2.12 Sampling and monitoring backfill performance underground

Sampling backfill is an essential part of backfill quality control in the backfill operation. The backfill material produced on the surface plant is prepared according to the standard required by the mine to meet the underground stability requirements. Transportation of hydraulic backfill over longer vertical and horizontal distances affect the material properties of backfill. The loss of solid particles is experienced through the process and this also affects the mechanical properties of the backfill end product. Although other material properties such as tailings RD and PSD are not measured at the filling stopes to further determine the actual loss, the strength obtained after UCS tests can be used to determine the change in strength. The correlation between the quality of backfill prepared on the surface and the backfill placed underground must be determined.

Underground sampling is essential in determining the actual performance of backfill underground. The placement of backfill underground to fill one stope can take up to a month to be completed. The actual strength of the backfill placed and cured in underground conditions must be determined to help optimise backfill preparation processes on the surface. Backfill performance in underground stopes depends on several factors which include the distance from the stope face, drainage properties of the fill material, the permeability of the geotextile material and curing conditions. It is necessary to quantify the stress-strain behaviour of backfill underground. This could be done through the installation of devices in the backfill stope which records the stress generation in the backfill relative to the distance from the face and the effect of backfill on stope closure (Malan, et al., 2007).

Different technologies are used to determine the stresses experienced in the in-situ backfill underground which includes total pressure cells, Goodman Jack tool, ANZI strain cells and the linear variable differential transformer (LVDT) cell. These methods were used to measure rock stresses underground and they have now been adopted in the backfill industry. The installation of such devices helps quantify and compare the in-situ stress-strain behaviour of different backfill materials placed underground which can be used to compare the performance of backfill underground to the laboratory test results of backfill prepared on the surface (Malan, et al., 2007).

The information recorded from the stress measurement devices can be used for computer modelling and developing a backfill model for a specific stope. This information can be used to optimise backfill by producing a backfill product with maximum strength properties at a lower binder content. Instruments such as hydraulic stress meters and hydraulic closure meters are used in the mining industry to record backfill performance. Limitations on recording backfill performance underground using these devices include the harsh conditions in the backfill stope, the presence of cement in the fill material, harsh chemicals in the drainage water. The lack of real-time recording of data through remote sensing is another limitation that makes it difficult to record continuous measurements (Malan, et al., 2007). Figure *2-15* shows the instrument used to measure backfill stress underground with the load cell on the right.

Figure 2-15: Components of the instrument used to measure backfill stress underground

Sampling underground backfill material is one of the erratic tasks that backfill operations faces. The core drilling method was found to be most practical and effective but the lack of access to the filled stopes was the main disadvantage for deep-level mines. The easier method which is mostly used is the collection of a wet backfill sample from the pipe filling the stope. The performance of the backfill placed underground can be determined from the samples collected from the filling pipe. To determine the overall performance of backfill within the stope is quite difficult but the stress measurement devices could be used to determine in-situ backfill performance.

2.13 Backfill Quality Control

The backfill quality must be controlled before being transferred underground to maintain desired performance after placement. Current quality control practices for backfill systems do not provide sufficient information regarding procedures followed to maintain consistency of the backfill quality. Quality tests such as relative density, PSD, permeability, UCS and triaxial tests are conducted to determine the mechanical properties of backfill. Routine testing and research related tests on the backfill material must be conducted to maintain and improve the quality of backfill produced in the plant. Backfill material properties are the most important since they affect the resultant performance of backfill after placement. Controlling these properties can help maintain a good quality backfill material and provide maximum performance underground. Backfill quality control is identified as a key area where improvement needs to be made to enhance the reliability of backfill system operation (Cooke, 2001).

The addition of a binder to a backfill to modify its properties (such as binding agents) can be very expensive since the binder contributes around 70% of the entire backfill operation. Although binders produce a quality backfill product, they can push up the cost of the backfill and render the overall mining cost unattractive (Bloss, 2014). Backfill is an engineered material, quality control of the material must ensure that in situ performance of the backfill material particularly its strength, permeability, RD, moisture content and PSD are within their tolerance limits. Due to the high cost of backfill operations, an ongoing search for cheaper binder products and enhancement of the tailings will not compromise the performance of backfill. A reliable backfill quality system is critical in every backfill operation. Backfill is a key component of the mining cycle which make it very important to ensure compliance and reliability of the backfill system (Bloss, 2014).

An effective management structure and performance measures are required to ensure a well-integrated system between metallurgical plant, backfill production and placement (Bloss, 2014). Other departments involved in the production of a reliable quality backfill product must be involved and an effective communication system must be established. As part of the management structure, production of the backfill should be managed by people with appropriate experience in minerals processing, mining, metallurgy, placement and rock engineering to maximise the efficiency and reliability of production. This is very important and ensures that maximum backfill performance is achieved at relatively lower binder costs.

Backfill is an engineered product designed to achieve specific physical characteristics at a certain point in the stoping cycle. Failure of backfill to meet the required specifications indicates that the system has been compromised at a certain point. This could be caused by failure to adequately design the backfill or failure to supply the required quality of backfill which provides the required physical properties after placement. A successful supply of good quality backfill to the stope can be achieved through a quality control procedure. The supply of backfill components must also be controlled to ensure the desired backfill product is produced (Bloss, 2014). Poor quality control can lead to different bad consequences such as:

- Poor control of cement (binder) dosage rates;
- Poor quality of cement supply (or other binders);
- Change in backfill particle size distribution;
- Excessive water dosage;
- Unplanned segregation of constituent materials upon placement in the stope; and

- Changes in operating practices (Bloss, 2014).

All of the above-mentioned consequences compromises the quality of backfill produced and its performance after placement. Regular laboratory-scale tests are recommended as part of the general quality control program (Bloss, 2014). Regular testing of the backfill physical characteristics does not guarantee desired backfill performance but it is important in determining changes or variations of backfill quality parameters from the design limits. In cases where the backfill preparation, reticulation or placement affect the final in-situ properties of the backfill and they are not adequately represented in laboratory tests, then the in-situ performance of backfill might be overrated by the laboratory tests (Bloss, 2014). In this case, it is important to conduct in-situ stress tests on the backfill placed underground. The sampling of underground backfill slurry is another method that could be used to determine the performance of in-situ backfill.

Pumped support products such as backfill consist of different components that are mixed either on the surface or underground. A quality assurance procedure for backfill materials contain the following components:

- Quality assurance testing for the separate components (tailings, binder, additives and water) before it is transported or pumped underground;
- Underground quality assurance procedures of the placed backfill (sampling for quality tests);
- Backfill slurries quality testing must be done more frequently and sampling points must be modified such that representative samples are obtained (Malan, et al., 2007).

Laboratory tests conducted on the surface indicates the expected performance of backfill underground and they are not definitive results of the actual performance of backfill after placement. A balance between the laboratory test results and in-situ results of backfill after placement must be established. Properties such as relative density, PSD, permeability, cyanide testing and water content can only be determined while the backfill material is in a slurry form. These parameters must also be sampled and tested both underground and on the surface.

The strength of the backfill material should be categorised into the performance before and after placement. The relative density of a hydraulic backfill material affects the flow rate and pipe wear, so it is important to monitor it throughout the preparation process. In other mining operations, the relative density is measured together with the flow rate to determine the relationship and monitor any deviations from the specifications of the mine (Malan, et al., 2007). Malan, et al. (2007) also suggested that a checklist might be useful for monitoring backfill quality underground more especially before and after placement. Quality assurance of the barricade material such as geotextiles, wire mesh and the poles is done by the manufacturer but the mine needs to have its quality assurance practices on such types of equipment (Malan, et al., 2007).

The evaluation of backfill performance underground is very important and should be conducted regularly. Routine underground evaluations on the backfill can be done through observations to evaluate the quality of barricade installations and identify problems that could affect the stability of the backfill paddock during placement. Monitoring of the backfill paddocks is critical and must be done routinely to eliminate the risk of failure. As part of the quality monitoring process, photographs before and after placement must be taken as part of the record-keeping of backfill quality installation (Malan, et al., 2007). Observations on installation, placement and backfill performance after placement must be recorded. Performance of backfill after placement can be evaluated by observing contact between the hangingwall and backfill, the stability of the hangingwall next to the backfill in response to the load generated during normal closure and seismic events. Malan, et al. (2007) proposed that mines should develop specific templates that can be used during underground assessments to record all the important information on the backfill.

2.14 Environmental Impacts of Backfill

The environmental factors associated with backfill are considered to be positive where backfill has been effectively used, and a negative where either filling is not adopted or has been considerably less successful. Where backfill has been effective, the stope void created during mining is essentially stabilised with little or no ground failure within the stope. There is a variety of materials which has been used for successful filling, including cyclone tailings (CCT), full plant tailings (FPT), or combinations, with or without binders. Mill tailings are the main source of backfill material in deep underground mine operations. Placing waste materials underground as backfill has a major environmental benefit in that this waste material does not have to be stored and rehabilitated on the surface (Lang & Jones, 2005).

Backfill reduces the overall amount of mining waste to be handled on the surface and the cost of rehabilitation. Mine waste materials have physical and chemical properties which can be difficult to manage environmentally. Gold tailings often have a fine fraction that can generate dust during and at the end of the mining operation. Acid rock drainage (ARD) is one of the major environmental problems in the mining industry and occurs when sulphide minerals are exposed to oxygen in a humid environment. Tailings and waste rock may contain barren sulphide minerals which are prone to oxidation and can produce acid. The acid may have a significant corrosive impact on the equipment used underground and will also permeate to the mine dewatering system and be discharged on the surface into the environment. The use of cemented backfill reduces the potential passage of oxygen through the fill material and the fractured ground which reduces the generation of acid. This also decreases the likelihood of mine voids becoming preferred drainage paths for underground water (Lang & Jones, 2005).

When backfill has been poorly implemented, the stope walls are likely to be unstable which negatively affects the mining activities. Caving and convergence of the hanging wall and footwall are likely to occur. There have been several cases where this has increased the ARD generated from mines. In severe conditions, subsidence can result which may develop a significant cone of depression above and around the void in question. In the most extreme cases, this has resulted in a sudden failure, resulting in the loss of buildings and other infrastructure into the void. It is important to maximise stope filling since it helps minimise the adverse surface environmental impacts of underground mining operations. Tailings used to fill underground stopes are treated with different chemicals and additives which needs to be carefully monitored since it can affect the health of workers underground and harm the environment. The risks, hazards and environmental impacts of backfill must be carefully studied and controlled to ensure that backfill is placed safely and maximum performance is achieved (Lang & Jones, 2005).

2.15 Summary of Literature Review

There are different types of backfill technologies used in the mining industry and the selection of a suitable product is dependent on several factors. Economic, logistical, geomechanical engineering and mining factors are used to determine a suitable backfill material for a specific mine. The advantages and disadvantages of each type of backfill were discussed and it was discovered that hydraulic fill is mostly used in South Africa's deep-level mines. Due to highly stressed working environments, high energy costs, long travelling distances and hot temperatures underground, hydraulic fill helps reduce the impact of these problems. The summary of backfill techniques discussed in this chapter and preferred method of binder, material composition, transportation, orebody, stoping method and geometrical structure is presented in Table 2-3.

Table 2-3: Summary of Backfill Methods used in the mining industry

Backfill Technique	**Hydraulic Fill**	**Paste Fill**	**Rock/Aggregate Fill**
Material	Fines, Mill tailings, sand deposits	Ultra-fines, tailings, coarse, fine sand	Coarser, waste rock, quarry, overburden rock
Binder or Additives	Cement, Fly Ash	Cement, pozzolans	Smelter slag, fly ash, cement
Transportation	Pipeline system, centrifugal pumping technology	Boreholes, pipeline system, pumped mechanically using piston/diaphragm pump.	Fill passes, surface and underground conveyors, fill holes
Geometrical Structure	Ascending slices, massive filling	Slices, Ascending slices	Massive filling
Orebody Shape	Tabular and Massive	Tabula and Massive	Massive, tabular, veins
Stope Method	Cut and Fill, Long-hole stoping, Bench stoping. Sub-level open stoping	Cut and Fill, Long-hole stoping, Bench stoping. Sub-level open stoping	Panel open stoping, cut and fill, benching, drift and fill, block caving.

There are many theories on the impact of backfill in the mining environment which have been proven through tests and observations in underground mines. There is a wide range of factors affecting the resultant strength of backfill after placement. The effect of different material properties of backfill on the stability and shrinkage properties has also been thoroughly studied. Material properties such as relative density, particle size distribution, permeability and strength are the most studied parameters in backfill operation. Their impact on placement and stability properties is significant. The geotechnical properties of backfill and its impact on the mining voids and the mining cycle was also reviewed.

The quality of backfill produced in the plant is affected by a range of factors that involves material properties. Operational factors such as the mixing of tailings with the binder and curing properties do contribute to the final strength obtained by the backfill material. Sampling, curing and testing of backfill are conducted as part of the quality control process. This process is required during preparation on the surface and placement underground. Routine sampling and testing must be conducted frequently to ensure the required backfill quality is supplied to underground stopes. Each component of the backfill must be tested for quality control and the results must be recorded. The performance of backfill underground must be determined through sampling and testing. Stress measurement devices are used to determine in-situ backfill stresses and the information obtained from these devices can be used to monitor the performance of backfill underground.

Factors affecting the strength of backfill have been determined from the material properties, operational properties and placement properties using the theories from previous studies. For this research, factors causing variations of strength tests results of backfill at South Deep mine were investigated. The impact of these factors on the strength of backfill was determined and practical solutions were developed. Operational and design factors affect the quality of backfill prepared by the backfill plant and quality control measures must be established to eliminate factors compromising the quality of backfill produced. The performance of backfill underground must be quantified and studied further in mining operations. Recent technologies should be adopted to determine real-time parameters such as closure, shrinkage, moisture content and curing temperature within the backfill stope.

3 RESEARCH METHODOLOGY

3.1 Introduction

This chapter presents a description of the research process. It also provides information regarding the method which was used to conduct this research and a justification for using this specific method. The Chapter also describes various phases of the research, which includes the selection of points of investigation, data collection and data analysis process. The validity and reliability of the data collected using qualitative research methods are also discussed and the way the deliverables of the research were met at the end of the study. This research identifies factors contributing to the variability of backfill strength results and their effects on the strength of backfill. The researcher conducted assessments and observations of the backfill production processes at the plant.

Points of the investigation were identified and sampling was conducted to determine the contributing factors to the inconsistent backfill quality product. Multiple samples were collected to determine the material characteristics of backfill at different points and they were tested. The results obtained from the samples were analysed using statistical methods and conclusions were made. Different factors were studied through sampling and testing and the researcher quantified the effect of each factor and ways to optimise the system to achieve maximum backfill performance. This allowed the researcher to draw a strategy that will assist the mine to optimise their backfill production system by maintaining consistency of the backfill quality and helping to reduce the cost of binder usage.

3.2 Research Methodology

A research methodology is a practical description of how the research was conducted. It specifically states how the researcher systematically designed a study to ensure valid and reliable results that address the research aims and objectives. The research format used in the investigation should be used as a tool to answer the research questions. This research aimed to identify contributing factors to the backfill strength variability and understand their effect on the strength of the backfill. The factors identified during this research are not the only ones and may differ in other backfill operations. The impact of these factors is quantified and analysed based on the results obtained from the samples collected. This research study was guided by the following research questions:

1) What is the current performance of the backfill practice and how can it be improved?

2) What are the constraints of the current backfill practice?

3) What backfill test standards are applicable?

4) What type of investigations will have to be done to find factors that cause backfill strength variability?

5) What type of data will have to be collected during the investigations?

6) What tests will have to be done?

7) Will the investigation provide a solution that will account for backfill logistical constraints?

8) What cost implications will the new practice have on the mine?

A quantitative research approach was selected as a suitable method to conduct this research study because it uses measurements and testing using numerical data to formulate relationships between variables. This research method allows the researcher to use descriptive, correlational and experimental research tools to investigate the factors causing variation of backfill strength results. These tools helped in examining whether there is a cause-and-effect relationship between different variables. Data was obtained by collecting samples at different points of investigation within the backfill preparation process. Sampling points within the preparation points were identified and samples were collected for different studies. For example, for UCS studies, the RD and PSD samples were collected and measured. This data was used to determine the relationship between these variables. Descriptive statistics and correlation methods were used to interpret and analyse the data. The reasons justifying the selection of this research method are discussed in the next subsection.

3.3 Justification for Using Quantitative Research

Borrego, et al. (2009) justify that most engineering researches seek to identify how outcomes (i.e., mechanical failure) are determined by reducing probable causes to a discrete set of variables. The quantitative research method focuses on gathering numerical data and making conclusions about the characteristics of a population or explaining a particular phenomenon. This method uses statistical, mathematical or numerical analyses of data collected through surveys, questionnaires, and polls, by manipulating pre-existing statistical data using computational techniques (USC Libraries, 2020). The characteristics of quantitative research are as follows:

- The data is usually gathered using structured research instruments.

- The results are based on larger sample sizes that are representative of the population.
- The research study can usually be replicated or repeated, given its high reliability.
- The researcher has a clearly defined research question to which objective answers are sought.
- All aspects of the study are carefully designed before data is collected.
- Data are in the form of numbers and statistics, often arranged in tables, charts, figures, or other non-textual forms.
- The project can be used to generalize concepts more widely, predict future results, or investigate causal relationships.
- The researcher uses tools, such as questionnaires or computer software, to collect numerical data (USC Libraries, 2020).

The main aim of a quantitative research study is to classify features, count them, and construct statistical models in an attempt to explain what is observed (USC Libraries, 2020). Descriptive and experimental designs are used in quantitative research to establish relationships between variables and establish causality. Quantitative research was found to be suitable for this study because the purpose of this study is to investigate factors, identify them and determine their effect on the strength of backfill.

The research aims to understand the current performance of the backfill and investigate the possible factors that cause variation of the backfill strength. The existing data was used to make a summary of the existing backfill results to determine the current performance of the backfill. Experimental research was conducted to investigate the cause and effect of the identified factors on the backfill strength. A correlation between factors identified and the strength of backfill was determined after investigating the effects of the factors on backfill strength. Statistical analyses methods were used to determine the extent of variation of backfill strength results, determine the effect of the factors identified and their impact on the overall backfill operational costs.

This research aims to understand the effect of different parameters such as operator, day or night shift, CCT and FPT plant on the strength of the backfill. Understanding these factors would help the researcher to develop improved strategies and actions to deal with the backfilling of historic voids and high profile mechanised long holes stopes. The strategy designed will improve the quality of backfill and maintain consistency of the backfill strength results. These strategies will also help optimise the backfill system such that the backfill operational costs are reduced. The research would bring a new understanding to the backfill operations by showing the impact of each process in the backfill plant on the quality of backfill material produced. The impact of the quality produced on mine stability and productivity would further be outlined as well as the importance of maintaining consistency of the backfill strength.

There are three categories of data collection methods used in quantitative research namely; experiments, surveys, systematic observations and secondary research (Borrego, et al., 2009). This study used secondary research, experiment and systematic observation methods to collect data. Assessments, observations and samples were collected during the data collection process. Systematic sampling was used to study the quality of backfill at each stage of production. These allowed the researcher to conduct a thorough investigation and specifically determine the effect of each factor on the backfill quality. Samples collected were tested and the results obtained were used to determine the effect of each variable on the backfill strength. The observations and assessments helped identify possible factors which were investigated through sampling and tested to prove their effect on the variation of backfill strength.

Once data was collected, it was processed and analysed using descriptive statistics to answer the research questions. The descriptive statistics gives a summary of the data and can represent it in the form of graphs, scatter plots and frequency tables to visualise the trend of the data.

3.4 Data Collection Process

The data collection section describes the tools and methods used to collect information and identify the variables being measured. It describes the methods used to obtain the data and if the data was pre-existing or was gathered by the researcher. If the researcher gathered it themselves, they should describe the type of instrument that was used and why it was used. No data set is perfect, any limitations in methods of gathering data should be stated (USC Libraries, 2020). The data collection process for this study was done in stages and they are described in steps below.

3.4.1 Literature study and mine background data review

A literature review on the current state of backfill technology in the mining industry was conducted and different types of backfill technologies were studied. The properties of different backfill products were also studied and their effect on the strength of the backfill material. Test standards applicable in the backfill industry were also reviewed and compared to the current practices. Compliance with the standards was also assessed for quality control and the impact of non-compliance on the test results.

Mine void data was reviewed and analysed to determine the extent of the voids to be backfilled. Dimensions, geotechnical state of the stopes and the strength requirement for each stope were determined. Historical mine backfill performance from 2017 was reviewed and analysed using previous test results. The existing test results from 2017 to 2019 were assessed mostly focusing on the performance and possible factors which might have caused variability. Strength results were measured against possible factors such as relative density, day/ night shift, operator and the type of product (CCT or FPT).

3.4.2 Observations and assessment of the backfill production process

Different studies were conducted to determine the factors contributing to the variability of backfill strength results and their effects. The backfill production process was observed and assessed before studies were conducted. This was done to understand the production process and its operational and design constraints. The backfill quality specifications were given and their limitations were stated in the backfill quality report provided by the mine. Processes from tailings transfer from the mill plant to the backfill plant, tailings preparation (both CCT and FPT), binder preparation, mixing and distribution to underground were assessed. The sampling, curing and testing procedures were observed and assessed at the plant. During the assessment, notes on events occurring during the process were made and recorded. This method assisted in identifying factors that can affect the quality of backfill.

3.4.2.1 Backfill preparation process

Understanding the processes used to produce backfill helped with identifying the constraints within the preparation process. This also helped classify each constraint according to respective points within the preparation process. The preparation process for each product was observed and assessed based on the current specifications. The gold tailings are produced from the metallurgical plant and are transferred to the backfill plant or the tailings storage facility. The mill tailings are transported to the backfill plant through a pipeline system into a backfill storage tank. The backfill storage tank then supplies the cyclone classified tailings (CCT) and full-plant tailings (FPT) production sections with the mill tailings. The CCT section produces classified tailings which are classified by hydro cyclones with multi-stage processes. The FPT section produces full-plant tailings which are dewatered by sedimentation in thickeners (Cooke, 2001).

a) CCT Preparation

The CCT preparation starts when the mill tailings from the backfill storage tank are transferred to the CCT make-up tank where they are stored until classification starts. Tailings are then transferred to the cyclones to be classified on a multistage filtration system where fine fractions of the mill tailings are removed. The classified tailings are then transferred to CCT storage tanks where they are mixed with ferrous sulphate to reduce the cyanide content. The classified tailings are then transferred to the CCT tank where they are filtered to meet the required relative density (RD) before mixing with the binder. The classified tailings are continuously agitated to prevent the settling of small particles. The binder slurry is prepared on the surface by mixing the dry binder with water at a controlled proportion. The binder slurry is transferred to the storage tank where it is continuously agitated and circulated to prevent hydration. The binder slurry is then mixed with classified tailings in the tundish (a cone-shaped tank where the mixing occurs).

During mixing, the mixed product is simultaneously transferred underground through a pipeline system. The sample is collected from a sampling point on the pipe that transfers the backfill to the underground working places. Figure 3-1 shows a flow diagram of the CCT preparation process from tailings classification in the cyclones to underground distribution.

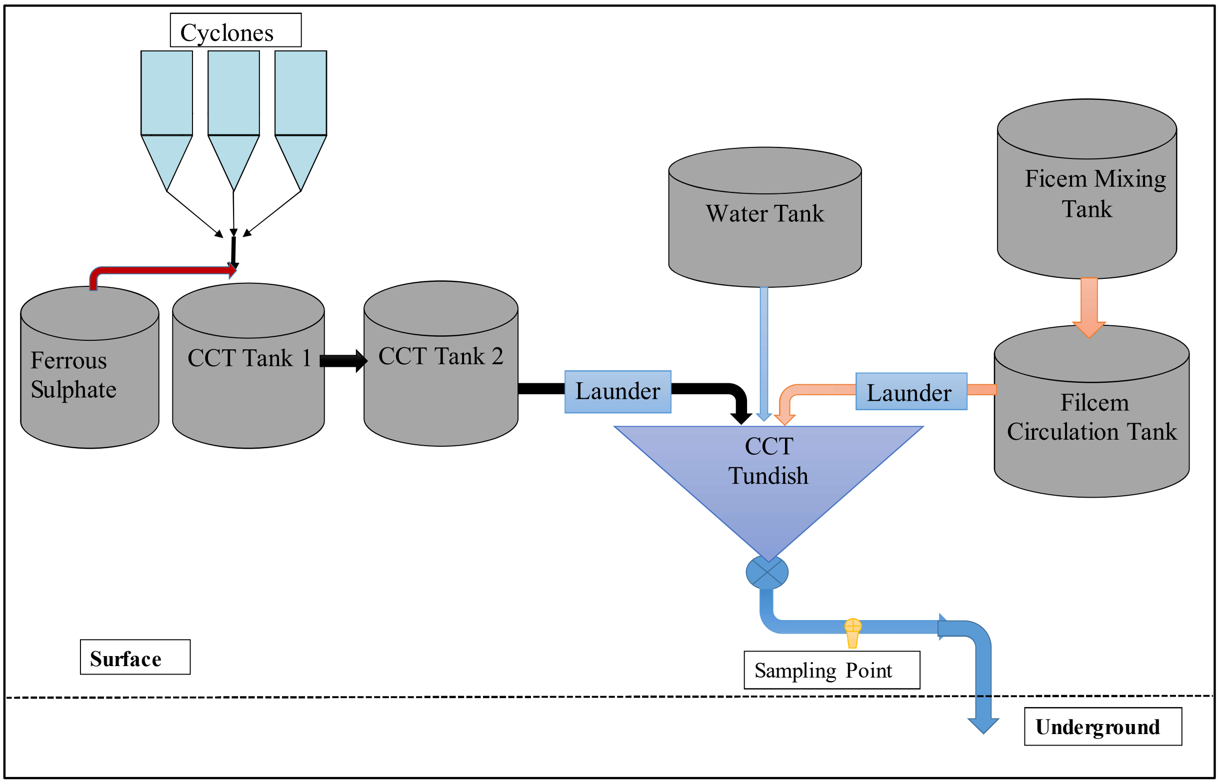

Figure 3-1: Flow diagram of the CCT preparation process

b) FPT Preparation

The preparation process of FPT starts when mill tailings from the backfill storage tank are transferred to the storage tank where they are also continuously agitated. The mill tailings are then transferred to thickeners where they are dewatered and flocculants are added to improve the filterability of fine particles. The thickened tailings are transferred to another tank where they are prepared to the required RD. The final product (FPT) is then transferred to the mixing tanks where it is mixed with the binder.

A binder slurry is prepared according to the required cement to water (C:W) ratio. The binder is then transferred to the FPT binder-circulation tank where it is circulated until the mixing process starts. The binder is added to the mixing tank together with FPT at different flow rates. The mixed FPT product is also simultaneously transferred underground during mixing through a pipeline system. Sampling is conducted after mixing and the required sample is collected from a sampling point on the pipes transferring the backfill product underground. Figure 3-2 shows a flow diagram of the FPT preparation process from the thickener to underground distribution.

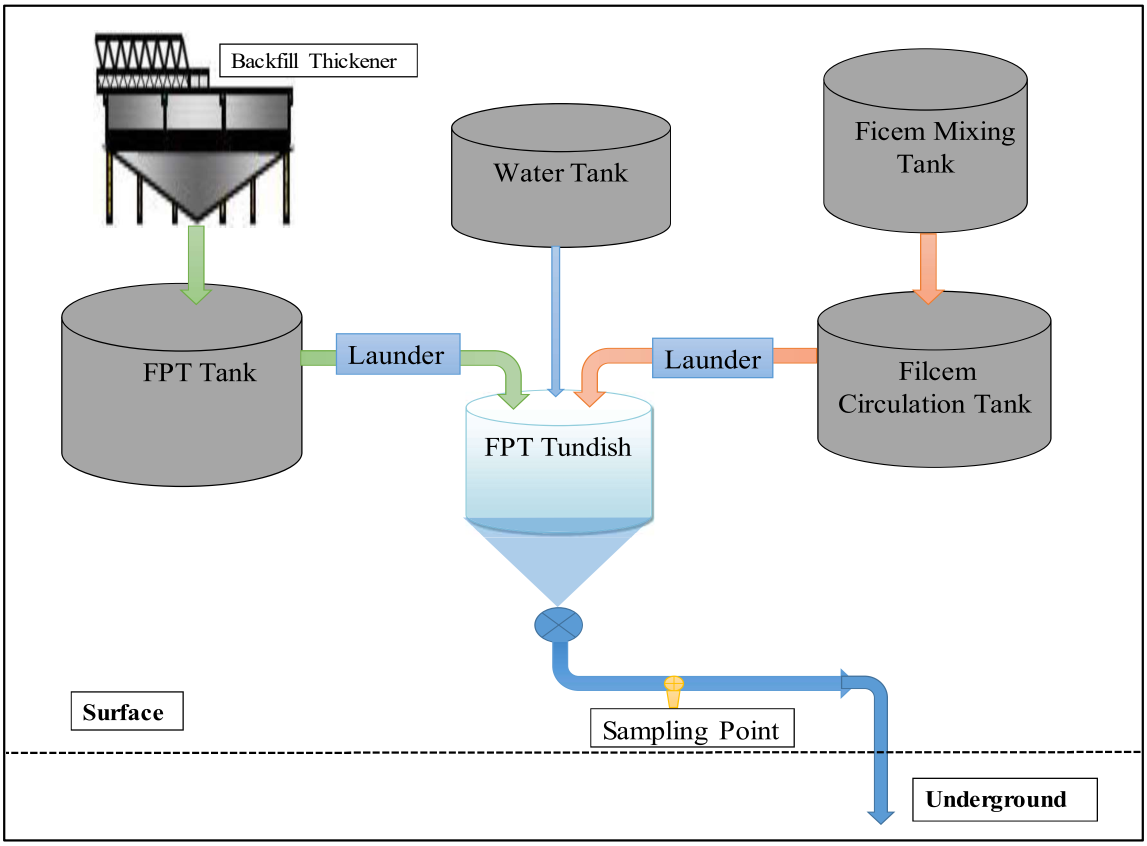

Figure 3-2: Flow diagram of the FPT preparation process

3.4.2.2 Sampling backfill

Sampling is conducted at different points for different purposes. The aim of the samples collected at the backfill plant is to monitor the quality of the backfill product produced by the plant. The samples were collected to measure the material characteristics of the backfill product. Characteristics such as RD, particle size distribution (PSD) and strength are measured from the samples collected. RD and PSD are measured at the backfill storage tank, cyclones, make-up tank, and storage and distribution tanks. The sample is collected, measured and the results are recorded instantly.

Strength tests are conducted after a period of 7, 28 and 56 days after curing. The samples collected to measure the strength are collected at the sampling points on the pipelines transferring to underground stopes. The samples are poured into 20-litre buckets, stirred and cast into cylindrical plastic moulds. The samples are left to drain for a few minutes before being encased into PVC casings and are later stored in the curing room. Figure 3-3 shows the backfill slurry being cast into cylindrical moulds according to different lines. The samples are left to drain and then they are later put inside PVC casings to maintain moisture during curing which is indicated in Figure 3-4.

Figure 3-3: Backfill slurry cast into cylindrical moulds

Figure 3-4: Backfill sample inside the PVC casings

Samples collected to measure relative density are collected at different sampling points. The samples are poured into a 1-litre container and weighed on a hanging scale which gives the relative density of the backfill slurry. Although there are digital devices used to measure the relative density of the backfill slurry in the tanks, the manual method is used at transfer points where the digital devices cannot be installed. The results obtained from the scale is recorded together with other parameters on the excel spreadsheet. Figure 3-5 shows the weighing scale used to measure the RD of tailings (CCT or FPT) and binder at transfer points in the backfill plant.

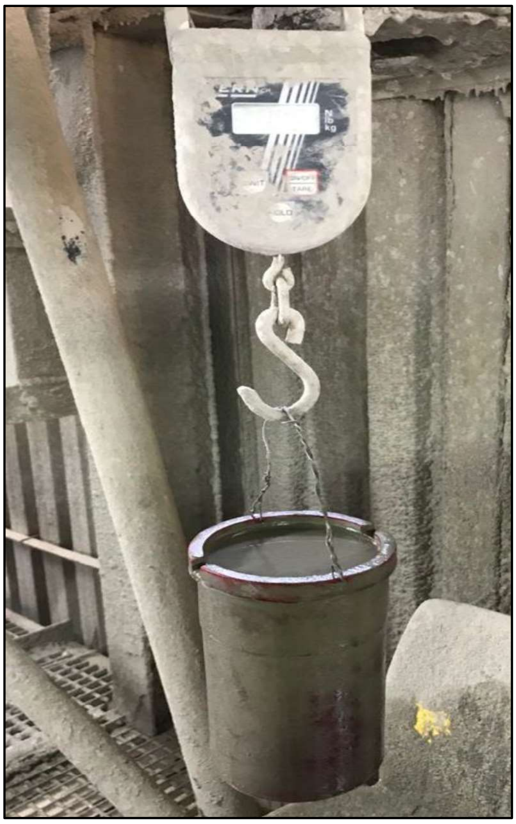

Figure 3-5: RD weighing scale

The particle size distribution is measured using a particle size analysing machine. A sample is collected from the storage tank or transfer point and drained using thick filter paper. The solids are put inside a jug filled with water. The sample is inserted onto the sizing unit and sizing is conducted. The results obtained from the sizer are recorded into a computer and the required percentage of fines is based on the required limit. An example of a particle sizer is presented in Figure 3-6.

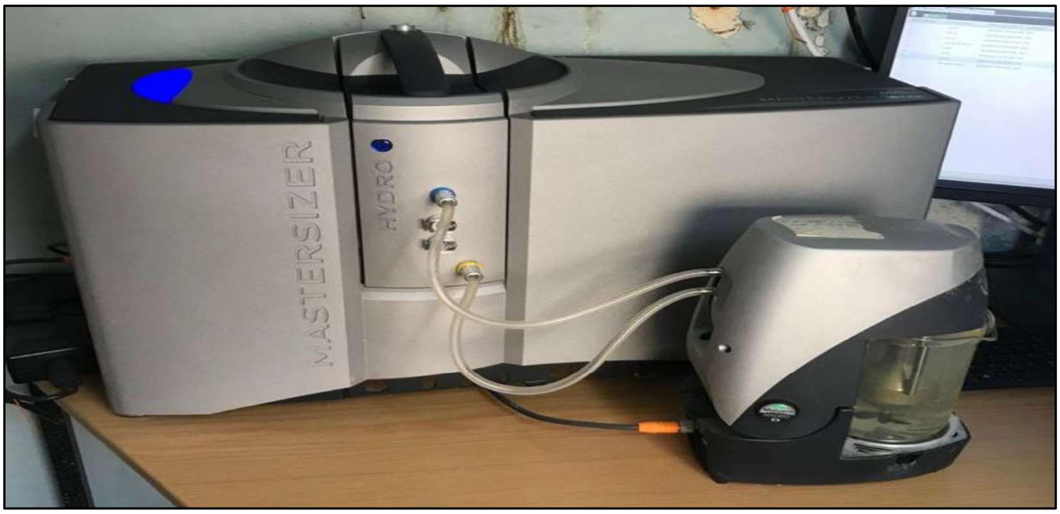

Figure 3-6: PSD sizing machine

3.4.2.3 Curing

The samples are placed on top of shelves with different levels around the curing chamber. The curing room is set at the corresponding temperature and humidity level with underground conditions. The samples are stored for 7, 28 and 56 days and they are only removed from the room on the day of testing. The conditions of the curing room play a major role in the strength development of the backfill sample and affect the strength test results (Kosmatka & Wilson, 2011). The air temperature in the curing room was kept at a range of 30 – 33°C. Samples were placed on the shelves and the floor due to less space. Figure 3-7 shows the curing room and backfill samples stored before they are tested for UCS.

Figure 3-7: Backfill samples stored in the curing room

3.4.2.4 UCS testing

The strength of the backfill material produced is measured using the uniaxial compressive strength (UCS) test which is following the ASTM D4832 standard procedure (ASTM D4832 - 16e1, 2016) and the IRSM suggested methods for determining uniaxial compressive strength (UCS) of rock materials. Specimen preparation is conducted before UCS testing is carried out. The backfill specimen is cut to the required height and diameter, smoothness and perpendicularity. The UCS test procedure involves placing the backfill sample between two platens of the MTS 10/GL press machine. A vertical load is then applied to the backfill sample until the sample fails. The maximum load at failure is recorded for three samples. The average load of the three test results obtained is used as the final strength value of the backfill sample (Ulusay & Hudson, 2007). The specimen dimensional conformity test is conducted during specimen preparation and the required physical qualities are indicated in Table 3-1.

Table 3-1: Specimen qualities required for UCS testing

Dimensional Conformity	
Specimen Shape	Right circular cylinder
Height to Diameter Ratio (H/D)	2.5 - 3
Flatness	0.02 mm
Perpendicularity	0.001 radian (0.05 mm/50mm)
Side Smoothness	0.3 mm

When the specimen meets the above mentioned dimensional requirements, it can be tested for UCS. Figure *3-8* shows the backfill specimen after the preparation process and dimensional conformity tests.

Figure 3-8: Backfill specimen after sample preparation.

The uniaxial compressive strength (UCS) is calculated using the maximum load (P_{max}) applied to the specimen before failure and the original surface area of the specimen. The formula used to calculate UCS is indicated in equation (3-1):

$$UCS = \frac{P_{max}}{\pi(\frac{D}{2})^2} \tag{3-1}$$

where P_{max} is the maximum load on the specimen in Newton (N) and D is the average diameter of the specimen in meters (m). The UCS is expressed in Mega Pascal (MPa) (Ulusay & Hudson, 2007).

3.4.3 Data collection on the studies conducted

The backfill preparation process, sampling, curing and testing procedures were assessed and reviewed as discussed in the previous subsection. The following study areas were identified and investigations were conducted after identifying different factors within the backfill process. The study areas included:

- Current sampling procedure application;
- Curing room temperature study;
- Cement to water ratio of the binder slurry make-up;
- Binder orifice size and flow rate;
- Mix design of tailings with a binder; and
- Correlation between underground and surface samples.

These study areas were investigated through sampling and testing the samples for material quality. The RD of the material was measured instantly at preparation and the distribution point. The UCS was measured through a compression test in the lab after 7, 28 and 56 days of curing. Observations and assessments during sampling, curing and testing was conducted to justify the results obtained from the test.

The backfill mixture comprises of tailings, cement and water. Based on the mine’s strength requirements, certain portions of each component are added to produce the mixture. The mixture aims to produce a backfill material that would yield strength which is above 0.55 MPa in 7 days and 1.2 MPa in 28 days. Based on the design requirements, the binder slurry mix must have cement to water ratio of 2:1. The required volume of tailings was estimated based on the number and size of the cylinder moulds used for sample preparation. The cylinders have a capacity of 3L each and must be filled to 100% to obtain an adequate sample with the required length.

Samples were collected to determine the effect of the different factors on the strength of the backfill material. For each sample collected the following information was recorded before and after storing. Table 3-2 is a template of the information recorded during sampling and testing. Comments are written to provide further information on events that occurred during the task. The information will also help analyse the results obtained after sample testing.

Table 3-2: Information recorded for each sample collected

Sample Properties	Information	Comments
Date of sample		
Shift	M/S or N/S	
Line	L21, L25, L26, L37, L38	
UG Transfer location		
FPT/ CCT RD		
Cement RD		
Binder % backfill Solids		
Operator		
Stress (MPa) in 7 days		
Stress (MPa) in 28 days		
Stress (MPa) in 56 days		

3.4.3.1 Current sampling procedure application

Sampling was conducted using the current procedures and samples were stored in the curing chamber. The current curing procedure was followed and the samples were cured at a temperature of 31°C. This study was conducted to determine any variation between samples collected using the same sampling procedure and with similar material properties. The researcher and the lab operator collected samples, cured them and tested them for UCS after 7 and 28 days. Samples were collected at both CCT and FPT distribution sections. The samples collected by the lab operator were used as control samples and were compared with samples collected by the researcher.

3.4.3.2 Curing room temperature study

Curing is the process of preserving a backfill material for a certain period to determine its characteristics. Curing controls the loss of moisture from the sample after it has been placed in the storing facility by providing time for the hydration of cement in the backfill material to occur. A study was conducted to investigate the effect of placing backfill samples in different locations and elevations in the curing room. This investigation was conducted to determine if the temperature around the curing room is uniform and this was done by measuring temperature around the curing room. Different positions to place backfill samples within the curing room were established to determine the temperature around the curing room at different elevations. The temperature at each level was measured at different positions.

3.4.3.3 Effect of temperature on backfill strength

Based on the results obtained from the curing room temperature study, more investigations were conducted to determine the effect of temperature on the strength of backfill samples. Backfill samples were collected from both CCT and FPT plants and were stored in the curing room at different shelf levels and different positions. The backfill samples were placed on cool, warm and hot temperature areas to determine the impact of temperature on their strength. Based on the heat circulation around the curing room and the position of heaters, the temperature study was necessary to see if the heat flow around the curing room was uniform at different elevations.

3.4.3.4 C:W ratio RD study

The purpose of the cement to water ratio study was to determine the optimum binder content that would yield the required backfill strength. The cement to water ratio measurements was made to determine the mix design of the binder at every relative density. The current cement to water ratio used at the mine is 2:1 but due to flushing water that is still accumulated on the pipes and other related losses, the final binder relative density drops during pipe transportation. This study was conducted to determine the number of solids lost in the transportation process before mixing with the tailings. This also assisted in determining the optimum relative density of the binder which will provide the required backfill strength

3.4.3.5 The effect of binder orifice size on the flow rate and UCS

The orifice diameter of the pipe pumping the binder is one of the factors which was identified to contribute to the variation of backfill strength results. It was identified that the binder orifice had a build-up of cement on its surfaces and it was changed to a different size. The binder orifice size affects the binder flow rate and the strength of backfill produced. A relatively narrow binder orifice allowed less volume of binder to pass through which reduced the flow rate. The orifice size reduces over time due to cement accumulation on the surface of the orifice. This reduces the size of the orifice over time and it must be monitored to present less volume of binder mixing with tailings. This study aimed to determine the optimum binder orifice size which will allow enough binder to mix with the tailings and yield the backfill strength required.

3.4.3.6 Benchmark binder and tailings mix design

A mix design study was conducted in the backfill plant laboratory using the tailings prepared by the plant and the dry binder. The mix design required the binder slurry to be at a cement to water (c:w) ratio of 2:1. This ratio was used when mixing tailings with a binder to produce the design backfill product. This study was done to accomplish a benchmark of the backfill strength requirements that were designed under controlled conditions. The benchmark was used to assess the variations and also determine the change in strength performance of the current backfill material.

The CCT benchmark mix design was conducted using CCT tailings, dry binder and water. The CCT material was poured into a 30 L bucket and was set to a weight of 20 kg. The binder content added to the tailings was at a percentage of 6, 8 and 10% of the total tailings mass. The mass of the dry binder and water used to make the binder slurry was calculated from the wet binder mass percentage. All measured ingredients were then mixed and cast into cylindrical PVC moulds. The samples were left to settle before they were put inside the cylindrical PVC casings which had closing caps to maintain the internal moisture content during curing.

The FPT binder mix design was conducted using the FPT tailings from the FPT preparation plant and the dry binder. FPT material settles quicker, so it should be stirred constantly soon after it is collected from the FPT preparation tank. The FPT material was poured into a 30-litre bucket and weighed to a mass of 24 kg. Due to the material properties of FPT, the mass was increased to account for the rapid water loss that occurs soon after casting. The mass of tailings, binder and water used in the mix-design was calculated, weighed and added to an empty container. All the contents were mixed, stirred and cast into cylindrical PVC moulds. The samples were left to settle and later cast into larger cylindrical PVC casings. The samples were placed on the floor due to a shortage of space on the shelves in the curing room. The samples were stored in the curing room for 7, 28 and 56 days to cure until the date they were tested for UCS.

3.4.3.7 The effect of temperature and elevation on the backfill mix-design

A study on the effect of temperature on the samples prepared according to varying binder content mix designs was conducted. The binder mix-design samples for both CCT and FPT were placed on the same curing position and shelf elevation. This study aimed to determine the effect of temperature and elevation on the UCS of backfill mix-design samples prepared in the laboratory. A curing position that had relatively moderate curing temperature and elevation from the floor was selected to cure the backfill samples. This study assisted in determining the optimum curing temperature which will allow the backfill material to cure and yield the required strength at a lower binder content.

3.4.3.8 U/G versus surface samples

The correlation between underground and surface sampling procedures was studied and samples were collected both on the surface and underground. The study aimed to establish a correlation between samples collected on the surface plant and samples placed underground. This correlation would also assist in determining the actual strength of the backfill placed underground. A backfill slurry was collected underground from the lines pouring in the long-hole stopes using a bucket. The slurry was stirred and cast into cylindrical moulds. The moulds were left open to cure next to the stopes underground. The sample was collected on the 7th day and taken to the surface plant for UCS testing. The correlating backfill sample collected at the surface plant was also tested.

This study was necessary to see the difference in the strength obtained at the backfill plant and the material placed underground. This study assisted in optimising the backfill material prepared on the surface to meet the underground stress requirements. The loss of solids in the backfill material and the decline in mechanical properties affect the strength of the backfill placed in the stopes. These factors should also be considered in the backfill design process so that backfill placed underground can effectively provide the required strength.

3.4.4 Practical solutions to maintain consistency of backfill quality

Inconsistent backfill results obtained on the surface shows that there is variation in the prepared backfill quality. This affects the stability of filled stopes underground and contributes to the overall mine stability. After studying factors that cause variability of backfill strength results, it was evident that the quality of the backfill material was inconsistent. The material properties of the tailings and binder, the mixing and curing processes were also inconsistent. A strategy to ensure that backfill operations prepare consistent backfill quality which effectively supports underground workings was developed. This strategy accounted for the operational and design constraints of the backfill plant.

Maintaining a consistent backfill quality can assist in achieving consistent backfill strength, obtaining maximum strength values at a low binder usage. Practical solutions to the currently identified factors were also developed as part of this strategy.

3.5 Data Analyses

Data analysis describe the procedures for processing and analysing the data. This section describes the specific instruments of analysis used to study each research objective, including mathematical techniques and the type of computer software used to manipulate the data (USC Libraries, 2020). The descriptive analysis method provides information on the basic qualities of data and includes descriptive statistics such as minimum, maximum, range and frequency. It also includes measures of central tendency such as mean, median, mode, and standard deviation (The University of Minnesota, 2020). In this research, a descriptive analyses methodology was used to analyse the existing data to determine the performance of backfill at the mine and the effect of different parameters on the strength of the backfill material. In doing so, this method helped identify some of the factors which caused the variation of the backfill material.

Conducting observations and assessment during the data collection process helped identify most underlying factors causing variability and they were studied in-depth. The effect of these factors on the strength of the backfill material was also investigated and the results obtained were analysed using a Gap analysis method. Gap analysis uses a side-by-side matrix which represents quantitative data that helps measure the difference between expected performance and actual performance of samples. This data analysis helps measure gaps in performance and measures required to be implemented to close the gap. This analyses method helped in determining the impact of each factor/ variable on the strength of backfill and helped determine practical measures which can be adopted to improve the strength of backfill by manipulating these factors.

The results obtained from different studies were combined and analysed to identify the factors causing variability in strength test results. Analyses of the results also accounted for activities that occurred during sampling. The data was represented in the form of graphs and charts to quantify the effect of identified factors on the strength of the backfill material. The extent of variation in strength test results was also be measured and compared to previous test results.

3.5.1 Gap analyses method

The gap analyses method is used to analyse data that will determine the performance of the operation and determine the gap between the set target and the actual performance. It is used by operations to determine their current performance by measuring the production outputs and the costs accrued. Using the gap-analyses method allows managers to create action plans to optimise the operation and fill in the gaps identified. This method is used when the company is unable to utilise its current resources to their full potential. This method uses four steps to analyse performance which involves defining the main goal, benchmarking the current state, analysing the gap and compiling the gap report.

The four steps of gap analyses are explained in the following bullet points:

- Step 1: Accurately outline and define the research goals or objectives. The objectives have to be realistic, measurable, attainable and specific.
- Step 2: Use historical data to measure current performance as it relates to the outlined objectives.
- Step 3: Analysed the data collected, compare the current performance with the targets and determine the gap.
- Step 4: Compile a report based on the quantitative data collected and quantitative reasons why there is a gap. Develop an action plan on how to close the gap or increase the current targets if the performance is higher than the set targets.

The gap analyses were used to determine the effects of factors identified on the backfill strength. The factors identified were manipulated and the backfill strength was determined to measure the impact of each factor. This gave the researcher an understanding of the impact of the factors and strategies which can be used to optimise these factors to obtain maximum backfill strength. Factors such as the mixing of the binder with tailings were further manipulated and gap analyses assisted in determining the constraints of the operation and developing innovative strategies to optimise the mixing process which will help reduce binder usage and obtain maximum backfill strength.

3.6 Validity and Reliability of the Data

Reliability and validity are concepts used to evaluate the quality of the research. They are tools used to critique quantitative research by indicating how well the research method, technique or test measures the object being studied. The quality of the research is measured using validity and reliability measurements. Reliability is about the consistency of a measure, and validity is about the accuracy of a measure (Mohajan, 2017). These research quality measuring tools are important when designing the research, planning methodology and reporting the results, especially in quantitative research.

Measurement allows us to quantify, or represent numerically, concepts such as UCS performance, backfill material characteristics and operations productivity. The effectiveness and efficiency of backfill to support underground mine voids must be measured or quantified. This will assist the mine to determine the stability of underground stopes and help in mine planning processes on the design of mining sequence over the short and long term. The development of standardized measurement instruments is important such that they ideally provide uniform and normative data. Standardized data gives assurance that the data was collected using a set of uniform procedures (Hoefer & Jordan, 2001).

3.6.1 The validity of the research

Thatcher (2010) defines validity as the extent to which any measuring instrument measures what it is intended to measure. He further describes validity as concerned with the relationship between what is being measured, nature and uses to which the measurement is being applied. A measuring instrument is evaluated concerning its purpose for use. There are three different types of validity in research, namely construct, content and criterion validity. If a measurement is unreliable then it cannot be valid, however, if a method is reliable it can also be invalid. Validity concepts are dependent on the researcher's methods of measurement and the confidence they have in the mathematical simulations when applied in the laboratory or clinical context. Today, there is a wide number of fully tested mathematical and digital signal processing methods used that can be rapidly evaluated using calibrated signals and a high-speed computer to determine the mathematical validity of any method (Thatcher, 2010).

Construct validity instrument measures whether you can draw inferences about test scores related to the concept being studied. Content validity looks at whether the instrument adequately covers all the content that it should for the variable. It looks into whether the instrument covers the entire domain related to the variable or the construct it was initially designed to measure. A criterion validity instrument is any other instrument that measures the same variable. Correlations can be conducted to determine the extent to which the different instruments measure the same variable (Heale & Twycross, 2015).

In this research, the research instrument used managed to cover all the content it should for each study conducted. The factors identified and studied during the data collection process were relevant to the scope of the study. The variables were investigated thoroughly through observations, sampling and testing to determine if they cause variation of the backfill strength. During the study, the researcher noted every activity and was on the lookout for anything unordinary occurring during the studies. These justify that the research instrument managed to cover all the content required for this research and is content valid.

The literature review conducted and previous reports gathered gave the researcher a guideline on the backfill material characteristics and the coherent factors which affect the strength of backfill. The research instrument used ensured that each variable was studied thoroughly and the results obtained provided the effects of the variable on the backfill strength without the contribution of other factors. To justify the construct validity of the instrument, more samples were collected and more tests were done on each variable that was studied. Conclusions on the effect of each parameter on the strength of backfill were also supported by the literature conducted before the study. Homogeneity and theory evidence indicated in the study shows that the research instrument is valid.

The correlation between different instruments used to conduct this research was determined during the study. The procedures used for different studies showed the relationship between different variables which were studied using different methods. The relationship between variables such as binder orifice, flow rate and UCS was determined using this research instrument and this also assisted in optimising the process to achieve maximum UCS values which is the main goal. The research instrument used correlated with other instruments measuring the same variables. The results obtained from the test correlated with what other researchers found using different methods. These then justify that the research instrument was criterion valid with convergent and predictive characteristics.

3.6.2 Reliability of the research instrument

Reliability refers to how consistently a method measures something. If the same research instrument can achieve the same result consistently under the same circumstances, the measurement is considered reliable (Mohajan, 2017). The basic description of reliability is that it measures consistency, there are three dimensions of reliability: stability, equivalence, and homogeneity. These dimensions are tested using different approaches to determine if an instrument is reliable: test-retest, internal consistency, interrater and parallel forms.

Test-retest reliability measures the consistency of results when you repeat the same test on the same sample at a different point in time. This method is used when measuring or testing a sample and you expect the results to stay constant. When doing tests or conducting a study, many factors can influence the results at different points in time. For example, the quality of a backfill material may be influenced by the binder content mixed with tailings and the curing room environment conditions. Test-retest reliability can also assess the resistance of the research instrument to other external factors. Test-retest is measured by calculating a correlation after conducting the same test on the same population group at two different times. A higher correlation value between the two sets of results shows higher test-retest reliability (Mohajan, 2017).

Internal consistency assesses the correlation between multiple items in a test that are intended to measure the same construct. Internal consistency is measured without repeating the test or involving other researchers and it is suitable to measure reliability for researches that only have one data set. When there is only one data set, the data can be divided into two halves and the overall score or results must reflect the same thing. Alternatively, when a set of measurements are designed to assess the same construct, the correlation between the results of all possible pairs must be calculated together with the average (Mohajan, 2017).

The inter-rater reliability method measures the degree of agreement between different people observing or assessing the same thing. It is used when the data is collected by researchers rating or judging or categorizing one or more variables. Parallel forms reliability measures the correlation between two equivalent versions of a test. It is used when two different assessment tools or sets of tests are designed to measure the same thing. This type of reliability is of good fit when the researcher wants to use multiple versions of a test to measure the same thing. It is important to ensure that all questions or test items to be conducted are based on the same theory and formulated to measure the same thing. A higher correlation of the results from the different tests determines a higher degree of reliability.

Test-retest, parallel and internal consistency reliability methods were found to be suitable for this study. This is based on the fact that different factors are studied to determine their effect on backfill strength. The main variable that is being studied in this research is the strength of backfill and different sets of studies and tests were conducted to determine their impact on the backfill strength. The correlation between different factors and their impact on strength was well established. This justifies that the research instrument is reliable.

3.7 Chapter Summary

This chapter outlined how this research was conducted, illustrated steps followed when the data was collected, described methods used to collect the data and the approach used to analyse the quantitative data. The current backfill practices were studied and evaluated. A review of the current performance was conducted and possible factors causing variability were identified. This helped the researcher to develop a strategy to investigate other factors causing variability of backfill strength. Constraints and factors causing strength variability were identified using assessments on preparation, sampling and curing processes. Different factors identified during each process were studied and their impact on the strength of backfill material was determined. All studies conducted and the research tool used to collect the data were explained. This research aimed to determine and understand the factors causing backfill strength results in variations. Studying different factors within the backfill production process, sampling, curing and testing through observation, sampling and testing allowed the researcher to achieve the research objectives.

4 REVIEW AND ANALYSES OF PREVIOUS TEST RESULTS

4.1 Introduction

This chapter discusses the results of samples collected from the CCT distribution plant in 2017 and 2018. The results were analysed based on the strength and relative density of the samples collected after the tailings were mixed with the binder. In 2017 backfill samples were tested for UCS after 7, 14 and 28 days of curing while in 2018 they were only tested after 7 and 28 days. The variance of backfill sample results was also analysed at each period of testing. The performance of the backfill is determined by the strength results obtained after sampling the backfill product on the surface (Backfill plant). The backfill samples are tested for UCS and the results obtained will determine if the backfill material has passed or failed the strength test. Backfill samples that obtain the strength value above the minimum required strength for 7, 14 and 28 days have passed the test.

Statistical analyses of the backfill strength results were used as a tool to determine the quality of the results obtained. The accuracy and precision of the results obtained from the backfill samples were analysed to determine the overall performance of the backfill. In metallurgical accounting, the minimum acceptable precision is 5% and the variance is set to a maximum of 0.005. These statistical parameters are important in determining the quality of samples collected and analysing the strength results obtained. The variance of the previous backfill sample results for both CCT and FPT was in the range of 0.093 to 0.137 which was above the maximum acceptable variance. The higher the sample variance, the lower the precision. Good sampling and good analytical procedure are the keys to achieving high accuracy and good precision. The previous strength results were analysed using statistical methods to determine the performance of backfill placed previously at the mine.

4.2 Analyses of CCT performance (2017)

The rock engineering department determined the strength requirement of the backfill product that was used to fill the long-hole stopes. The required strength for 7 days was 0.3 MPa, 14 days was 0.4 MPa and 28 days was 0.85 MPa. Some samples failed and others went beyond the required strength. CCT quality data is represented in **Appendix A**. The metallurgy department determined the relative density (RD) and the particle size distribution (PSD) of CCT that would give the required strength. The relative density (RD) required to meet the required strength was 1.7 t/m^3 CCT at a PSD of less than 10% of 10 µm particles.

The binder used is Filcem and it is mixed with water to make a binder slurry before mixing with CCT. The RD of the binder slurry was determined based on the strength requirements and the minimum value required was 1.65 t/m^3. Table 4-1 shows the overall summary of CCT strength results for 7, 14 and 28 days obtained in 2017.

Table 4-1: Overall summary of the 2017 CCT strength and relative density data

	Strength			**RD**	
	7 Days	**14 Days**	**28 Days**	**CCT**	**Binder**
Samples Tested	649	184	617	652	652
Limits	0.3 – 0.8	0.4 - 0.8	0.85 – 1.5	1.7-1.75	1.6 -1.65
Sample <Lower Limit	108	23	155	16	23
Sample within Range	267	42	119	302	375
Samples > Upper Limit	274	119	360	334	254
Passed Samples	541	161	479	636	629
% Pass	**83.36**	**87.5**	**77.63**	**97.40**	**96.32**

The percentage pass for the samples collected in 2017 is very good since most samples passed the strength test. The RD of the CCT and Filcem also met the minimum requirement. A total of 649 samples were tested for 7 days strength and 83.36% of them passed. Over 274 of the total samples tested obtained strength values of more than 0.8 MPa at 7 days. The total number of samples tested for 14 days period was 184 of which 87.5% achieved the strength above the required strength limit. 617 samples were tested for strength at 28 days and 77.63% of them obtained strengths above the required strength limit. The CCT and Filcem relative densities prepared met the minimum required strength most of the time. The performance of the relative density (RD) preparations was above 95%. The following table gives the descriptive statistics of the 7, 14 and 28 days strength test results of CCT samples.

4.2.1 Statistical analyses of CCT strength results

The descriptive statistics of CCT sample strength results obtained in 2017 is shown in Table 4-2. The statistics for 7 days shows that the mean strength was 1.3 MPa, the maximum strength was 8.78 MPa and the standard deviation was 1.51 MPa. The standard deviation value is high and this shows that the data is more spread out. More than half of the samples tested have relatively higher strengths than the mean strength which was also proved by the skewness of 2.04 MPa which shows that the data is skewed to the right. The 14 days statistics also show that most samples had relatively high strength values and the standard deviation and the variance was relatively higher than in 7 days.

Table 4-2: Descriptive statistics of the CCT 7, 14 and 28 Days Strength Data for 2017

Statistics	**7 Days**	**14 Days**	**28 Days**
Mean	**1.30**	**2.48**	**2.34**
Standard Error	0.059	0.18	0.087
Median	0.67	1.41	1.45
Mode	0.42	0.41	5.77
Standard Deviation	1.51	2.48	2.18
Sample Variance	2.29	6.17	4.77
Kurtosis	4.13	0.39	1.92
Skewness	**2.04**	**1.17**	**1.5**
Range	8.78	10.01	11.29
Minimum	0	0.08	0
Maximum	8.78	10.09	11.29

The average strengths for all periods are above 0.85 MPa which is the minimum required strength for 28 days. The standard deviation at 7 days was 1.51 MPa and increased to 2.18 MPa in 28 days. The strength values obtained for 14 days had the highest standard deviation of 2.48 MPa. The mean strength obtained for 7 days was four times the minimum required value and for 28 days it was 6 times the minimum required value. The variance of this data was very high with an average precision of 103% for all curing periods. Figure 4-1 shows the proportion of sample strengths for a curing period of 7 days.

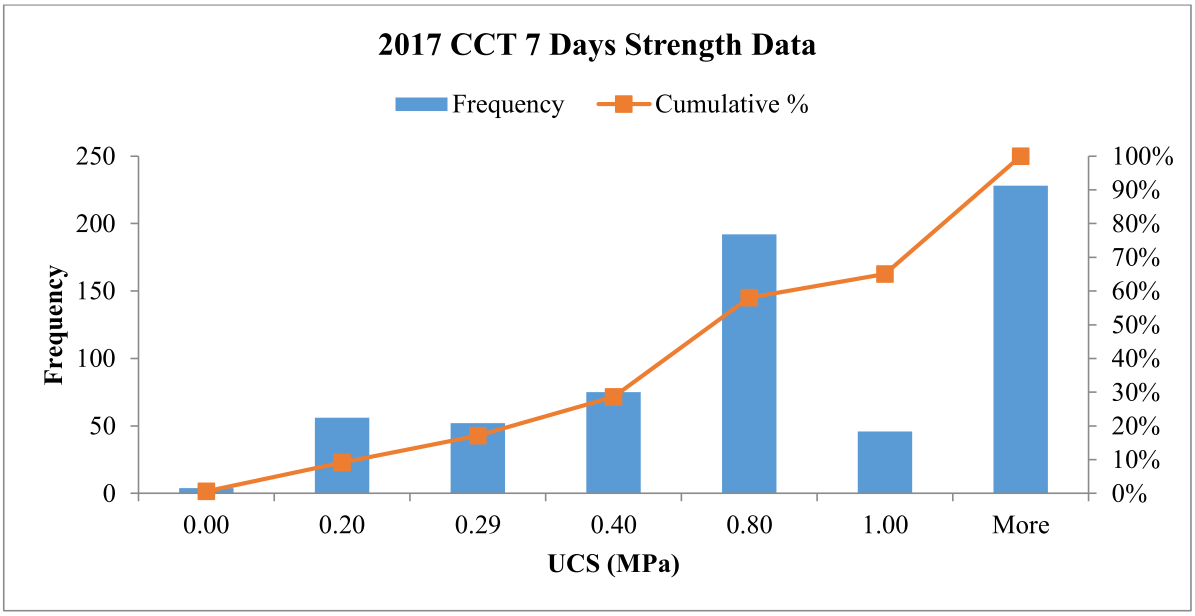

Figure 4-1: The 2017 CCT 7 days' strength histogram

The histogram has an exponential distribution curve with a very gentle slope with more samples having strengths greater than 0.8 MPa.

Figure 4-2 represents the histogram data for a curing period of 14 days. The 14 days of strength data have an exponential distribution pattern. The curve has a very gentle slope which gradually increases at the end. The number of samples is less at lower strength values and most samples had values greater than 1.0 MPa.

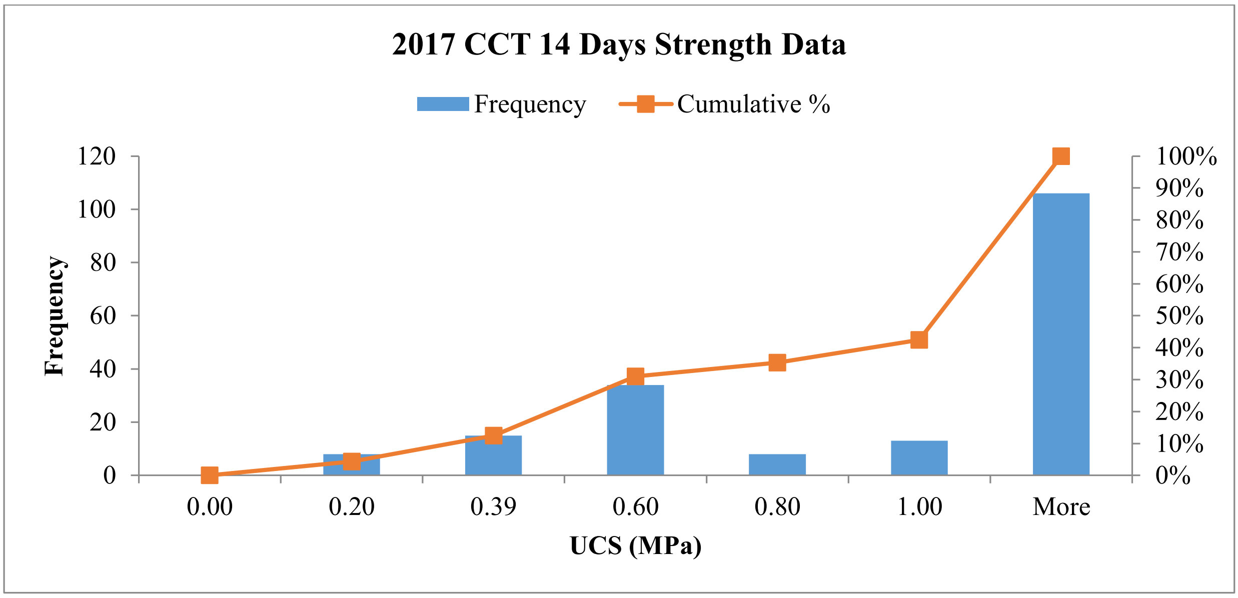

Figure 4-2: Histogram graph of the 2017 CCT 14 day's strength results

There is less variance of data at 28 days curing period, as can be seen in Figure 4-3. The number of samples at all ranges are well distributed although most samples have UCS values greater than 2 MPa. The data has a distribution of a linear pattern.

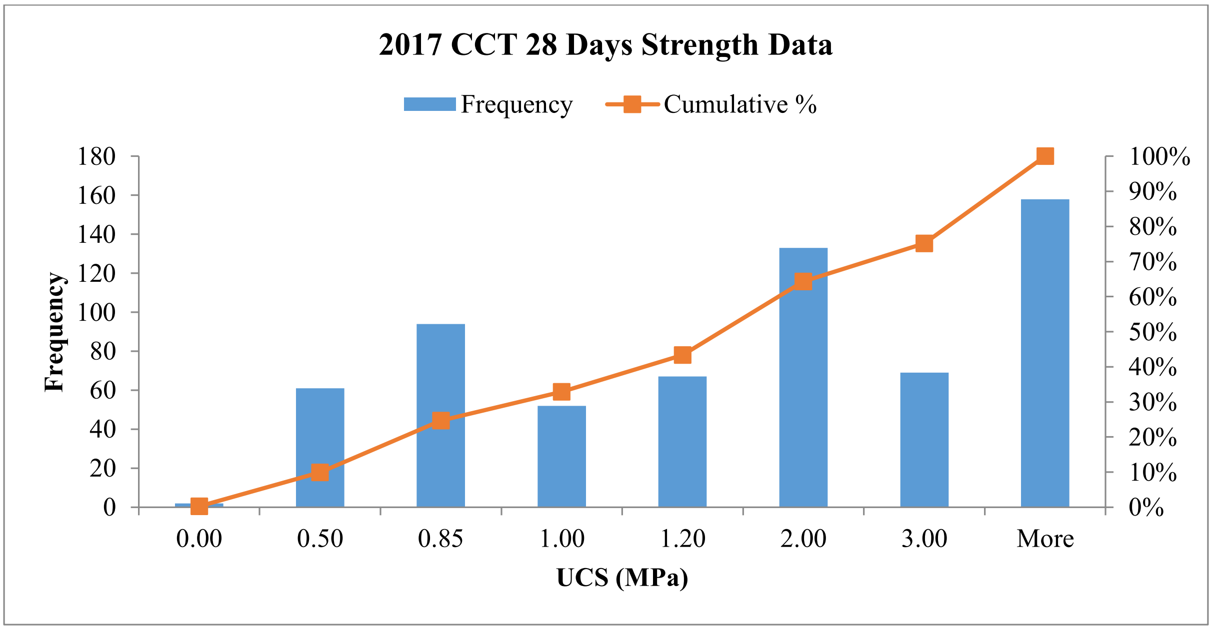

Figure 4-3: Histogram graph of the 2017 CCT 28 day's strength results

4.2.2 Analyses of CCT results according to shifts

The difference between night shift and morning shift test results was investigated from the previous sample test results. The following data were collected to investigate the difference between the two shifts and the amount of variability of results from each shift.

4.2.2.1 Morning shift

The following table gives a summary of the strength and relative density data collected at the CCT distribution section during morning shifts. The raw data collected is represented in a graph included in **Appendix B**. The performance of the samples collected is indicated in Table 4-3.

Table 4-3: The overall summary of Morning Shift strength and relative density data for 2017

	Strength			**RD**	
	7 Days	**14 Days**	**28 Days**	**CCT**	**FILCEM**
Total No. of Sample	304	304	304	305	305
Defects	2	196	16	0	0
Qualified Samples	302	108	288	305	305
Limits	0.3 - 0.8	0.4 - 0.8	0.85 - 1.5	1.7-1.75	1.6 -1.65
Sample <Lower Limit	72	26	93	9	23
Sample within Range	58	38	53	91	172
Samples > Upper Limit	172	44	142	205	110
Passed Samples	230	82	195	296	282
% Pass	**76.16**	**75.93**	**67.71**	**97.05**	**92.46**

A total of 302 qualified samples were tested and out of the total, 230 samples passed the strength test. Out of the 230 samples which passed, 172 of them passed beyond the required strength making 74.8% of the total number of samples which passed. At 14 days test, 82 out of 108 samples passed the strength test and out of the total that passed, 44 of them passed beyond the required strength. At 28 days, 288 samples were tested and 195 of them passed, 93 failed. Out of the total that passed, 72.8 % of them passed beyond the required limit.

The descriptive statistics in Table 4-4 shows that the average strength of samples tested for all the periods is above the 28 days strength limit. The standard deviation of the strengths is in a range of 1 to 1.6 MPa which shows that the strength values are more spread out. The sample variance was in a range of 1 to 2.63 MPa for 7, 14 and 28 days curing period. This proves that there is a huge variation between the strength values.

Table 4-4: Descriptive Statistics for 2017 CCT Morning Shift data for 7, 14 & 28 Days strength

Statistics	7 Days	14 Days	28 Days
Mean	0.97	1.28	1.61
Standard Error	0.064	0.13	0.093
Median	0.67	0.72	1.14
Mode	0.8	0.31	0
Standard Deviation	1.04	1.38	1.62
Sample Variance	1.07	1.91	2.63
Kurtosis	14.0	4.51	6.53
Skewness	3.13	2.08	2.23
Range	8.638	7.15	11.28
Minimum	0	0.09	0
Maximum	8.64	7.24	11.28
Sum	256.02	137.83	492.32

4.2.2.2 Night shift

The following table gives a summary of the strength and relative density data collected at the CCT distribution section during night shifts. The raw data collected is represented in a graph included in **Appendix C**. The performance of the samples collected is indicated in Table 4-5.

Table 4-5: The overall summary of night shift strength and relative density data for 2017

	Strength			RD	
	7 Days	14 Days	28 Days	CCT	FILCEM
Total No. of Sample	348	76	349	305	305
Defects	1	0	0	0	0
Qualified Samples	347	76	349	305	305
Limits	0.3 - 0.8	0.4 - 0.8	0.85 - 1.6	1.7-1.75	1.6 -1.65
Sample <Lower Limit	36	3	64.00	9	23
Sample within Range	138	4	107	91	172
Samples > Upper Limit	174	69	178	205	110
Passed Samples	312	73	285	296	282
% RD Pass	**89.91**	**96.05**	**81.66**	**97.05**	**92.46**

Most of the samples taken during the night shift passed with an overall pass rate of over 80%. The RD recorded for both CCT and FPT were within the required RD limits. The CCT RD samples collected had about 69% of the total samples being above the required RD and Filcem RD had about 39% of the samples above the limits.

The descriptive statistics in Table -4-6 shows that the average strength for samples tested for 7 days was five times the minimum strength limit while the standard deviation of the mean was 1.77 MPa. The mean strength for 28 days was 3 times the minimum limit and had a standard deviation of 2.44 MPa. The night shift strength values are relatively spread apart more compared to morning shift strength values. The sample variance ranges from 3.12 MPa to 7.24 MPa which is also very high. There are relatively huge variances and deviations of sample results for the night shift.

Table -4-6: Descriptive Statistics for 2017 CCT Night Shift data for 7, 14 & 28 Days strength

Statistics	**7 Days**	**14 Days**	**28 Days**
Mean	1.68	4.2	2.85
Standard Error	0.095	0.31	0.13
Median	0.805	4.28	1.65
Mode	5.77	5.77	5.77
Standard Deviation	1.77	2.69	2.44
Sample Variance	3.12	7.25	5.96
Kurtosis	1.48	-0.90	0.49
Skewness	1.46	0.29	1.073
Range	8.66	10.01	11.18
Minimum	0.12	0.08	0.11
Maximum	8.78	10.09	11.29
Sum	585.38	319.26	995.14
Count	348	76	349

4.3 Analyses of FPT Performance (2017)

The 2017 FPT sample results were compiled, analysed and represented in the form of a bar graph included in **Appendix D**. The graph shows the strength results for 7, 14 and 28 days of the curing period. The relative density of FPT and the binder is also represented on the graph. The results are inconsistent and the effect of the relative density of both the binder and FPT is not evident. Analyses of the performance of FPT in terms of strength and relative density are discussed in this section.

The FPT sample data collected were summarized in Table 4-7 and the overall performance of FPT was determined. The strength results obtained after a curing period of 7, 14 and 28 days was summarised. The performance at all periods was relatively low. The total number of samples collected were 299 and were tested for 7, 14 and 28 days.

Table 4-7: The overall summary of the 2017 FPT strength and relative density data

	Strength			**RD**	
	7 Days	**14 Days**	**28 Days**	**FPT**	**FILCEM**
Total No. of Sample	299	81	299	299	299
Defects	17	7	21	3	2
Qualified Samples	282	74	278	296	297
Limits	0.3 - 0.8	0.4 - 0.8	0.85 - 1.5	1.7-1.75	1.6 -1.65
Sample <Lower Limit	119	24	150	41	10
Sample within Range	87	15	49	141	90
Samples > Upper Limit	75	35	79	114	197
Passed Samples	162	50	128	255	287
% RD Pass	**57.45**	**67.57**	**46.04**	**85.28**	**95.99**

The total number of samples tested for 7 days strength was 299 of which 57.45% of them obtained UCS of higher than 0.33 MPa. A total of 81 samples were tested for 14-days strength and 67.57% of the samples passed. The strength results of samples tested for 28 day curing period was 46% which indicates that more than half of the FPT samples failed the strength test. Ideally, if samples pass in 7 days, they should pass in any other future periods given that the curing conditions are kept constant and the sample is homogeneous. The pass rate for the three periods must be within the same range. The RD of both FPT and Filcem were obtained at the required values most of the time. The operators prepared FPT and Filcem to the required RD values and the performance of the RD samples collected was above 85%.

4.3.1 Statistical analyses of FPT strength results

Table 4-8 is a summary of the descriptive statistics of the FPT sample tests for the 7, 14 and 28 days curing period. From the data calculated in the descriptive statistics, it can be seen that the FPT sample data is positively skewed. Most of the samples have low to moderate strength values and fewer samples have high strength values.

Table 4-8: Descriptive statistics of the FPT for 7, 14 and 28 Days strength data for 2017

Statistics	**7 Days**	**14 Days**	**28 Days**
Mean	0.75	1.27	1.41
Standard Error	0.06	0.19	0.097
Median	0.33	0.71	0.69
Mode	0	0	0
Standard Deviation	1.03	1.7	1.69
Sample Variance	1.062	2.88	2.84
Kurtosis	6.57	5.54	3.84
Skewness	2.49	2.29	1.96
Range	5.77	8.48	10.39
Minimum	0	0	0
Maximum	5.77	8.48	10.39
Sum	223.76	102.94	422.22
Count	299	81	299

The mean strength of samples in all curing period are above the required strength (limit) and the standard deviations are relatively higher than the average strengths. The FPT samples are more spread out with a significant amount of variance at a range of 1 to 169 MPa.

Figure 4-4 represents the distribution of the FPT sample data for a 7-days curing period. The data is evenly spread out in different strength values and more than 50% of the data met the minimum required strength. The graph has a positively skewed distribution.

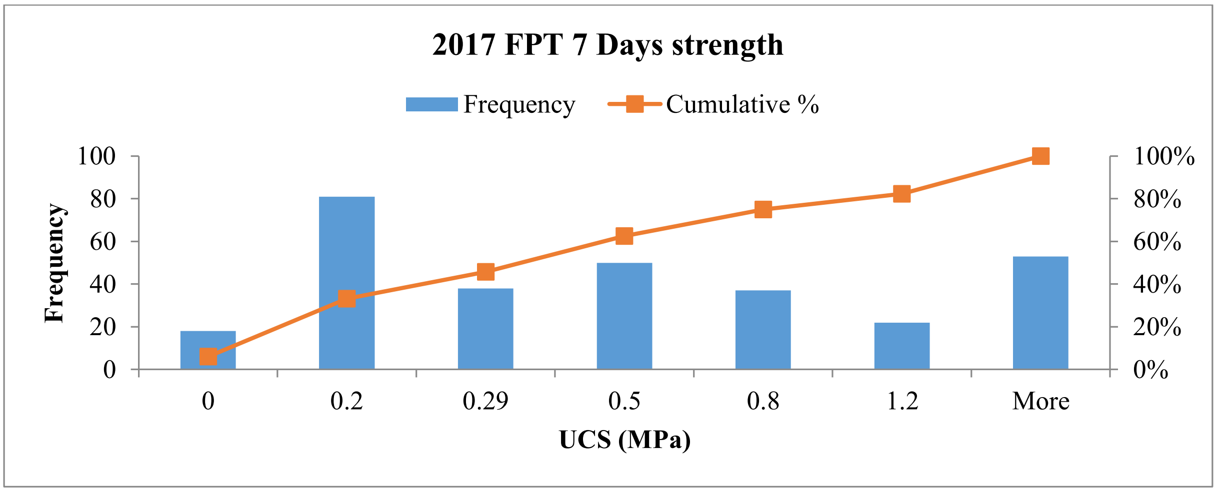

Figure 4-4: Histogram showing FPT 7 Days strength data for 2017

As discussed in the summary, the 14 days results performed better than all other periods. Most FPT samples passed and the graph shows a positively skewed distribution. More than half of the data is above the required limits. Figure 4-5 shows the histogram of the FPT 14 days period strength test results.

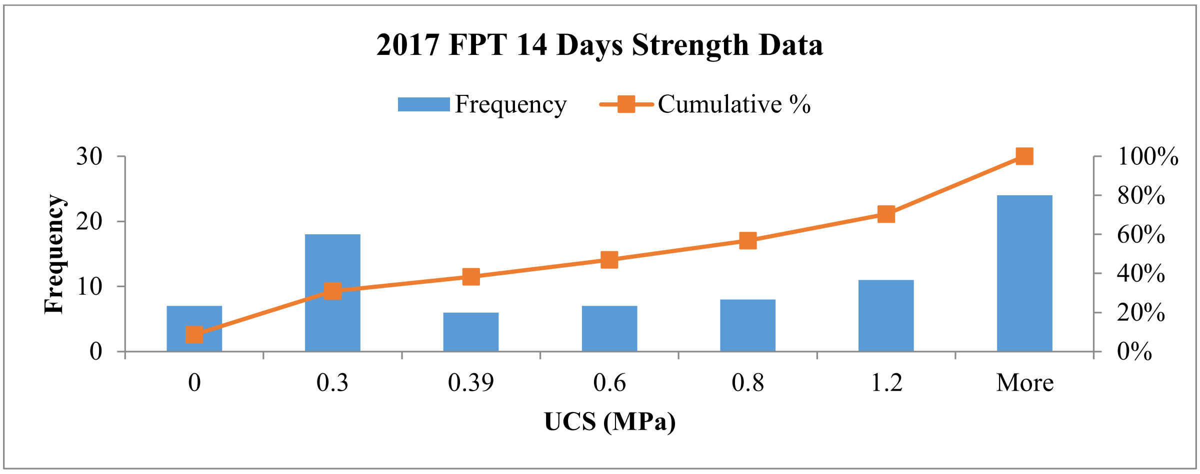

Figure 4-5: Histogram showing FPT 14-days strength data for 2017

Figure 4-6 shows a clear positively skewed distribution of sample data for the 28-days curing period. Although there is a moderate proportion of samples with strength values higher than the required strength, most FPT samples have lower strength values at 28 days.

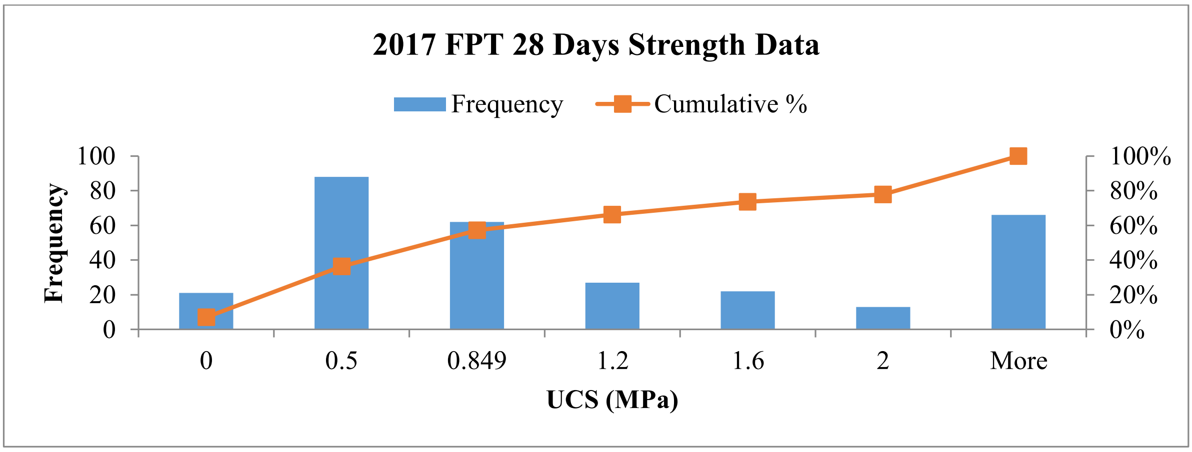

Figure 4-6: Histogram showing FPT 28-days strength data for 2017

4.3.2 Analyses of FPT results according to shifts

The 2017 FPT sample results were also analysed according to shifts. The data was represented in the form of graphs included in **Appendix E** and **Appendix F.** The results were studied and the difference between the two shifts was identified.

4.3.2.1 Morning shift

Morning shift data is represented in **Appendix E** and from the graph, it is evident that the level of variability between sample results is high. Some samples have extremely high values and some have extremely low values. The performance of samples collected during the morning shift are presented in Table 4-9.

Table 4-9: The summary of the performance of FPT at 7, 14 and 28 days for the morning shift

	Strength			**RD**	
	7 Days	**14 Days**	**28 Days**	**CCT**	**FILCEM**
Total No. of Sample	148	47	148	148	148
Defects	8	4	12	0	0
Qualified Samples	140	43	136	148	148
Limits	0.3 - 0.8	0.4 - 0.8	0.85 - 1.5	1.7-1.75	1.6 -1.65
Sample <Lower Limit	66	15	80	15	8
Sample within Range	50	10	30	68	51
Samples > Upper Limit	21	18	25	65	89
Passed Samples	71	28	55	133	140
% RD Pass	**50.71**	**65.12**	**40.44**	**89.86**	**94.59**

A total of 140 samples were tested for 7 days strength and 50.7% of them passed the test. The samples tested for 14 days strengths were 47 and 65.1% of them passed. The 28 days strength test results were relatively lower than 7 and 14 days strengths with a pass mark of 40.4%. The RD of both FPT and Filcem were obtained and most of the values were above the required RD limit.

Table 4-10 represents the descriptive statistics of the morning shift strength results of 7 and 28 days shows a positively skewed distribution. The mean strengths for all testing periods are slightly above the required minimum strengths.

Table 4-10: Descriptive statistics of morning shift sample test results

Statistics	**7 Days**	**14 Days**	**28 Days**
Mean	0.49	0.99	1.072
Standard Error	0.043	0.16	0.095
Median	0.32	0.63	0.69
Mode	0.15	0.81	0.54
Standard Deviation	0.50	1.06	1.11
Sample Variance	0.25	1.12	1.24
Kurtosis	4.14	5.23	9.48
Skewness	2.02	2.10	2.71
Range	2.6	5.14	7.02
Minimum	0	0.07	0
Maximum	2.6	5.21	7.02
Sum	68.95	42.68	145.76
Count	140	43	136

The standard deviation of the samples at all periods are slightly above the mean strengths. The FPT sample data for the morning shift is not too spread out as compared with CCT morning shift samples. The variance of the FPT sample strength data is relatively less than CCT strength data although most FPT samples failed.

4.3.2.2 Night shift

The sample data for the night shift is represented in **Appendix F** and from the graph and the level of variability between sample results is still high. Table 4-11 shows that most of the FPT samples collected during the night shift passed and some achieved extremely high strength values. Although the overall results showed a lower performance, night shift results were studied.

Table 4-11: The summary of night shift sample results for 7, 14 and 28 days

	Strength			**RD**	
	7 Days	**14 Days**	**28 Days**	**CCT**	**FILCEM**
Total No. of Sample	151	34	151	150	150
Defects	7	2	7	2	1
Qualified Samples	144	32	144	148	149
Limits	0.3 - 0.8	0.4 - 0.8	0.85 - 1.5	1.7-1.75	1.6 -1.65
Sample <Lower Limit	55	1	71	26	2
Sample within Range	37	5	19	73	39
Samples > Upper Limit	52	17	54	49	108
Passed Samples	89	22	73	122	147
% RD Pass	**61.81**	**68.75**	**50.69**	**81.33**	**98.00**

The strength results at 7 and 14 days had a pass percentage of over 60% while 28 days had 50.7%. Almost half of the samples collected failed the 28 days strength test. The relative densities of both FPT and Filcem performance were good.

Table 4-12 represents the descriptive statistics of the night shift sample results. The night shift data has a clear positively skewed distribution for the 7 and 14 days testing period. Considering the minimum required strengths for all periods, the calculated standard deviation of the mean is higher than the mean strength. This shows that the strength data for the night shift is more spread out and the sample variance is also high.

Table 4-12: Descriptive statistics of night shift sample test results

Statistics	**7 Days**	**14 Days**	**28 Days**
Mean	1.08	1.88	1.92
Standard Error	0.11	0.40	0.17
Median	0.48	0.864	0.93
Mode	0.22	0.15	5.77
Standard Deviation	1.32	2.26	2.03
Sample Variance	1.73	5.10	4.12
Kurtosis	2.33	1.74	1.25
Skewness	1.74	1.57	1.36
Range	5.77	8.48	10.39
Minimum	0	0	0
Maximum	5.77	8.48	10.39
Sum	154.81	60.26	276.46
Count	144	32	144

4.4 Summary of 2017 CCT and FPT Results

The overall data for 2017 CCT samples show a high amount of variability of strength values for samples tested. The effect of relative density on the strength of samples is negligible. The difference between the morning shift and night shift sample results were investigated. The results obtained showed that night shift samples passed at higher percentages as compared to the morning shift. The night shift has more samples that were tested as compared with the morning shift. The average strength for the night shift was relatively higher as well as the standard deviation. The sample variance was also higher for night shift samples. These analyses show that night shift samples performed higher than morning shift samples and the factors contributing to this performance must be investigated. These factors must be identified to optimise the performance of backfill at the mine.

There is a huge amount of variability in the FPT strength test results. The correlation between the relative density of the tailings and the strength is not visible. The performance of FPT is relatively low with almost half of the total tested samples failing the strength test. The FPT sample data is moderately spread out and the sample variance is relatively lower than CCT samples. The difference between morning and night shift results for FPT is that there are less variability and deviation of samples for the morning shift as compared to the night shift. The night shift results had a relatively high variance but it performed better than the morning shift by obtaining over 60% pass for 7 and 14 days tests. The morning shift had poor performance for 28 days of strength tests by obtaining a 40% pass rate while the night shift obtained 50.7%.

4.5 Analyses of CCT Performance (2018)

The strength and RD requirements for CCT in 2018 are the same as in 2017. The backfill plant stopped collecting samples for 14 days strength test due to the minimum change in strength between 7 and 14 days. The sample data for 2018 CCT results are presented in **Appendix G**. Samples were collected and tested for strength in the 7 and 28 days curing period. The results obtained in 2018 for CCT are presented in Table 4-13 below. About 485 samples were tested for strength and 453 of them achieved strength values above the minimum limit. The performance of the CCT product was 93.4 % in 7 days and 82.9 % in 28 days. These relative densities for both CCT and Filcem were also achieved with over 97 and 100% pass rates.

Table 4-13: Summary of 2018 CCT test results for 7 and 28 days

	Strength		RD	
	7 Days	**28 Days**	**CCT**	**FILCEM**
Total No. of Sample	531	531	531	531
Defects	46	5	25	25
Qualified Samples	485	526	506	506
Limits	0.3 – 0.8	0.85 - 1.5	1.7-1.75	1.6 -1.65
Sample <Lower Limit	32	90	11	0
Sample within Range	335	278	304	178
Samples > Upper Limit	118	158	191	328
Passed Samples	453	436	495	506
% Pass	**93.40**	**82.89**	**97.83**	**100.00**

4.5.1 Statistical analyses of CCT results

The descriptive statistics of CCT strength results are represented in Table 4-14. The mean strength of CCT at 7 days was 0.8 MPa and 1.57 MPa in 28 days. The mean strength values for both testing periods were above the minimum strength limit. The standard deviation for 7 days was almost equal to the mean with a value of 1.81 MPa and was less than the mean value at 28 days curing period. The strength values are less spread out in 7 days than in 28 days. The strength values are positively skewed and the range for both periods is very high.

Table 4-14: Descriptive statistics for 2018 CCT strength results

Descriptive Statistics	7 Days	28 Days
Mean	0.80402	1.569924
Standard Error	0.03689	0.051046
Median	0.58	1.21
Mode	0.5	5.77
Standard Deviation	0.81239	1.170715
Sample Variance	0.65998	1.370573
Kurtosis	20.4708	4.485982
Skewness	4.1263	2.151997
Range	5.69	5.61
Minimum	0.08	0.16
Maximum	5.77	5.77
Sum	389.95	825.78
Count	485	526

Figure 4-7 shows the distribution of the CCT strength in 2018 and it shows that the data had a relatively high number of samples that yielded higher UCS values. There is a high frequency of CCT samples that yielded UCS values in the range of 0.8 and 1 MPa. There were relatively fewer samples that yielded UCS values below the minimum limit.

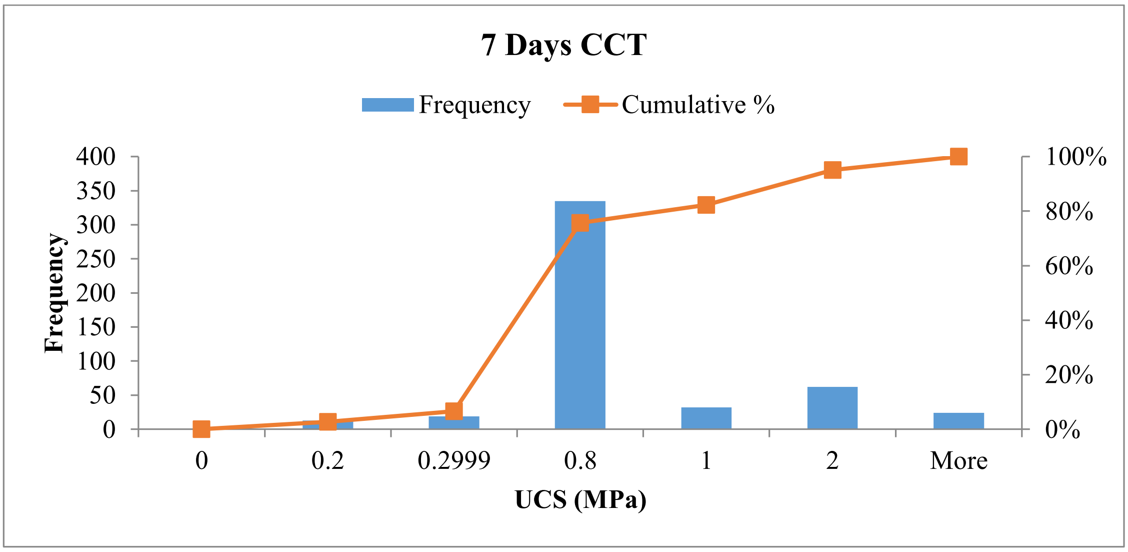

Figure 4-7: The strength distribution of 2018 CCT results at 7 days curing period

The distribution of the 28 days is represented in Figure 4-8 and it also shows a high number of samples that yielded higher UCS values. There is a high frequency of samples that yielded strength values in the range of 1.5 and 2 MPa.

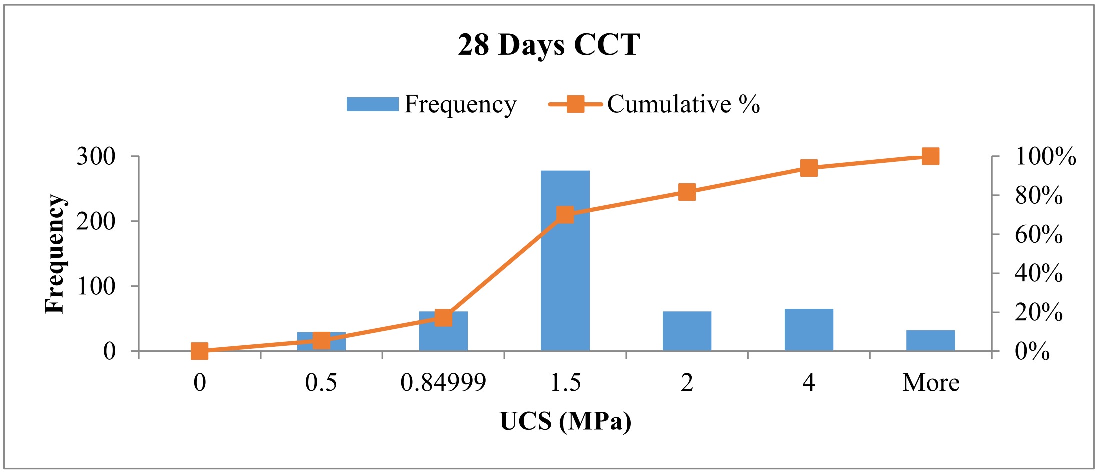

Figure 4-8: The strength distribution of 2018 results at 28 days curing period

4.5.2 Analyses of CCT results according to shifts

The 2018 CCT sample results were analysed according to shifts. The data was represented in the form of graphs included in **Appendix H** and **Appendix I**. The results were studied and the difference between the two shifts was identified. The results obtained for both morning and night shifts were collected to determine if there is a difference in the results and determine if the difference does contribute to strength variability.

4.5.2.1 Morning shift

Table 4-15 gives a summary of the strength and relative density data collected in 2018 at the CCT distribution section during morning shifts. A total of 228 CCT samples were collected and tested during the morning shift in 2018. The strength results at 7 days had a pass percentage of over 96% while 28 days had 86%. The relative densities for both CCT and Filcem were above 96%. The performance of backfill prepared during the morning shift was very good.

Table 4-15: Morning shift results for 2018 CCT samples

	Strength		**RD**	
	7 Days	**28 Days**	**CCT**	**FILCEM**
Total No. of Sample	248	248	248	248
Defects	20	5	3	3
Qualified Samples	228	243	245	245.00
Limits	0.3 - 0.8	0.85 - 1.5	1.7-1.75	1.6 -1.65
Sample <Lower Limit	8	34	9	0
Sample within Range	159	137	142	90
Samples > Upper Limit	61	72	94	155
Passed Samples	220	209	236	245
%Pass	**96.49**	**86.01**	**96.33**	**100**

The descriptive statistics for the morning shift data is represented in Table 4-16. The mean strength obtained at 7 days is 0.77 MPa and 1.49 MPa in 28 days. The standard deviation of the mean is 0.53 MPa for 7 days and 0.94 MPa for 28 days curing period. The strength values are less spread out for the morning shift. The data is positively skewed and the range of the strength values is 3.89 MPa at 7 days and 5.61 MPa at 28 days. These parameters show that the data set has less variability as compared to the overall data. The performance of the CCT samples is also very good with less variability.

Table 4-16: Descriptive statistics for 2018 CCT morning shift strength data

Descriptive Statistics	**7 Days**	**28 Days**
Mean	0.77	1.49
Standard Error	0.035	0.06
Median	0.62	1.25
Mode	0.48	1.11
Standard Deviation	0.53	0.94
Sample Variance	0.28	0.88
Kurtosis	9.57	5.68
Skewness	2.69	2.24
Range	3.89	5.61
Minimum	0.12	0.16
Maximum	4.01	5.77
Sum	175.8	363
Count	228	243

4.5.2.2 Night shift

The results obtained for the night shift are presented in Table 4-17 and they also show very good strength and RD performance. A total of 257 CCT samples were collected and tested for strength during the night shift. The 7 days samples achieved 90% while 28 days achieved 80%. The relative densities for both tailings and Filcem were perfect and had a pass rate of over 99%. Although the relative densities were within the required limits, the strength achieved in both 7 and 28 days was lower than the morning shift samples.

Table 4-17: Nightshift results for 2018 CCT samples

	Strength		**RD**	
	7 Days	**28 Days**	**CCT**	**FILCEM**
Total No. of Sample	283	283	283	283
Defects	26	0	22	22
Qualified Samples	257	283	261	261.00
Limits	0.3 - 0.8	0.85 - 1.5	1.7-1.75	1.6 -1.65
Sample <Lower Limit	24	56	2	0
Sample within Range	176	141	161	88
Samples > Upper Limit	57	86	98	173
Passed Samples	233	227	259	261
% Pass	**90.66**	**80.21**	**99.23**	**100.00**

The descriptive statistics of the night shift strength data are presented in Table 4-18. The mean strength for 7 days was 0.83 MPa with a standard deviation of 1 MPa. The strength values of the mean, mode and median show that the data is positively skewed. The range of the strength values is 5.69 MPa which is slightly higher than the 28 days strength range.

Table 4-18: Descriptive statistics of the CCT night shift strength results

Descriptive Statistics	**7 Days**	**28 Days**
Mean	0.83	1.64
Standard Error	0.062	0.079
Median	0.53	1.14
Mode	0.5	5.77
Standard Deviation	1.0	1.34
Sample Variance	1.0	1.78
Kurtosis	15.4	3.20
Skewness	3.80	1.96
Range	5.69	5.59
Minimum	0.08	0.18
Maximum	5.77	5.77
Sum	214.13	462.75
Count	257	283

The variance of the strength data for both 7 and 28 days is relatively higher than the morning shift data. More samples were tested for the night shift than in the morning shift, the range and the mean strength values were higher for night shift CCT samples.

4.6 Analyses of FPT Performance (2018)

This section discusses the overall performance of 2018 FPT samples and their properties. The previous results were compiled and analysed to determine the performance of FPT in terms of strength and RD. The results obtained are represented in Table 4-19. The UCS performance of FPT samples was higher in 7 days than in 28 days curing period. There were over 50% of the samples that achieved strengths above the required minimum limit. The tailings and binder were also prepared to the required relative densities. Most of the time the operators were within the required RD limits and over 90% of the samples were above the minimum RD limit.

Table 4-19: Overall UCS analyses of FPT samples

	Strength		**RD**	
	7 Days	**28 Days**	**FPT**	**FILCEM**
Total No. of Sample	161	161	161	161
Defects	8	2	9	9
Qualified Samples	153	159	152	152
Limits	0.3 - 0.8	0.85 - 1.5	1.7-1.75	1.6 -1.65
Sample <Lower Limit	40	55	1	1
Sample within Range	42	21	12	12
Samples > Upper Limit	71	83	139	139
Passed Samples	113	104	151	151
% RD Pass	**73.86**	**65.41**	**93.79**	**93.79**

4.6.1 Statistical analyses of FPT results

The descriptive statistics of the 2018 FPT samples is shown in Table 4-20. The data is divided according to testing periods which further gives the variance of the results between the two periods. For 7 days curing period, the mean is 1.32 MPa and the standard deviation from the mean is 1.47 which is almost equal to the mean. The distribution of the data is negatively skewed with skewness of above 1.5 MPa. The range of the 2018 FPT samples is 5.73 MPa, which shows a high level of variability in the data.

Table 4-20: Descriptive statistics of 2018 FPT samples for 7- and 28-days curing period

Descriptive Statistics	7 Days	28 Days
Mean	1.32	2.20
Standard Error	0.12	0.150
Median	0.69	1.58
Mode	0.19	5.77
Standard Deviation	1.47	1.89
Sample Variance	2.17	3.59
Kurtosis	1.49	-0.77
Skewness	1.51	0.77
Range	5.73	5.67
Minimum	0.04	0.1
Maximum	5.77	5.77
Sum	201.18	349.29

4.6.2 Analyses of FPT Results according to shifts

The 2018 FPT sample results were analysed according to shifts. The data was represented in the form of graphs included in **Appendix K** and **Appendix L**. The results obtained for both morning and night shifts were collected to determine if there is a difference in the results and determine if the difference does contribute to strength variability.

4.6.2.1 FPT morning shift results analyses

The FPT data collected was categorised according to shifts to see the difference in performance for the day and night shifts. The performance of the FPT morning shift samples in terms of UCS and relative density is given in Table 4-21. The results show that morning shift samples passed the UCS test with over 70% at 7 days and 66% at 28 days. The number of samples which passed the UCS in 28 days were relatively lower than in 7 days. The relative densities achieved 89% for tailings RD while the binder RD was at 100%. The FPT was prepared at the required RD and the binder was also accurately mixed to the required RD. The difference in the number of samples that passed the UCS test in 7 and 28 days is relatively lower than the night shift.

Table 4-21: The performance of the FPT morning shift samples

	Strength		**RD**	
	7 Days	**28 Days**	**FPT**	**FILCEM**
Total No. of Sample	66	66	66	66
Defects	3	1	0	0
Qualified Samples	63	65	66	66
Limits	0.3 - 0.8	0.85 - 1.5	1.7-1.75	1.6 -1.65
Sample <Lower Limit	17	22	7	0
Sample within Range	16	9	51	8
Samples > Upper Limit	30	34	8	58
Passed Samples	46	43	59	66
% RD Pass	**73.02**	**66.15**	**89.39**	**100.00**

The descriptive statistics of the FPT morning shift UCS data is given for 7 and 28 days in Table 4-22. The average UCS for 7 days was 1.37 MPa and 2.32 MPa for 28 days curing period. The standard deviation of the mean is greater than the mean which shows that the UCS values are highly spread out. The mean has a relatively higher UCS value than the median and the mode has the smallest value. This shows a data distribution that is skewed to the right with a high number of samples having UCS values that are lower than the mean value in 7 days.

Table 4-22: Descriptive statistics of the UCS of FPT morning shift samples

Descriptive Statistics	**7 Days**	**28 Days**
Mean	1.37	2.32
Standard Error	0.19	0.24
Median	0.71	1.65
Mode	0.4	5.77
Standard Deviation	1.51	1.97
Sample Variance	2.28	3.89
Kurtosis	1.15	-1.10
Skewness	1.39	0.61
Range	5.72	5.67
Minimum	0.05	0.1
Maximum	5.77	5.77
Sum	86.23	150.81

The distribution of the UCS values of FPT morning shift samples in 28 days shows a data distribution that is more spread out than 7 days of UCS data. The standard deviation of the mean for 28 days is 1.97 MPa and the skewness is 0.61. The statistics for 28 days shows a lognormal distribution that is slightly skewed to the right. The data range is almost similar for the 7 and 28 days curing period with UCS values of 5.72 and 5.67 MPa respectively.

4.6.2.2 FPT night shift results analyses

The performance of FPT samples collected on night shifts is represented in Table 4-23. The UCS and relative density of the samples were analysed and their performance was determined from the results obtained. The results obtained for 7 and 28 days UCS has a high level of variance since most samples failed the 28 days UCS test. The relative densities of both the tailings and binder were prepared to the required value. Over 75% of the CCT RD samples and over 89% of binder RD were prepared to the required limit.

Table 4-23: The FPT performance on the night shift

	Strength		**RD**	
	7 Days	**28 Days**	**FPT**	**FILCEM**
Total No. of Sample	95	95	95	95
Defects	5	1	9	9
Qualified Samples	90	94	86	86
Limits	0.3 - 0.8	0.85 - 1.5	1.7-1.75	1.6 -1.65
Sample <Lower Limit	23	33	14	1
Sample within Range	26	12	68	4
Samples > Upper Limit	41	39	4	81
Passed Samples	67	51	72	85
% RD Pass	**74.44**	**54.26**	**75.79**	**89.47**

The descriptive statistics results for both 7 and 28 days are represented in Table 4-24. The mean FPT strength for 7 days is 1.28 MPa and the standard deviation is 1.45 MPa. The range of the FPT strength for 7 days is 5.73 MPa which is almost 5 times the average strength. The relationship between the mean, mode and median shows that the data is negatively skewed with a skewness value of 1.62 MPa. The descriptive statistical parameters indicate a relatively high level of variance of FPT samples during the night shift. The mean FPT strength for 28 days is 2.11 MPa while the standard deviation is 1.8 MPa and the range is 5.66 MPa. The variability of sample data for 28 days is higher than that of 7 days.

Table 4-24: Descriptive Statistics of the UCS of 2018 FPT Night Shift samples

Descriptive Statistics	**7 Days**	**28 Days**
Mean	1.28	2.11
Standard Error	0.15	0.19
Median	0.68	1.58
Mode	0.19	5.77
Standard Deviation	1.45	1.84
Sample Variance	2.11	3.40
Kurtosis	1.93	-0.44
Skewness	1.62	0.91
Range	5.73	5.66
Minimum	0.04	0.11
Maximum	5.77	5.77
Sum	114.95	198.48

4.7 Summary of 2018 Results

The 2018 CCT samples achieved very high strength performance for both 7 and 28 days. The CCT material was prepared for the required relative density. Although there was a high variability of strength values for samples tested, most of them achieved strength values above the minimum limit. The effect of relative density on the strength of samples was not evident. Morning shift samples achieved higher strength values than night shift samples.

The 2018 FPT strength results were lower than the CCT results. The correlation between the relative density of the tailings or filcem and FPT strength was not visible. The strong performance of FPT samples was relatively low and achieved a pass rate below 75%. The morning shift samples performed better than the night shift by obtaining over 70% pass for 7 and 66% for 28 days strength tests. The night shift had poor performance for 28 days of strength tests by obtaining a 54% pass rate and 74% for 7 days.

4.8 Summary of Previous Results Analyses

The strength results are affected by other factors excluding the relative density of the tailings. The relative density of the binder does not correlate with the strength values obtained from the samples. Both relative densities do not seem to affect the strength results of the samples taken. The performance of CCT was higher in 2018 than in 2017 with a pass rate of 93% in 7 days and 83% in 28 days curing period. The average strength obtained was relatively higher in 2017 than in 2018 with a mean UCS of 1.3 MPa in 7 days and 2.23 MPa in 28 days curing period. The standard deviation of strength values obtained in 2017 was relatively higher and the data set was spread out by 1.51 MPa in 7 days and 2.18 MPa in 28 days curing period. Statistics showed a high variability of CCT strength values in 2017. In 2017, most samples that passed the UCS test were collected during the night shift and in 2018 morning shift samples had a higher pass rate.

The performance of FPT samples for 2017 was lower for both periods of curing. This improved in 2018 when the FPT samples achieved a 74% pass rate in 7 days and 65% in 28 days. The means UCS value achieved in 2017 was relatively lower with a value of 0.75 MPa in 7 days curing period and 1.41 MPa in 28 days curing period. The standard deviation from the mean was relatively higher in 2018 than in 2017 with a deviation of 1.47 MPa in 7 days and 1.89 MPa in 28 days curing period. The range of the data set was slightly higher in 2017 with a range of 5.77 MPa in 7 days and 10.4 MPa in 28 days curing period. The performance of samples collected during the night shift was relatively higher than the morning shift results in 2017 and 2018.

The backfill material which obtained better fill performance was CCT for both the years 2017 and 2018. FPT had a lower pass rate, lower mean UCS and a higher standard deviation. This shows that there was a relatively higher strength variability of backfill samples collected from FPT than CCT material. The consistency of sample test results must be monitored for all periods. A strength performance curve must be compiled to help predict the performance of samples at a later (28 days) stage by using the earlier (7 Days) strength results.

5 STUDIES CONDUCTED TO DETERMINE FACTORS CAUSING BACKFILL STRENGTH VARIABILITY

5.1 Introduction

This chapter discusses the studies conducted and the results obtained from the UCS tests. The studies were undertaken to investigate the cause of variability of backfill strength test results. Studies conducted include benchmark for the backfill mix design, sampling procedures, curing room environment conditions, binder flow rate, binder orifice size, day and night shift results, CCT and FPT plant and operator efficiencies.

5.2 Benchmark for Backfill Mix Design

Manual mixing of tailings and binder was conducted to establish a benchmark of the current mix design and the required mix design by the plant. The study was done on both FPT and CCT products. The relative density and specific gravity of tailings were used to calculate the percentage of solids in the slurry. From the percentage of solids in the tailings, the actual amount of dry binder solids was calculated. These numbers assist in calculating the actual amount of binder used in the backfill plant which can be used to optimise binder usage and cost. The following equations were used to calculate the percentage of tailings and binder solids in the slurry.

$$\%\, tailings\ solids\ =\ SG_{tailings} \times \frac{RD_{tailings} -\ SG_{water}}{RD_{tailings}(SG_{slurry} - SG_{water})} \tag{5-1}$$

$$Mass\ of\ tailings\ solids = \%tailings\ solids * mass\ of\ wet\ tailings \tag{5-2}$$

$$\%\ \text{binder solids}\ = \frac{\text{Total Mass of dry binder (kg)}}{Total\ mass\ of\ tailings\ solids} \times 100 \tag{5-3}$$

5.2.1 CCT mix design

The amount of the CCT tailings solids present in the slurry were calculated using the CCT RD of 1.7 t/m^3 and specific gravity (SG) of 2.7 t/m^3. The percentage of CCT tailings solids was calculated to be 65.4%. The CCT solids percentage was used to calculate the actual mass in the CCT slurry of 20kg. The actual mass of tailings was used to calculate the number of binder solids in the backfill slurry. Table 5-1 shows the calculations and measurements made in the backfill mix design.

Table 5-1: Measurements and values obtained from the percentage of solids calculations

Binder %	CCT RD	CCT tailings (kg)	Wet Binder (kg)	Dry Binder (kg)	Water (kg)	CCT solids (kg)	Binder solids (kg)
6%	1.70	20	1.2	0.80	0.40	13.1	6.12
8%	1.70	20	1.6	1.07	0.53	13.1	8.15
10%	1.70	20	2	1.33	0.67	13.1	10.19

The percentage solids of the binder were slightly higher than the initial measurement of the dry binder. These calculations were also used to determine the optimum mix design that will have a binder content that will provide the required strength for the backfill material. The CCT material was collected from the CCT preparation tank at a relative density of 1.7 t/m^3. The binder slurry relative density at a c:w ratio of 2:1 was measured to be 1.845 t/m^3. The binder slurry and CCT tailings were mixed in a 30-litre bucket and cast into cylindrical moulds. The samples were stored in a curing chamber for 7, 28 and 56 days. The samples were placed on the floor due to less space available. The results obtained are represented in Figure 5-1.

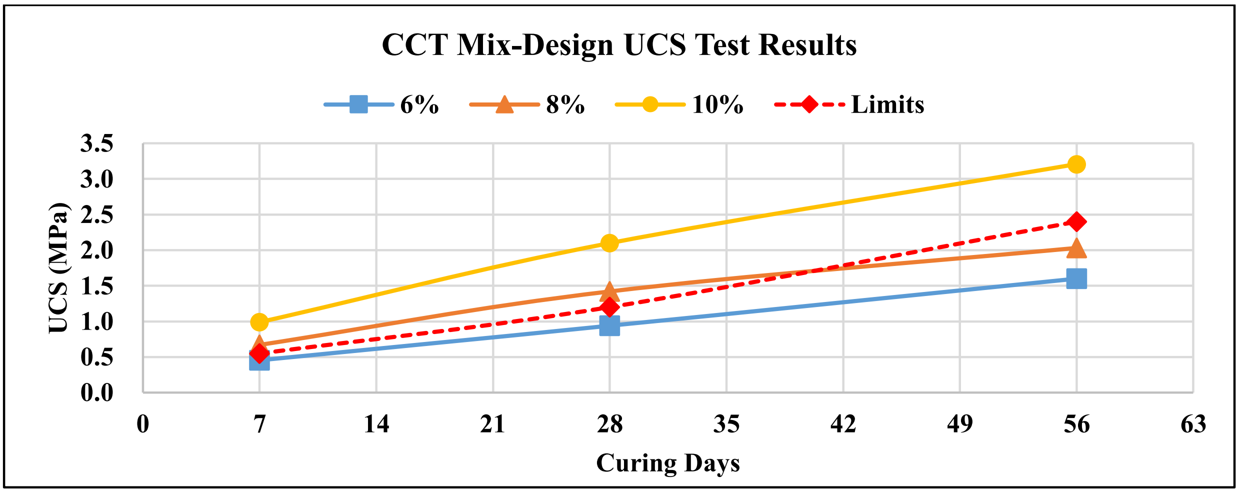

Figure 5-1: CCT and Binder Mix Design

The results presented in Figure 5-1 shows that the mix design that meets the strength requirements for all curing periods is at 10% binder content. The backfill samples which had a binder content of 10% achieved 0.99 MPa for 7 days, 2.10 MPa for 28 days and 3.10 MPa for 56 days curing period. The strength values achieved are almost twice the required strength. The backfill samples prepared at 8% binder content achieved 0.67 MPa for 7 days, 1.42 MPa and 2.03 MPa for 56 days curing period. Samples with the binder content of 6% failed the strength test for all curing periods. This shows that when preparing CCT at a relative density of 1.7, the suitable binder content that will yield the required strength for 7- and 28-days curing period is from 8%. When designing for the long term, the suitable binder content at a relative density of 1.7 is 10%.

5.2.2 FPT mix design

The percentage of solids in the FPT material and the binder was calculated using equations (1) and (2). The results of the calculations are represented in Table 5-2. The FPT slurry at a relative density of 1.75 and a specific gravity of 2.7 had 68.07% of solids which is more than CCT at 1.7 RD with 65.4% solids.

Table 5-2: FPT binder mix-design mass content

Binder %	FPT RD	FPT tailings (kg)	Wet Binder (kg)	Dry Binder (kg)	Water (kg)	FPT solids (kg)	Binder solids (kg)
6%	1.75	24	1.44	0.96	0.48	16.3	5.88
8%	1.75	24	1.92	1.28	0.64	16.3	7.84
10%	1.75	20	2	1.33	0.67	13.6	9.79

The results obtained from the UCS test of the FPT binder mix design are represented in Figure 5-2. The UCS test results obtained indicate that all samples mixed at 6, 8 and 10% binder content failed the test. All the samples obtained very low strength values for all curing periods. Strength values for 7, 28 and 56 days were lower than the minimum strength required. This was surprising because the CCT mix-design samples achieved better UCS results which were above the required limit.

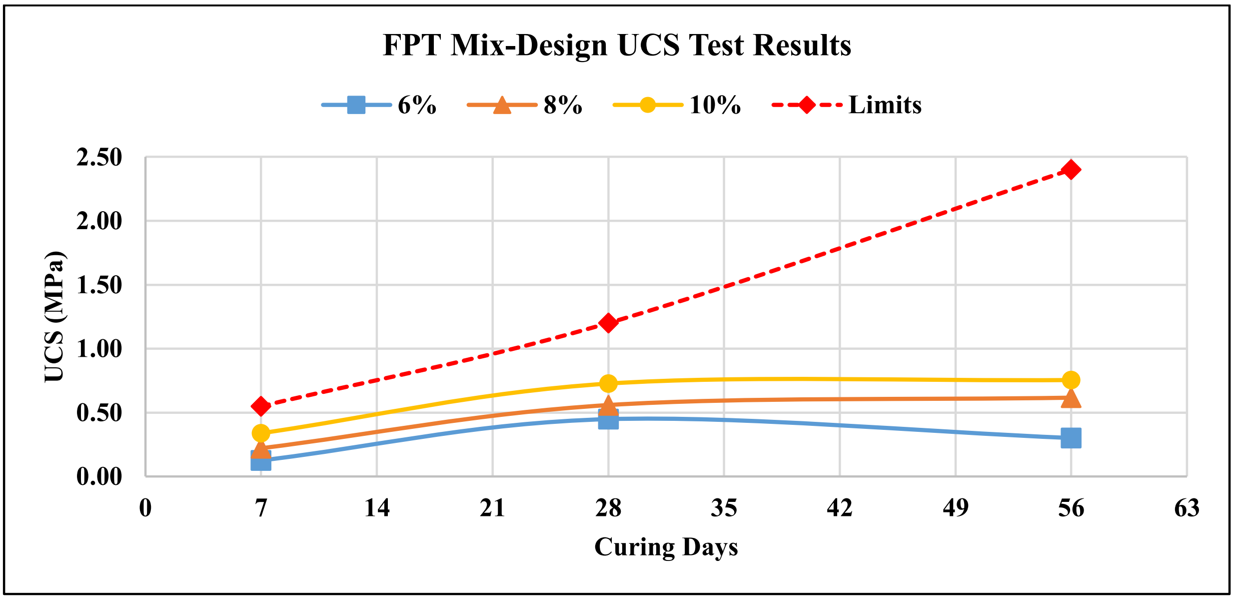

Figure 5-2: The FPT binder mix design

The maximum strength obtained by FPT samples with a binder content of 6% was 0.45 MPa at 28 days curing period. At 56 days curing period, the strength obtained is 0.3 MPa which is relatively lower than 28 days strength. The strength results for the FPT samples with a binder content of 8% achieved a maximum strength of 0.65 MPa at 56 days curing period. The maximum strength obtained by the FPT samples at 10% binder content is 0.75 MPa at 56 days curing period. The curing conditions for both CCT and FPT was different and also yielded varying UCS test results. An investigation was conducted to find factors that contributed to varying test results of the CCT and FPT mix designs. Other studies were conducted to validate the effect of factors identified on the UCS of backfill samples.

5.3 Sampling Procedure Application

The researcher wanted to investigate the current sampling procedure practised at the backfill plant. The procedure was followed and more backfill samples were collected and stored in the curing room for 7 and 28 days. This study was conducted to determine any variation between samples collected using the same sampling procedure and with similar material properties. CCT and FPT samples were collected and cured at a temperature of 31ºC. The samples collected were placed on different shelves in the curing room. The elevation levels were named from the floor moving upward. Level 1 was at an elevation of 80cm, Level 2 at 140 cm and Level 3 at 200 cm from the floor. The shelf elevation layout is represented in Figure 5-3.

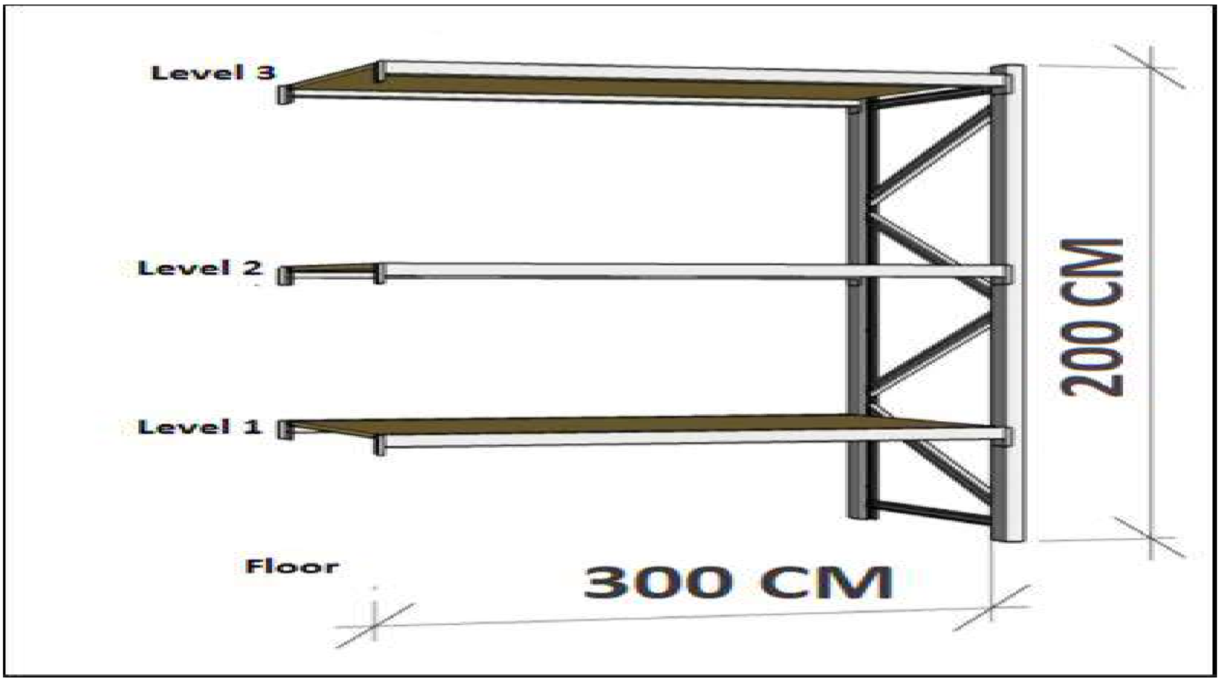

Figure 5-3: Shelf elevation levels

The information of CCT samples collected is represented in Table 5-3 below. There were two sets of samples, one collected by the researcher (study) and others collected by the operator (control). The study samples in Batch-1 were placed on the top shelf named Level 3 in the curing room whilst those collected by the lab operator were placed on the shelf below the top shelf which was named Level 2. The second batch (Batch 2) of samples were collected and the study samples were placed on the floor and control samples were placed on Level 1. The shift, line, relative density and curing temperature of each batch for both samples were the same.

Table 5-3: Sampling and curing information for CCT samples collected

Sample Properties	**Batch 1**		**Batch 2**	
	Study Sample 1	**Control sample 1**	**Study Sample 2**	**Control sample 2**
Number of samples	6	6	9	6
Curing position	Shelve (Level 3)	Shelve (Level 2)	Shelve (Floor)	Shelve (Level 1)
Temperature (°C)	31	31	31	31
Shift	M/S	M/S	M/S	M/S
Line	L25	L25	L26	L26
Name	CCT	CCT	CCT	CCT
Relative Density	1.73	1.73	1.7	1.7

The UCS test results obtained from samples collected at Batch 1 are represented in Figure 5-4. The graphs show that the study samples yielded higher strength values compared to the control samples. The difference in the strength yielded by the two groups of backfill samples at 7 days was minimal. A significant difference of over 0.55 MPa was shown at 28 and 56 days of curing. The strength values achieved by the two groups of samples were above the minimum limit by about 55%.

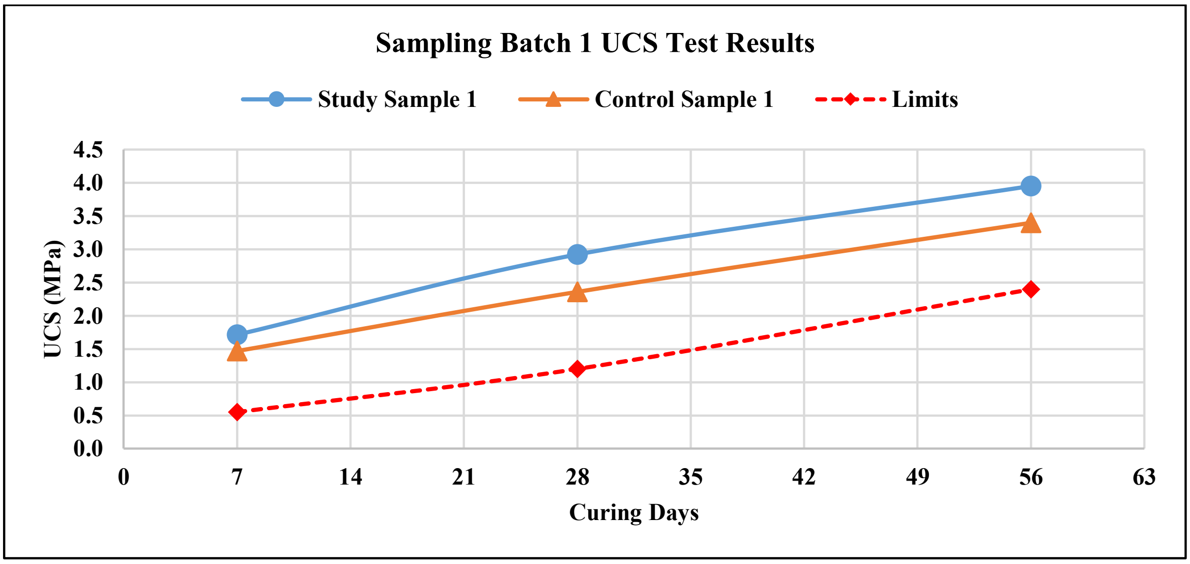

Figure 5-4: UCS test results for sampling batch-1 of CCT

The second batch of samples was collected and stored in different shelf positions. The study samples were placed on the floor and control samples were placed on Level 1. The results obtained are represented in Figure 5-5.

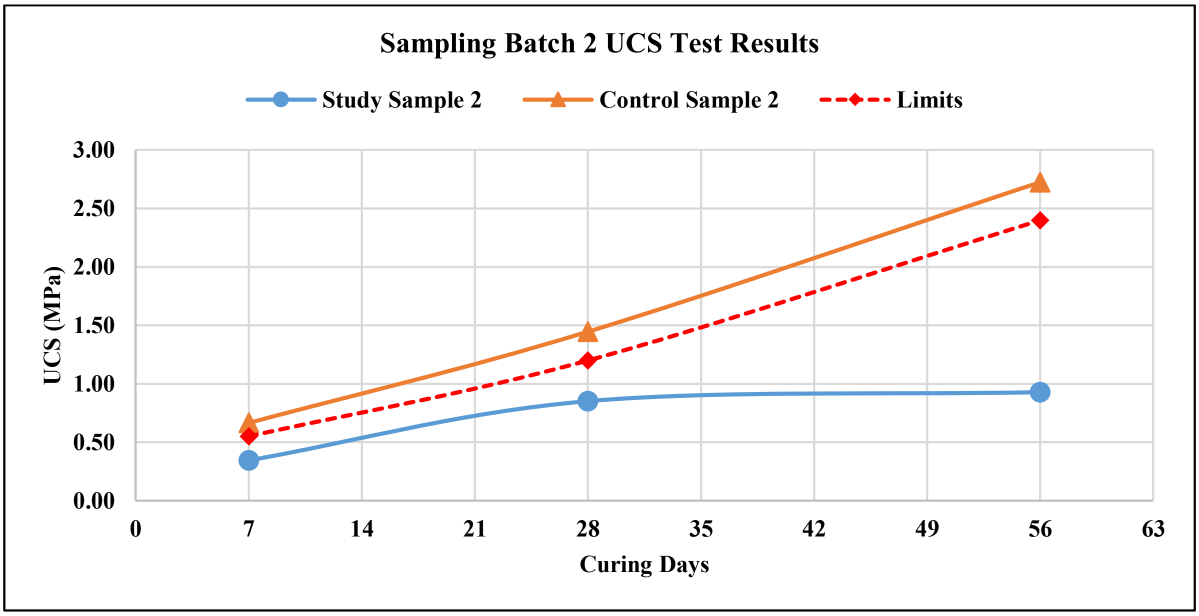

Figure 5-5: UCS test results for sampling batch-2 of CCT

The strength test results of Batch 2 are different from Batch 1 such that the study samples achieved relatively lower UCS values on Batch 2. The UCS values achieved by control samples were slightly above the minimum strength limit. The strength variance between the two groups of samples is significant. The strength values vary by 0.55 MPa for 7 days, 0.6 MPa for 28 days and 1.8 MPa for 56 days of the curing period.

The difference in the strengths obtained from the two groups of samples indicates that variability among samples stored in the curing room is a possibility. The cause of variability of the backfill strength test results was investigated using the information sheets filled during the sampling and curing tasks. The main factors that were discovered to have caused the variation of strength test results of the two groups of backfill samples were the difference in curing temperature around the curing room and the elevation of samples from the floor. These factors were investigated and the outcome of the study is discussed in the next section.

5.4 Curing Room Temperature Study

This study was conducted to determine if the temperature around the curing room is uniform and this was done by measuring temperature around the curing room. The sampling procedure study indicated that samples collected from the same batch and stored at different elevations in the curing chamber yielded different results. The position of the heater within the curing room was found to be placed above the curing room entrance door, blowing hot air from the top-down towards the centre of the room. Another heater was placed at the bottom of the shelves in the curing room. Figure 5-6 shows a layout of the curing room which includes the position of heaters and shelves. Different positions to place backfill samples within the curing room were established to determine the temperature around the curing room at different elevations. The temperature at each level was measured at positions labelled A to H as indicated in Figure 5-6.

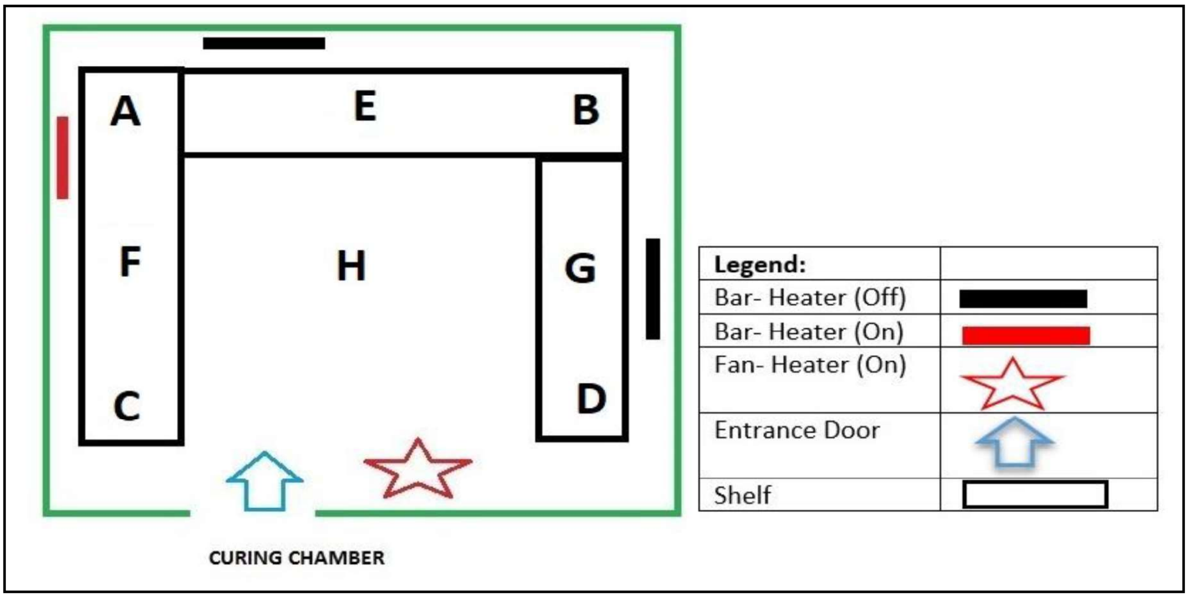

Figure 5-6: Curing room layout

The curing temperature study was conducted and the results of the temperatures measured at each position were compiled. The results were categorised according to their elevation from the floor and are represented in Figure 5-7. The results obtained from the study show a huge variance of temperature at all positions. The temperature reading at position A has the highest temperature of above 36°C and position D has the lowest temperature of 31°C. Position F has the second-highest temperature of about 34°C and G has the second-lowest temperature of 32°C in the curing room. Position A, E and F are next to the bottom bar heaters and that is the reason why they obtained relatively higher temperatures than other positions. Positions B, C, D and G are far from the heaters on the floor. They obtained relatively lower temperatures since enough heat did not reach their area. Positions B, C and E obtained moderate temperature readings in the range between 32 to 34°C.

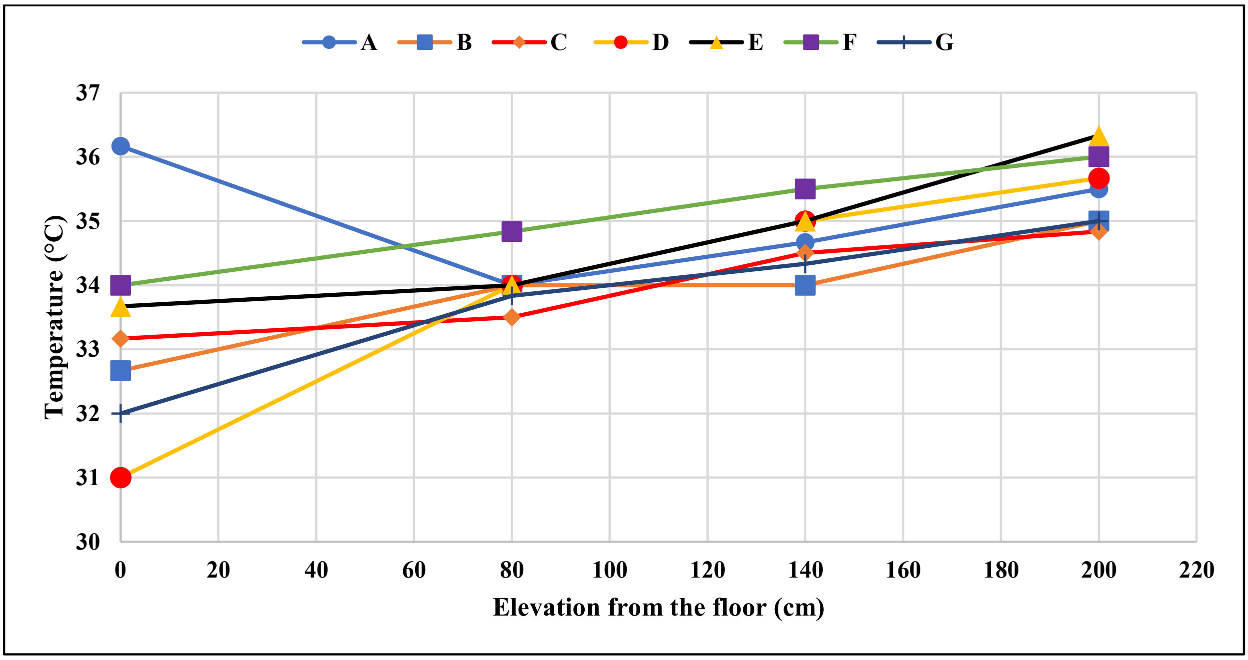

Figure 5-7: The temperature change with elevation graphs for the curing room

The temperature results obtained from elevation Level 1 (80 cm) of the curing room shows that the position with the highest temperature is F at a temperature of 34.5°C while position C has the lowest temperature of 33.5°C. Positions A, B, D, E and G obtained moderate temperature readings within a range of 33.8 to 34°C.

The results for Level 2 (140 cm) show that the position with the highest temperature is F with a temperature of 35.5°C. The position that had the lowest temperature reading was B at a reading of 34°C and the other positions had temperature readings that ranged from 34.3 to 35°C. The results obtained for Level 3 (200 cm) indicates that at the top shelves, position E had a relatively high-temperature reading of 36.3°C. The positions with the lowest temperature reading were C, B and G with readings ranging from 34.8 to 35°C. The other positions obtained temperature readings in the range of 35.5 to 35.7°C.

Except for position A, all other positions show an increase in temperature as the elevation increases. The average change in temperature between shelf levels is shown in Figure 5-8. The average change in temperature from the floor to Level 3 is 2.54°C while from the floor to Level 1 is 0.94°C. Figure 5-8 shows that the change in temperature between Level 1 and Level 2 is almost equal to the temperature change between Level 2 and Level 3. This is due to an equal change in elevation of 60 cm between the shelf levels. The average temperature gradient calculated using the elevation and average change in temperature in the curing room is 1.27°C per metre.

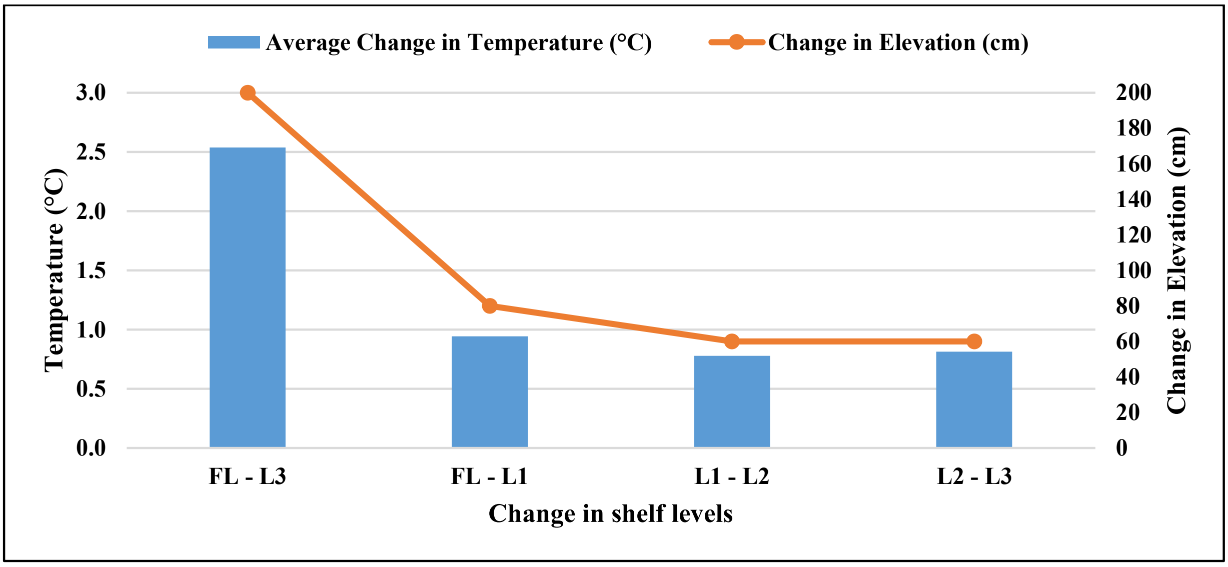

Figure 5-8: The change in temperature between shelf levels in the curing room

Based on the position of the bar heaters and the direction of airflow from the top fan heater, the air temperature with the curing room is bound to vary. The change in temperature from the floor to the top shelf is significant. Cemented hydraulic fill strength is affected by curing temperature. Curing temperature affects the rate of strength development within the backfill material during curing. The backfill samples placed close to the heaters and in the direction of heat from the fan heater are bound to cure at a relatively faster rate than in other positions. Backfill samples cured at different temperatures are bound to yield different strengths which led to having a high variability of backfill strength results.

5.5 Effect of Temperature on Backfill Strength

Based on the results obtained from the curing room temperature study, more investigations were conducted to determine the effect of temperature on the strength of backfill samples. Backfill samples were collected from both CCT and FPT plants and were stored in the curing room at different shelf levels and different positions. The backfill samples were placed on cool, warm and hot temperature areas to determine the impact of temperature on their strength. Table 5-4 shows the backfill sample properties and information about the sampling task conducted.

Table 5-4: Backfill sample properties for temperature and elevation study

Sample Properties	**Temp Level Study**							
	Floor	Level 1	Level 2	Level 3	Floor	Level 1	Level 2	Level 3
Number of samples	4	4	4	4	4	4	4	4
Shift	M/S	M/S	M/S	M/S	M/S	M/S	M/S	M/S
Pipeline No.	L25	L25	L25	L25	L38	L38	L38	L38
	CCT				**FPT**			
Tailings RD	1.72	1.72	1.72	1.72	1.73	1.73	1.73	1.73
Cement RD	1.68	1.68	1.68	1.68	1.72	1.72	1.72	1.72

The CCT product was prepared at a tailings relative density of 1.72 RD while the binder was prepared at 1.68 RD. The CCT samples were placed at position A on the floor, Levels 1, 2 and 3 in the curing room. The results obtained from the strength test are represented in Figure 5-9. The study conducted on CCT and the effect of curing temperature show that at position A, the CCT sample strengths yielded good results since the strength values were above the minimum strength limit. The strength values for all levels follow the same trend as the temperatures obtained in Figure 5-7. The strength values obtained by CCT samples were relatively high on the floor, decreased at Level 1 and then increased again at Level 2. The CCT strength values increased from 2.68 MPa at Level 2 to 2.73 MPa at Level 3 for 28 days curing period. The strength values for 7 days decreased at Level 3.

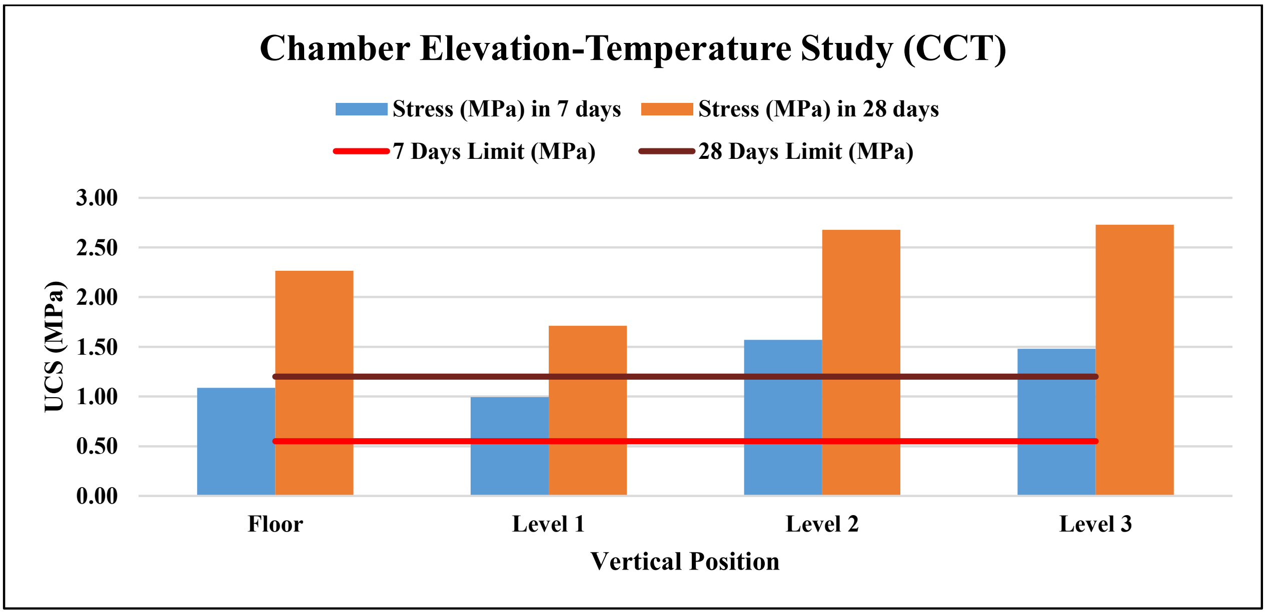

Figure 5-9: The effect of temperature change with elevation on CCT UCS

The FPT product was prepared at a relative density of 1.73 RD and a binder relative density of 1.72 RD. The FPT samples were placed at a point C in the curing room. The results obtained are represented in Figure 5-10. The strength values obtained for FPT samples placed on the floor and Level 1 failed the UCS test while Level 2 passed with values that were slightly above the minimum limit. Level 3 obtained satisfactory results for 7 days and obtained a very high strength value at 28 days. The strength value obtained at 28 days was more than 3 times the minimum strength limit.

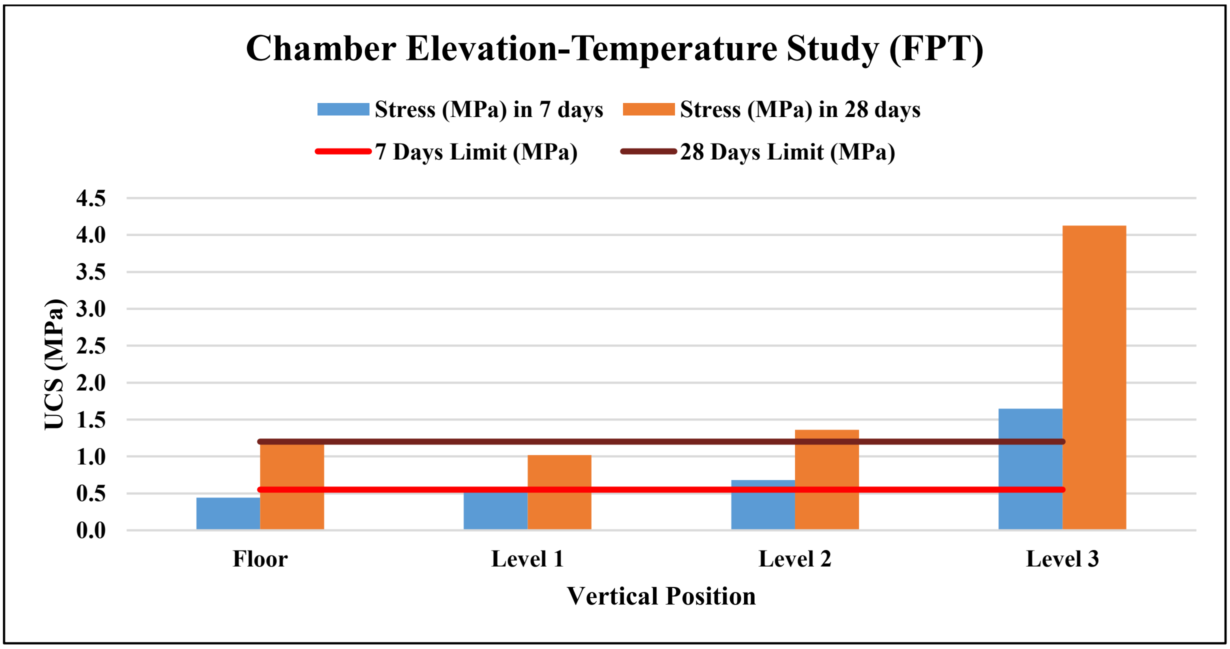

Figure 5-10: The effect of temperature increase with elevation on FPT UCS

5.6 Effect of Temperature and Elevation on the Backfill Mix-Design

The first study done on the mix design for CCT and FPT did not give conclusive results since they were affected by different curing conditions. A second study was conducted to determine the optimum mix design at constant atmospheric conditions. The mix-design samples for both CCT and FPT were placed on the same curing position and shelf elevation. This study aimed to determine an optimum backfill mix design that provides the required UCS at a constant temperature. A curing position that had relatively moderate curing temperature and elevation from the floor was selected to cure the backfill samples. The selected position and shelf level to cure the mix-design samples was position E at shelf Level 2. The samples were stored in the curing room at a hydrometer temperature reading of 33°C. The results obtained for both CCT and FPT are represented in Figure 5-1 and Figure 5-2.

The second CCT mix design was prepared at a tailings relative density of 1.7 RD. The samples were placed on Level 2 at position E and the UCS test results obtained are represented in Figure 5-11.

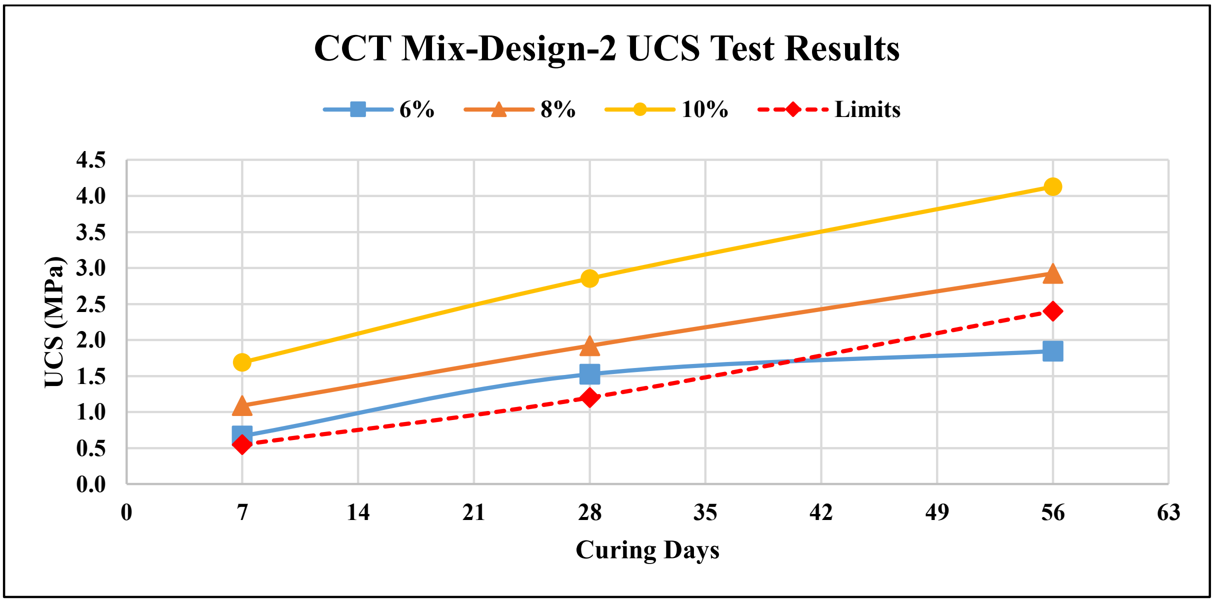

Figure 5-11: UCS test results for CCT mix design 2 at 1.7 RD

All samples prepared at 6, 8 and 10% binder content passed the UCS test at 7 and 28 days curing period. For the curing period of 56 days, only 8 and 10% binder content samples passed the UCS test. Samples prepared at 6% obtained a maximum strength of 1.53 and 1.84 MPa at curing periods of 28 and 56 days respectively. The strength development rate for 6% decreased over the long-term resulting in achieving strength values below the minimum limit. The strength values for 8 and 10% binder content also shows a decreased strength development rate but achieve strength values above the minimum limit. The strength development curves for CCT are linear in the early periods (7-28 days) of curing and start flattening at 56 days.

The FPT mix design was prepared at a relative density of 1.72 RD and was stored in the curing room at a temperature of 31°C. The samples were also placed on the top shelf and were tested for UCS after 7, 28 and 56 days. The results obtained from the UCS test are represented in Figure 5-12.

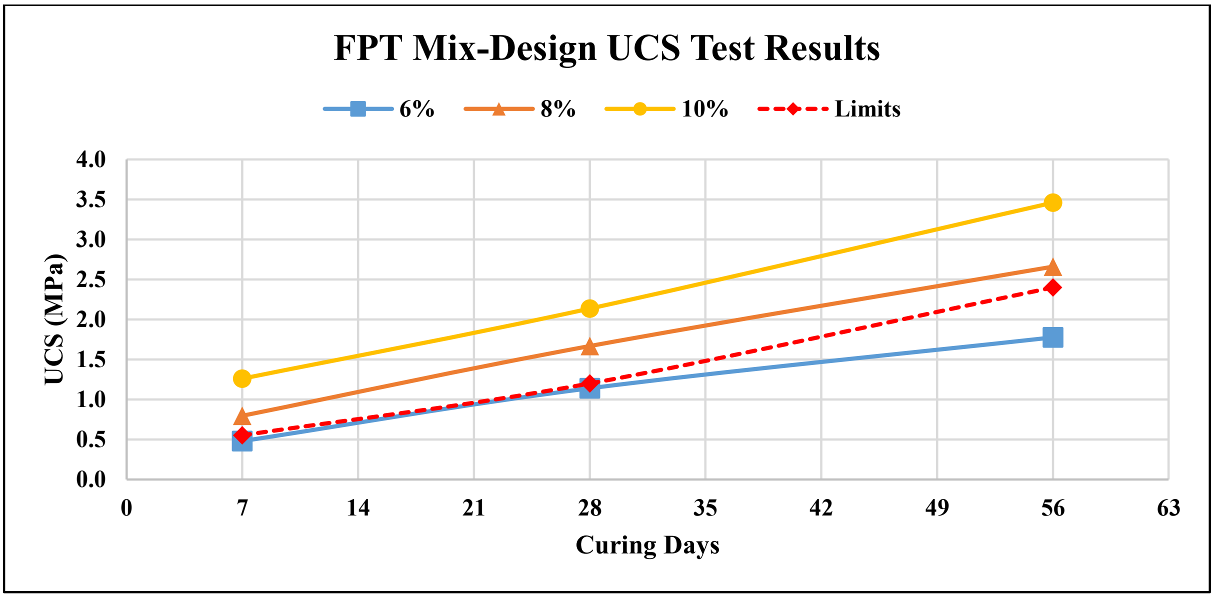

Figure 5-12: The UCS test results for FPT mix design 2 at 1.72 RD

The samples prepared at a binder content of 6% obtained strength values that were below the minimum strength limit for all curing periods. Samples prepared at 8% achieved strength values that were above the limit and obtained a maximum strength of 0.79, 1.67 and 2.66 MPa for 7, 28 and 56 days respectively. The samples prepared at 10% binder content achieved strength values that were almost twice the minimum strength limit. The strength development curves for FPT shows linear patterns from 7 to 56 days. Flattening of the curve will only occur at a much later stage after 56 days curing period.

The results obtained for both CCT and FPT show a similar trend of a straight line which shows that the UCS of backfill samples increase with time. CCT mix-design achieved relatively higher UCS values than FPT. When the transportation and processing loss is accounted for, the suitable binder content for CCT was estimated to be 8% since it gives slightly higher UCS values at 7 and 28 days. At 56 days it gives slightly lower UCS values than the minimum limit. The optimum binder content for FPT would be 10% since the UCS is above the minimum limit at all curing periods.

5.7 C:W Ratio RD Study

The purpose of the mix design study was to determine the optimum binder content that would yield the required backfill strength. The cement to water ratio measurements was made to determine the mix design of the binder at every relative density. Table 5-5 shows the mix design parameters and the measurement made to make binder slurry mixes. The original mix in the binder mixing tank is in the ratio of 2:1 but due to flushing water that is still accumulated on the pipes and other related losses, the final binder relative density drops during pipe transportation. After conducting the study, it was identified that a minimum binder relative density of 1.7 had good flow properties. A minimum of 30% of the original solids is lost in the process.

Table 5-5: Binder slurry mix-design

C:W	Mass of Cement (kg)	Mass of Water (kg)	RD (kg/L)
1.00	1.6	1.6	1.5
1.10	1.6	1.45	1.55
1.20	1.6	1.33	1.57
1.30	1.6	1.23	1.62
1.40	1.6	1.14	1.65
1.50	1.6	1.07	1.675
1.60	1.6	1	1.7
1.80	1.6	0.89	1.76
2.00	1.6	0.8	1.845

5.8 The Effect of Binder Orifice Size on the Flow Rate and UCS

The actual flow rate of the binder and tailings mixing in the distribution tanks was not measured. This was due to the absence of flow meters to measure the rate at which both tailings and binder are poured into the tundish. A bucket test was used to measure the number of seconds it takes to fill up a 10-litre bucket with the binder. The longer it takes to fill the bucket, the lower the binder flow rate. Based on the current procedures and design specifications from the backfill plant, the minimum binder flow rate that provides the required volume of binder to mix with the tailings is 1 l/s. This means that the 10-litre bucket must be filled with a binder within 10 seconds. During the binder flow rate tests, it was identified that the flow rate of the binder was inconsistent. The previous results of bucket tests were reviewed to determine the inconsistencies in the binder flow rate for both CCT and FPT.

The effect of binder orifice size on the flow rate and strength was further investigated and a study was conducted to determine this effect. The binder orifice size on both CCT and FPT was altered for certain periods to determine the effect of increasing or decreasing the binder orifice at each plant. The flow rates were measured and backfill samples were collected to determine the strength obtained for each orifice size. The results obtained for all orifice sizes were compiled and the average flow rate for each size was calculated and the relationship between the two variables was represented in the form of graphs.

The results obtained at the CCT plant for flow rate measurements at different binder orifice sizes are represented in Figure 5-13. The CCT binder flow rate increased with increasing binder orifice size. The orifice sizes that obtained flow rates above the minimum flow rate limit was 30 and 35 mm with 1.22 and 1.85 l/s respectively.

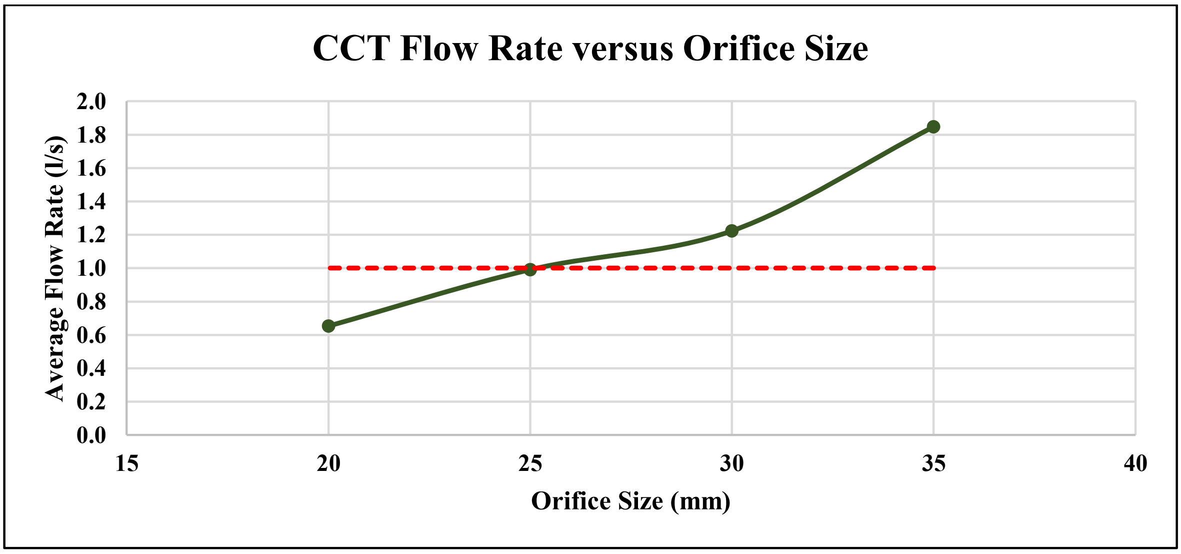

Figure 5-13: The change in flow rate with increasing binder orifice size at CCT plant

The results obtained for CCT UCS at varying binder orifice sizes are represented in Figure 5-14. The graphs show that the backfill samples only passed the UCS test at binder orifice sizes of 25, 30 and 35 mm for both 7 and 28 curing periods. The trend of the graphs for both 7 and 28 days is similar and it shows an increase in strength from 20 to 25 mm orifice size. The strength then decreased from 25 to 30 mm to a UCS of 1.36 MPa and increased at 35 mm to a maximum strength of 2.16 MPa for 7 days. The UCS values achieved at 25 and 35 mm were thrice the minimum strength limit for 7 and 28 days curing period while at 30 mm the UCS was twice the minimum strength limit.

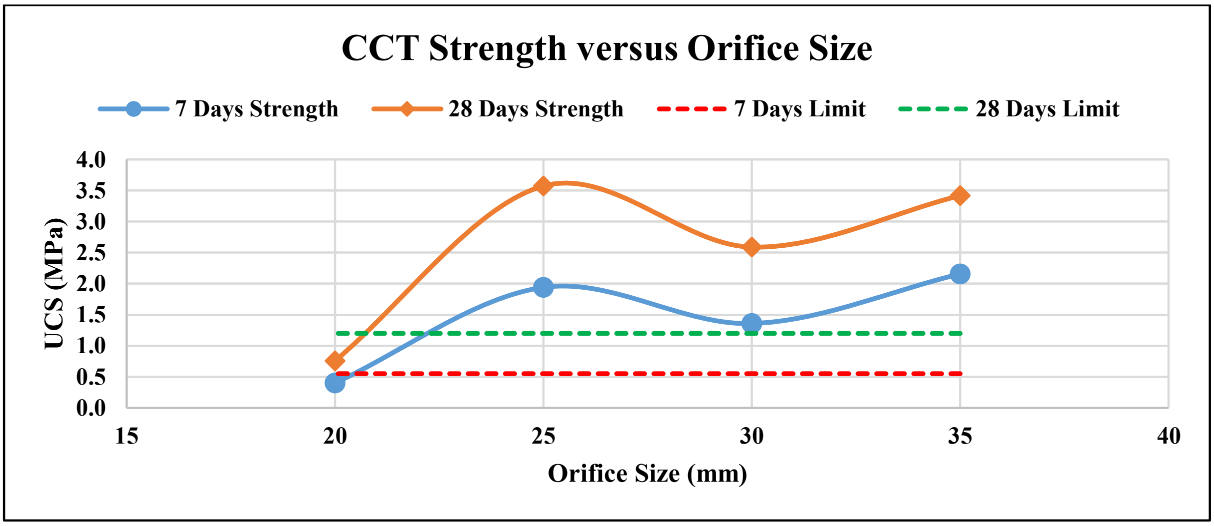

Figure 5-14: The change in CCT UCS with increasing binder orifice size

The binder orifice size and flow rate study was conducted at the FPT plant. The binder orifice sizes which were studied at the FPT plant were 20 and 45 mm. The results obtained from the flow rate measurements at these binder orifice sizes are represented in Figure 5-15. There is an increase in flow rate with increasing orifice size. The orifice sizes that would achieve flow rates above the required flow rate limit are 25 mm diameter and above. The maximum flow rate measured at a binder orifice size of 45 mm was 2.32 l/s while at 20 mm was 0.89 l/s. The flow rate measured at 45 mm achieved twice the minimum flow rate limit.

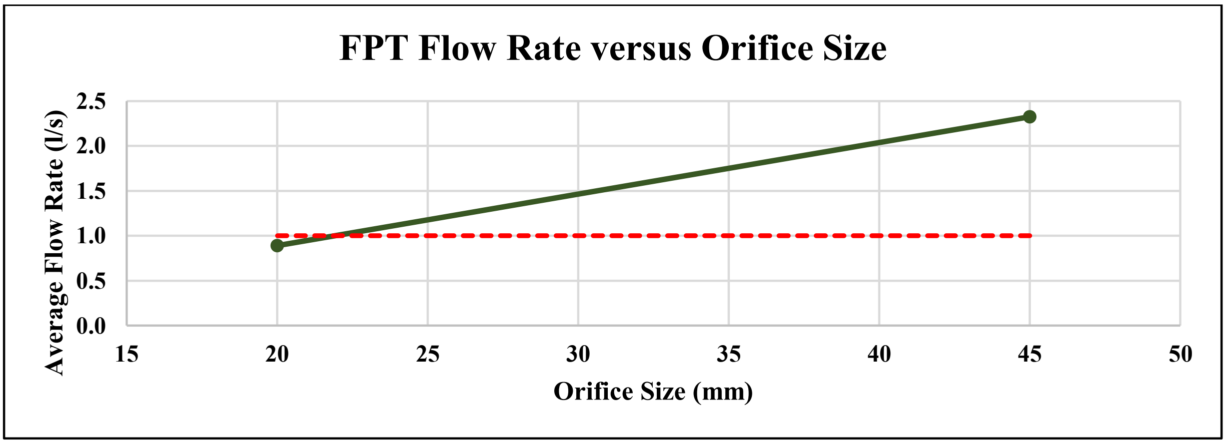

Figure 5-15: The change in the binder flow rate with increasing binder orifice size

The backfill strength results obtained at varying orifice sizes at the FPT plant are represented in Figure 5-16. The graphs indicate that the UCS of FPT samples increased with increasing binder orifice size. The FPT samples only obtained UCS values that were above the minimum limit at a binder orifice size of 45mm. The FPT samples at 20 mm obtained relatively low UCS values and were below the minimum limits.

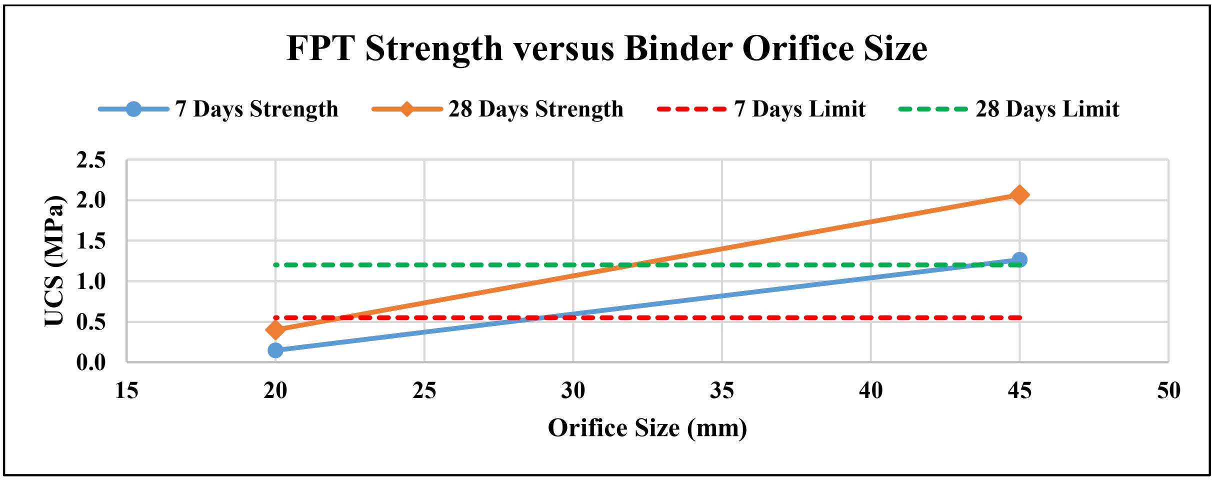

Figure 5-16: The change in FPT UCS with an increase in binder orifice size

The change in the binder orifice size affects the binder flow rate. The inconsistency in the binder orifice causes an inconsistent flow rate which yields inconsistent backfill strength results. An increase in the binder orifice size increases the flow rate and increases the UCS of backfill samples. The optimum orifice size for both CCT and FPT must be determined to allow enough volume of binder to mix with tailings. The optimum orifice size must also account for binder build-up that would reduce the size of the orifice and lead to reduced flow rates over time. A bigger orifice size can yield higher UCS values than required and also increase binder consumption. From the results obtained for CCT, a binder orifice of 30 mm would be suitable for the CCT plant. An optimum orifice of 35 mm would be suitable for the FPT plant.

5.9 U/G versus Surface Samples

This study aimed to determine the correlation between underground and surface backfill performance. This correlation assisted in determining the actual strength of the backfill placed underground which would help the mine design a backfill product that will yield the strength required by the underground voids.

The results for the CCT sample obtained from the surface plant and underground are represented in Figure 5-17. The results show that for Batch 1, both groups obtained almost similar UCS values which were also above the minimum strength limit. The underground samples achieved relatively lower UCS than surface samples for Batch 1, 2 and 3. Batch 1 and 2 of surface samples passed the UCS tests for 7 days curing period while only Batch 1 of underground samples passed. Batch 3 samples obtained lower UCS values for both surface and underground while for Batch 4 the underground samples passed the test with a UCS value of 0.554 MPa.

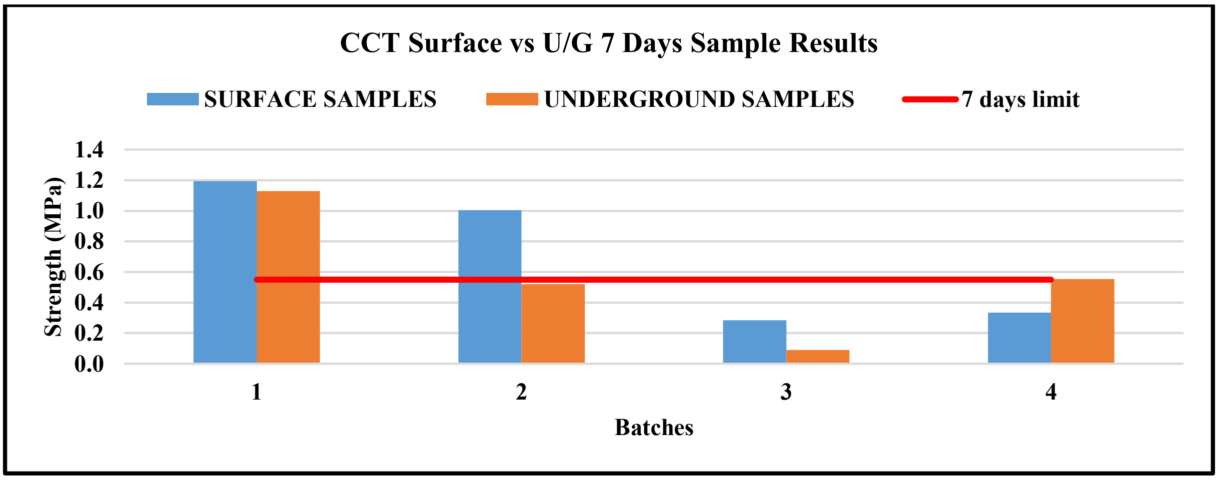

Figure 5-17: The 7 days UCS results for surface plant and underground CCT samples

The results for FPT samples obtained from the surface plant and underground are represented in Figure 5-18. The UCS for underground samples at Batch 1 and 3 is relatively higher than surface samples and they achieved strengths above the minimum limit. The surfaces samples achieved relatively higher UCS values than underground samples at Batch 2, 4 and 5. Surface samples passed the strength test at Batch 1, 3 and 4.

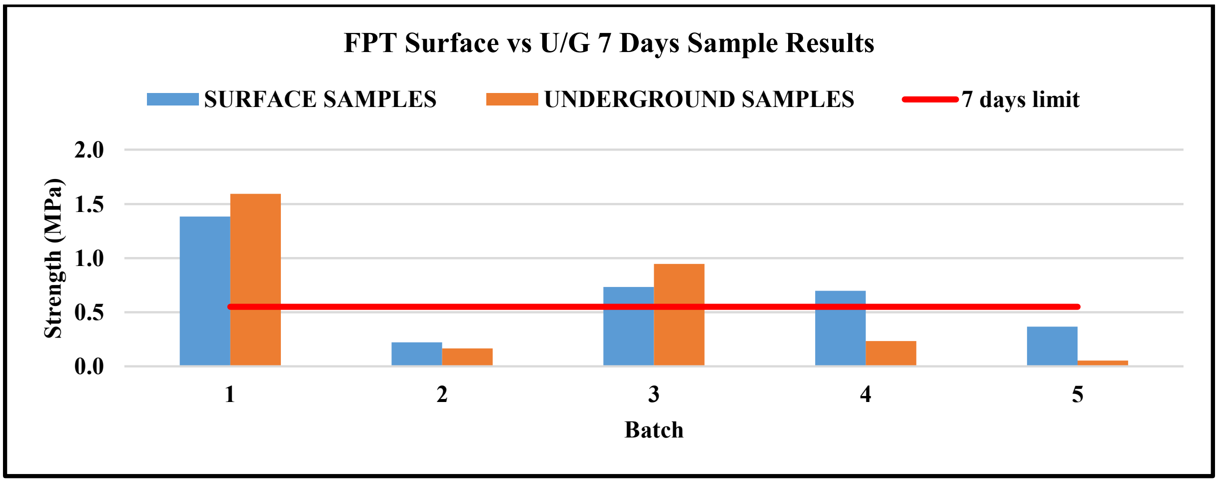

Figure 5-18: The 7 days UCS results for surface plant and underground FPT samples

The average UCS change between the surface and underground CCT samples is 0.24 MPa while for FPT is 0.25 MPa. The difference in curing conditions for both underground and surface also contribute to the varying UCS values. The losses experienced by the backfill product transported from the surface to underground stopes also contribute to the difference in UCS achieved by the backfill samples. Since the underground samples were placed next to the long-hole stopes, the curing conditions might not be accurate to the conditions inside the stope. Backfill coring should be adapted to give more accurate results of the placed backfill underground.

5.10 Chapter Summary

The curing room environmental conditions played a huge role in the process of strength development of the backfill material. Both CCT and FPT were affected by the change in curing temperature and elevation. The curing room conditions were not consistent around the room since the position of the heaters were scattered. The fan blowing heat from the top of the room was facing one direction and other positions on the shelves did not receive enough heat. At temperatures above 34 ºC and elevations above Level 1, the backfill samples obtained higher strength values than at lower temperature positions. The inconsistencies of the environmental conditions around the curing room caused the variability of backfill strength achieved during the UCS tests.

The process of mixing the binder with tailings was erratic since both tailings and binder were concurrently mixed and transferred underground. The change in the binder orifice size caused a great change in the strength values achieved during the UCS test. This study also assisted in choosing an optimum orifice size that would yield the required backfill strength. The binder orifice size also affected the flow rate of the binder mixing with the tailings. The optimum orifice size for CCT material was 30 mm with flow rates above 1.2 l/s and UCS of 1.36 MPa for 7 days and 2.59 MPa for 28 days curing period. The optimum orifice size for FPT material was 40 mm and achieved strength values of 1 MPa in 7 days and 1.7 MPa in 28 days of curing.

The mix design of the binder slurry was also studied to determine the optimum mix ratio which would provide the required flow properties and provide maximum strength to the backfill material. The optimum c:w ratio determined was 1.6:1 and gave a relative density of 1.7. The correlation between underground and surface backfill samples was studied to help design an optimal backfill product. The results obtained from the underground samples were compared with surface sample results and the average change in strength for CCT was 0.24 MPa and 0.25 MPa for FPT. The correlation between the two results shows that the strength of the material placed underground was lower than the samples collected on the surface.

The factors causing backfill strength variability were identified and investigated. The impact of these factors on the backfill strength was also determined. Based on the limitations of the research, there might be other factors that cause variability of backfill strength at the mine. The direct impact of operator efficiency, day/ night shift on the strength of backfill was negligible.

6 PRACTICAL SOLUTIONS TO MAINTAIN CONSISTENCY OF BACKFILL QUALITY

6.1 Introduction

Factors causing variability of backfill strength tests results were identified and their impact on the strength of backfill was also determined. The variation of strength results was caused by inconsistencies in the preparation process, mixing and curing which affected the quality of the backfill product. The current factors identified were studied further and practical solutions were developed to help manage or eliminate the factors causing variability of the backfill quality. The current backfill quality control procedures were reviewed and were found to be ineffective in monitoring backfill quality at all stages. The turnaround time to implement corrective measures was very long (week) and reporting of real-time quality parameters was not well communicated. The standard procedure for quality control in certain processes was not clear and this cause inconsistency in the code of practice. Quality control and quality monitoring are very important in a mine backfill system and help limit the occurrence of inconsistencies in the quality of backfill produced by the plant.

Inconsistent backfill quality within a backfill system can be detected through sampling at different points within the backfill plant. Large variations of parameters such as the relative density (RD), particle size distribution (PSD) and the uniaxial compressive strength (UCS) of the backfill material is a great concern in the backfill operation. The variation in the PSD of the backfill material with some of the material having a high amount of ultrafine poses a concern to the drainage, shrinkage and strength development of backfill (Killassy, et al., 2011).

6.2 Model to Develop Practical Solutions and Maintain Consistent of Backfill Quality

Identifying operational constraints in the backfill system helps create practical solutions to the current problems and maintain a consistent backfill quality. It is very important to account for the current logistical constraints when developing a solution to the current backfill problems. The solutions developed were designed in such a way that they are sustainable and practical to the current backfill system. As a process of developing practical solutions to help maintain consistency, a model was designed. The design of the model to maintain consistency of the backfill quality involves solving the current backfill problems, monitoring the backfill preparation process and establishing a quality control procedure. The model designed to develop solutions to the current problems and maintain backfill quality consistency is presented in Figure 6-1.

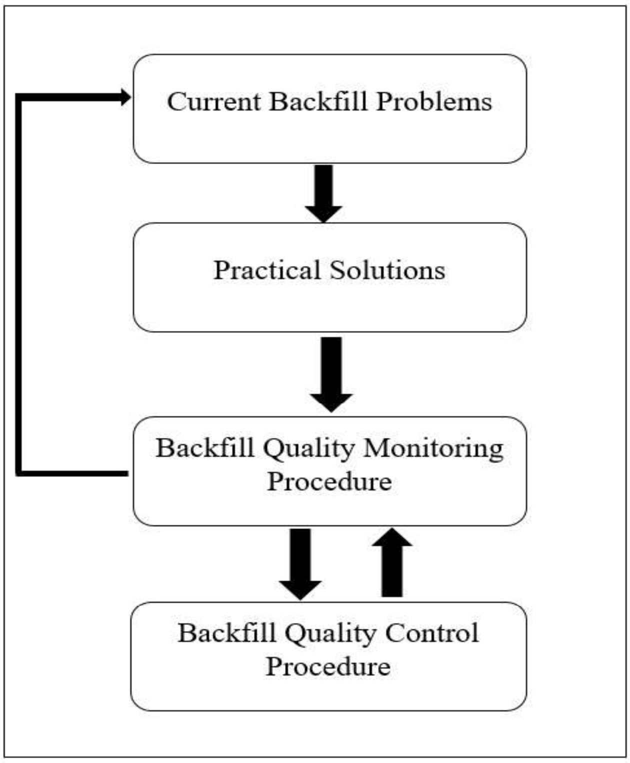

Figure 6-1: Strategy to maintain consistent backfill quality

Based on the current factors, the model was designed to highlight the weakest link in the backfill quality control process. This will help monitor quality at all stages and ensure that consistency is maintained within the system. It was identified that the quality monitoring procedure is the weakest link in the process. The backfill system must establish a strong quality monitoring procedure to ensure that identified problems can be corrected earlier in the process. An effective backfill quality control procedure must be developed to ensure that consistent quality is produced and the performance of backfill is improved.

The production process of the backfill must be regularly monitored to ensure that the desired backfill quality is produced and meets the strength requirements of the stopes. These would also allow the mine to optimise the backfill system such that maximum backfill strength is achieved at a possibly low binder content. Backfill quality control and monitoring are essential in every backfill operation. These methods also assist in maintaining consistent backfill quality.

6.3 Practical Solutions to the Current Backfill Problems

The factors causing variability of strength were studied and practical solutions were developed to help maintain a consistent backfill quality. The solutions developed for each factor was designed such that it is sustainable and cost-effective. The current backfill technologies applied in the mining industry, recent backfill methods and equipment used were taken into consideration when developing solutions for the studied backfill operation. An optimum backfill system must contribute to achieving maximum value for the mine and be of low cost per backfill tonne placed. The overall backfill design and optimisation process were also considered in the process.

6.3.1 Backfill quality during preparation

The preparation of tailings in the backfill plant involves thickening and classifying tailings to the required PSD and RD. The backfill plant must establish a narrow bracket for the RD and PSD of tailings produced at the plant to maintain consistent backfill quality. Since the mine uses cemented hydraulic fill (CHF), the tailings are mixed with a cementitious binder before they are transferred underground. The relative density of the tailings and the binder must meet the required limits before they are mixed. The tailings are transported by pipes over long distances which may affect the solid content of the backfill product at the discharge point. The relative density of the tailings at the mixing station must be measured to ensure that the material is still within the required RD bracket.

There are instant RD and PSD measuring devices available in the industry market which allows operators to measure backfill properties before they are transferred to the next process location. This technology allows operators to reject backfill material if the material is of poor quality. This helps the plant managers to make the necessary amendments or changes earlier in the process which could improve the quality of backfill material sent underground. The RD and PSD reading must be taken several times in a shift both manually and automatically using SCADA readings. The Mine Health and Safety Council (MHSC) recommends backfill operations to measure RD of the backfill material every hour (Malan, et al., 2007). It is beneficial for the plant to have RD and PSD charts for every shift to monitor changes and equipment efficiency at the plant. Statistical analyses of the values obtained from the reading must be done to monitor any variations.

Recent technologies like the Rhosonics slurry density meter (SDM) and Alia SDM have drawn attention to many mine backfill operations. The SDM instrument uses non-intrusive ultrasonic sensors to measure the real-time density of mineral slurries. The SDM has been applied in slurries with higher density levels with large pipe diameters. These instruments help backfill operators to control pump velocities, recirculate the backfill slurry when the relative density is below the required value and has an accuracy of 0.005 RD within 0.5% of a full scale. An example of an SDM is presented in Figure 6-2.

Figure 6-2: Rhosonics slurry density meter (SDM) (Rhosonics, 2020)

This technology can help monitor the backfill quality around the plant by measuring the consistency of the tailings and binder RD. Its ability to detect higher backfill slurry densities can prevent clogging of the pipes (Mining Technology, 2018).

6.3.2 Binder flow rates and orifice size

The addition of a binder to the gold tailings changes the resultant mixture to be a more viscous material (Baguley, 1988). The binder slurry is prepared at the desired cement to water ratio (c:w) which produces a specific relative density and flow rate. It has been determined that the binder orifice size affects the flow rate and the volume of binder mixing with the tailings. The binder slurry must be prepared at the required c:w ratio which provides good flow properties. The relationship between the relative density of the binder and the c:w ratio was established to determine the amount of dry binder which was used at every batch.

A bracket for binder RD reading must be established at the plant to ensure that the right amount of binder solids mix with the tailings. The tailings and binder slurry are mixed concurrently at different flow rates. This process occurs at the CCT and FPT plants. The backfill product is transferred underground at the same time while the binder and tailings are added to the mixing tank. The relative density and flow rate of both tailings and the binder must be measured at the mixing station. There are flow meters in the backfill industry that could be installed at the mixing station to measure the flow rate for both binder and tailings. The readings could be used to establish optimum flow rates for both components. The relationship between the RD and the flow rate of each component must be studied to further optimise the mixing process.

Operational constraints in the mixing process can be addressed by introducing an automated system. This includes installing measuring devices such as relative density, flow rate, samplers and continuous mixers which can be operated remotely in a control room. These can assist in maintaining constant values of the RD and flow rate at the mixing station. The production of consistent backfill mixes that yield consistent strength can be achieved through automated systems. Figure 6-3 shows the slurry flow meter and density meter installed on one pipe. Many mining operations use ultrasonic flow meters that can measure flow rates up to 110 litres per second. The non-invasive ultrasonic flow meters are also available in the market and can be installed outside the thick pipes (Flexim, 2019).

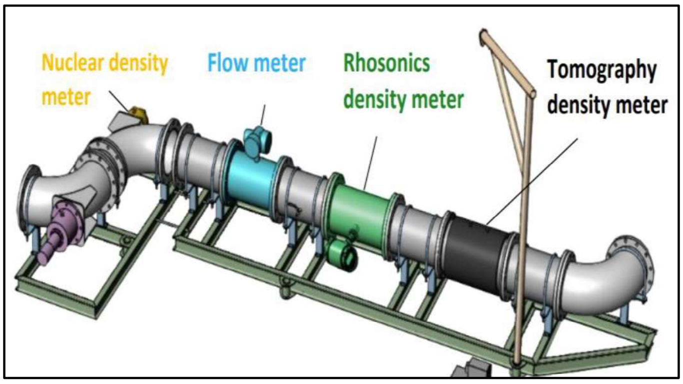

Figure 6-3: Flow rate and density measuring instruments on a pipe (Rhosonics, 2020)

These devices can be used to maintain a consistent flow rate and density of the tailings and binder at the mixing station. As part of the quality control and monitoring, these devices must be inspected regularly (every shift) and calibrated to ensure accurate readings are provided. To determine the impact of a consistent binder flow rate on binder usage, the flow rate versus binder usage must be recorded and analyzed regularly. This information can be presented in weekly backfill quality meetings. This information can be used to optimise binder usage using the flow rates and RD of binder produced.

6.3.3 Curing environment conditions

The curing room atmospheric conditions affect the strength of backfill obtained after a certain period. It has been identified that the atmospheric conditions in the curing room were not consistent and this caused a variation in the strength of backfill obtained during UCS testing. Inconsistent curing conditions yielded inconsistent backfill strength and this factor was also proved by the literature. At higher temperatures, the backfill material yields higher strength that is relatively lower temperatures. The temperature and humidity in the curing room were not monitored and this affected the UCS results obtained from the laboratory. To maintain constant curing conditions in the curing room, quality control and quality monitoring procedures must be enhanced in the backfill plant.

The curing room must be designed such that the temperature and humidity are kept constant or within narrow limits. An air circulation device must be installed such that it equally distributes heat to all samples stored in the curing room. The heating system in the curing room must ensure that samples placed at different elevations are cured at the same temperature and humidity level. There are different heating or curing systems used in the concrete industry which were adopted by backfill operations. The curing room atmospheric conditions are set at a certain temperature and humidity level simulating the conditions underground. To maintain constant curing conditions, the following methods were developed for curing backfill in the laboratory and underground.

6.3.3.1 Curing backfill in the laboratory

Curing backfill samples from the backfill plant involves storing the backfill samples in the moist room where the temperature and humidity are kept constant. The process of curing is important in the fact that it affects the development of strength of the backfill material during that period. The impact of an inconsistent backfill curing environment on the backfill strength have been stated. This problem could be solved by designing a curing room that could provide constant temperatures and humidity to the backfill samples throughout the curing period.

The curing conditions in the surface moist room must match the underground curing conditions. The underground conditions are not stable and this allows the plant to establish a temperature and humidity level bracket acceptable to cure backfill samples. The bracket must be narrow such that consistent curing is provided to the backfill samples. The ASTM standards for curing concrete are used to design backfill curing systems in the mining industry and some of the guidelines on the curing environment required to involve:

- Construct a moist room with durable walls that allow minimum heat or cold transfer from the outside environment. Insulation of the walls must be able to minimise the impact of any change of temperature or humidity in the surrounding area. The atmospheric conditions must be kept constant within the room.

- A heating system installed must provide consistent temperature and humidity in the room. Heaters, humidifiers and air conditioners may be used to heat up or add moisture to the room.

- The use of thermostats to control the temperature within the room in case conditioning is not available is also acceptable. Hydraulic thermostats and electronic digital temperature control system devices can be used to monitor temperature and humidity in the curing room.

- Sensors must be installed to measure the temperature in the curing room and the reading can be displayed remotely. This allows the operator to adjust the temperature if the readings are higher or lower than the required temperature. The sensor for detecting moisture in the room can be installed to monitor changes in the moisture content.

A moist room that can provide consistent atmospheric conditions is important such that it allows consistent curing of the backfill samples. This provides the backfill to cure and yield consistent strength values.

6.3.3.2 Curing backfill underground

Atmospheric conditions underground and the curing of backfill in the stope are inconsistent. The temperature and humidity in the stope must be recorded to determine the impact of the atmospheric conditions underground on the backfill strength achieved. Temperature and humidity readings must be taken and compared to the surface moist room readings. These readings could be used to monitor the backfill strength obtained at different curing temperatures and humidity. The change in atmospheric conditions at the stopes must be monitored and if possible, the ventilation underground or at the stope must be optimised such that it provides constant air temperatures. The impact of other heat sources on the curing temperature must also be accounted for when optimising the ventilation at the stope.

Although maintaining consistency of atmospheric conditions underground may be a challenge, consistent curing conditions do provide consistent strength properties to the backfill material. This could assist in improving backfill performance underground and maintaining stope stability.

6.3.4 Sampling and testing backfill placed underground

Sampling backfill is normally conducted on the surface, at the backfill plant. Sampling backfill underground is erratic due to the lack of access to the backfilled stope or harsh atmospheric conditions. The quality of backfill placed underground is not effectively monitored. Quality control and monitoring procedures underground must be emphasized to ensure successful performance of backfill is achieved underground. Although sampling and testing of backfill geomechanical properties are conducted on the surface, these do not represent the quality underground. Sampling and testing of backfill quality must be conducted underground.

Parameters such as RD, permeability, PSD and water content must be determined from the backfill slurry placed underground. The results must be recorded and analysed using statistical analyses methods. Underground backfill quality results must be compared with the ones on the surface to determine the change in the quality. This will help optimize the preparation of backfill on the surface and optimize the use of binder at the plant.

The stress conditions in the backfill stope can be determined using devices such as total pressure cells, Goodman Jack tool, ANZI strain cells and the linear variable differential transformer (LVDT) cell. These devices were used to measure rock stresses underground and they have now been adopted in the backfill industry. In-situ backfill stress and closure can be measured in the backfill stope. The data recorded by these devices can be used to determine the behaviour of backfill in different stoping areas. The results obtained from these devices must be compared with the results of the laboratory tests. The variation of the results must be determined and the results must also be analysed using the statistical analyses method.

The core drilling method was found to be most practical and effective but the lack of access to the filled stopes was the main disadvantage for deep-level mines. Sampling backfill slurry from the filled stope is one method that is used although is quite difficult to conduct. Backfilling one stope in deep-level mines can take up to a month. The strength of backfill poured over the period cannot be determined from one sample or a group of samples taken during that period. To determine the overall performance of backfill within the stope is quite difficult but a simulation could be used to model the backfilled stope.

A method was developed to help determine the overall strength of backfill placed in one stope after a certain period of filling. The method involves using a simulation stope (slab) which is filled over a month and cured next to the stope underground. The simulation would be tested for strength after 7, 28, 56 and 72 days of curing. The methodology which can be followed to conduct this simulation for underground backfill placement involves:

- A square-shaped container of a minimum volume of 2 cubic meters, with small holes to allow fill drainage and geotextile bags can be used as barricades;
- A simulated stope and the lines transferring to the stopes must be determined. The container must be placed in the moist room to allow curing to occur while the filling is conducted;

- At each transfer during each shift, the batch transferred to the stope must be sampled and cast into the simulator container. This must be done at each shift and the sample must be stored in the curing room and covered to allow enough moisture in the sample;
- When the filling has been completed at the stope, the sample can be left to cure and UCS testing can be done at 7, 28, 56 and 72 days. This will help determine short and long term strength of the backfill material;
- Samples from the backfill slab can be collected by coring the slab at four to six different areas on the backfill slab;
- The average UCS obtained from all samples can be used as the actual strength achieved. Other mechanical properties such as shear strength, drainage, shrinkage, failure mode and permeability can also be studied from the simulation.

When sampling or drilling the cores on the backfill slab, strict sampling standards must be followed to ensure that the samples collected are representative of the entire backfill slab. This method can be used to determine the actual behaviour of backfill placed underground and also determine the impact of inconsistencies in the backfill quality on the overall stope stability. Parameters such as the water content, permeability and percolation rate can be determined from the simulation. The impact of other variables can be studied by using this method to determine their impact on the strength of backfill underground. Although the environmental conditions are not the same as the ones in the curing room, the correlation factor can be used to determine the actual strength of backfill underground.

6.4 Backfill quality monitoring in the mine

Backfill quality monitoring is often underemphasized but it is very critical when running a backfill operation. To obtain a constant, high-quality backfill material, quality monitoring measures must be implemented. The most important parameters which should be strictly monitored in a hydraulic backfill operation are:

- Tailings relative density and particle size distribution (PSD)
- Binder relative density and c:w ratio
- Binder and tailings flow rates
- Curing temperature and humidity

These parameters affect the performance of backfill underground and must be monitored regularly. Sampling, curing and testing procedures must be assessed regularly to ensure the samples collected are representative and the results obtained are accurate. Regular inspections of devices installed in the backfill system must be conducted and calibrated. Quality monitoring of backfill underground involves the inspection of the installation of barricades and the filling process. The quality of the geotextiles, wire mesh and poles must also be monitored (Malan, et al., 2007). Sampling and testing of the wet backfill collected from the stopes must be conducted and the results obtained must be recorded.

6.5 Backfill quality control at the mine

To run a successful backfill operation that produces maximum quality backfill material requires the involvement of almost all technical departments in the mine. The rock engineering, backfill plant, metallurgical plant, underground placement and engineering, geology, surveying, mining etc., must be involved in the running of backfill in the mine. Quality standards and performances must be communicated to keep each department updated on the day-to-day running of backfill operation (Killassy, et al., 2011). To maintain consistency of the backfill quality produced at the plant and underground, the following control measures can be adopted:

6.5.1 Backfill Quality Control Team (BQCT)

Communication is key in quality control and monitoring because it allows information to be shared regularly and keeps relevant personnel updated on the current backfill quality performance. Effective communication allows the implementation of corrective measures to be conducted relatively earlier, improves the backfill quality produced and saves costs for the mine. In most backfill operations, there are no dedicated backfill quality control teams and the level of communication in terms of quality standards and backfill performance is poor. Backfill forms part of the mine design process and more attention should be given to its performance and quality control procedures. Communication between relevant departments regarding backfill quality and performance should be communicated regularly.

The backfill quality assessments and inspection must be done by a dedicated team that will be able to identify problems and apply corrective measures earlier in the backfill production process. The backfill quality control team (BQCT) must consist of representatives from all relevant departments including Rock Engineering, Metallurgy, Backfill Production, Underground Placement, Mining, Geology, Ventilation, Finance etc.

The team must carry out backfill quality control duties of backfill both on the surface and underground. The following responsibilities must be carried out:

- Be involved in daily backfill production processes including assessment and inspection of the backfill plant and underground placement;
- Conduct necessary sampling and testing of the backfill material such as tailings RD, PSD, cyanide content, permeability and strength;
- Monitor the backfill preparation, mixing and curing processes on the plant and underground.
- The binder preparation process and usage must be monitored and the information must be recorded and presented to relevant departments;
- Compile backfill quality reports and present them to relevant committees weekly.
- Compare backfill quality reports of backfill quality prepared on surface and underground. Use the report to optimise the current backfill system.

The responsibilities of a BQCT may not be limited to the above-mentioned and must be clearly defined. Having a dedicated BQCT eases the load on the backfill plant operators and supervisors so that they could focus on running the plant and their operational responsibilities. BQCT will ensure that backfill produced is of the required quality, placed accordingly, efficiently and effectively supports underground workings. The team must ensure that a consistent backfill quality is maintained both at the preparation plant and underground. These will also help reduce binder costs for the mine at higher backfill strength performances. The communication between various departments regarding backfill quality will be effective and made easier.

6.6 Chapter Summary

The introduction of mechanisation and automation in the mining industry has made it possible for mining operations to reduce mining-related accidents and improve employee safety in the mines. Regardless of other socio-economic factors involved in the introduction of mechanisation and automation systems, the benefits provide massive improvements in productivity, safety and reduced cost for mine operations. The backfill preparation processes affect the quality of the backfill material. To maintain a constant backfill quality in the plant, backfill operations must introduce systems that will enable them to monitor quality in real-time, remotely and within a short period.

Implementing these systems reduce the amount of work required to manually measure parameters around the plant, improves the accuracy of readings and improves worker safety and productivity. The recent backfill quality testing devices used in the backfill industry have shown massive improvements in quality control of backfill. The real-time measurements of backfill quality parameters allow the plant to improve the backfill material to a better quality once the poor quality measurements are detected. This also helps improve the consistency of backfill quality and thus the strength obtained after curing (Killassy, et al., 2011).

7 CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

The main function of backfill in underground mines is to assist in managing the stability of mining-related voids. Backfill is one of the tools that are used to increase the flexibility of ore extraction strategies and allows for improved ore recovery. The adoption of bulk mining methods in narrow tabular mines increased the use of cemented fill due to higher stresses in the mining voids. The nature and properties of backfill have become more important in that backfill has become an important structure that affects the mining cycle and the mine design. It is now very important to have a greater understanding of the material properties of each component of the backfill that is used to produce a backfill material that is placed underground as a form of support. This understanding is required to ensure reliable and consistent backfill performance, optimise backfill costs and improve backfill quality.

Inconsistency of backfill strength results can be caused by several factors which range from preparation to testing. Identifying factors causing the variability of backfill strength results can help maintain the consistency of the strength results. The review and analyses of the previous backfill strength data helped in determining the relationship between the strength results and the material properties measured during sampling. Some of the factors which were suspected to cause variability are operator efficiency, day/ night shift and the number of batches. These factors were investigated and the results showed negligible or no relationship with the backfill strength results. The assessments conducted on the preparation, mixing, sampling, curing and testing processes provide enough understanding of the backfill quality and its properties.

The factors which were identified to cause variability of backfill strength results are in the mixing and curing processes. These factors showed a significant impact on the strength of backfill as compared to other factors which were investigated. The plant can prepare CCT and FPT tailings to the required RD and PSD. The binder can also be mixed to the required mix ratio but the ratio of tailings to the binder that is mixed in the tanks cannot be measured. The inconsistency in the amount of binder mixing with the tailings can lead to samples achieving inconsistent strength results. Since the mine does not produce batches of the mixed product, determining the amount of binder in every sample collected is difficult. The change in the binder orifice size affects the volume of binder mixing with the tailings. The results showed that the wider the orifice size, the higher the flow rate and the higher the backfill strength. The optimum binder orifice size must be determined to allow enough binder to mix with the tailings and achieve the required backfill strength. The orifice must also be maintained regularly to prevent binder accumulation on the orifice walls which will decrease the volume of binder flowing through.

The benchmark study was conducted to determine the strength which can be achieved if the contents are mixed in one container and tested. These results were used as a baseline for the samples collected from the backfill plant pipelines. This study also assisted in determining other factors which cause variability of backfill strength results and determining the optimum binder content when the curing conditions are kept constant. Although the mix-design does not represent the reality, the results obtained showed that the impact of factors such as curing environment on the samples prepared to the required mix-design. The backfill mix-design for the tailings and binder can be used to determine the optimum content of each backfill component and reduce the binder costs. The correlation between the design and actual backfill plant samples was determined.

The binder slurry mix design was studied to determine the optimum relative density of the binder slurry and the losses which occur during the transportation process. The optimum binder to water ratio which yielded the required flow properties and provided the required strength was determined from this study. The correlation between the strength values achieved from surface plant samples and underground samples was determined. This assisted the plant in determining the amount of loss from the surface to underground stopes that the backfill material experiences. These also can assist in optimising the mix design of tailing with a binder and other backfill properties.

The curing process affects the development of the strength of the backfill material. The environmental conditions in the curing room determine the strength that the backfill sample will yield after a certain curing period. The curing temperature, humidity and elevation from the floor were studied and they showed that they do contribute to the strength achieved by the backfill material. At higher temperatures, humidity and elevation, the backfill material achieves higher strength values. When the curing temperature and humidity is not uniform at all elevations and positions around the curing room, the backfill samples achieve different strength results. This also causes the variability of strength values for samples collected from the same batch, with similar material properties.

When the curing conditions are uniform for all samples, the strength results obtained will be similar or have minimal variance. Maintaining uniform curing room environmental conditions can assist the mine to maintain consistency and also reduce the amount of binder used. A curing room must be designed such that it provides constant atmospheric conditions to all samples. The curing room design must follow the standards provided by the ASTM. Recent devices such as remote sensors can be installed in the curing room and measure the temperature and humidity. Thermostats and humidifiers can also be controlled remotely in the curing room. Inspection of these devices is very important and must be done every shift to ensure accuracy.

Sampling backfill is an essential part of backfill quality control in the backfill operation. Sampling backfill underground is quite difficult due to the lack of access to the filled stope. The backfill slurry pumped underground travels longer distances and there is a loss of solid particles during the process. It is important to conduct a backfill quality test at the stopes to determine the change in the quality of the backfill. Parameters such as relative density, permeability, water content and strength must be determined from the backfill material pumped into the stopes. Stress measuring equipment can be used to measure in-situ stress of backfill underground. A simulation of the backfill stope can be used to determine the backfill strength after being filled for a certain number of days. This can assist in determining other properties of backfill and its behaviour when it is constantly being filled.

Backfill quality control and monitoring are essential in every backfill operation and assist in maintaining consistent backfill quality. A good quality control procedure and monitoring results in the successful performance of backfill underground. Backfill quality control and monitoring procedures are important in the running of a backfill operation and also affects the mining cycle. Quality control and monitoring within the backfill system have the following advantages:

- Ensures the set backfill quality standards are maintained;
- Reduces the cost by eliminating the need for using more binder and additives;
- Improves the strength of backfill placed underground and the overall mine stability;
- Improves backfill performance underground providing good hanging-wall contact and stability for the mine.

Backfill quality monitoring procedures must be strictly implemented in backfill operations to maintain consistency and improve performance. Backfill quality monitoring can help identify constraints and find sustainable and practical solutions for the backfill system.

The factors identified in this research were mostly operational factors and some were caused by the design constraint of the plant. Factors such as the dosing of cement/binder with tailings are caused by the design constraint of the plant. The absence of flow meters for both tailings and binder makes it difficult to determine the binder content in the backfill mix. The concurrent mixing and transfer of binder with the tailings in the mixing tank do not allow effective mixing to occur. The simulation of the mixing process showed that when the tank is below the 30% level, the backfill material has a higher binder content than when it is at levels above. This was because the binder slurry is pumped constantly while the tailings pump is stopped when the tank is full. The samples collected when the tank is full achieved low strength results while the samples collected when the tank is almost empty achieved higher strength values. This was the case at the FPT plant. At CCT, the samples collected included two to three full tundishes since they had less volume.

The performance of backfill is dependent on its material, placement and curing properties. For backfill to achieve successful performance, it must be prepared to the required material properties, placed correctly and cured in the right environmental conditions. The components of the backfill material prepared and the processes involved in the production of backfill contributes to the strength obtained after testing. Factors that were identified showed that the tailings and binder slurries are prepared to the required quality but the processes involved after preparation can compromise that quality. The study has shown that the mixing of the binder with tailings, sampling, curing and UCS testing processes contributes to the backfill strength results. Inconsistencies in these processes also cause variability of strength values achieved by the backfill material.

7.2 Recommendations

Consistent monitoring of backfill quality ensures that the required strength properties are obtained at set binder usage. A consistent backfill end product is vital since the paddock of backfill is as strong as its weakest link. Establishing backfill quality limits ensures that the backfill material has good placement properties and achieves the required strength. Introducing an automated system to the current backfill quality monitoring practice can assist in reporting real-time backfill properties at different points in the plant and underground. This also allows corrective measures to be implemented instantly during the backfill preparation process.

The mixing of tailings with binder requires effective agitation to blend the two components before it is sent underground. The production of backfill batches which involves the mixing of known volumes of tailings and binder would assist in determining the amount of binder used per batch and volume of backfill placed per stope. These would also assist in planning by preparing the required volume of tailings and binder for each stope and make a significant impact in saving binder cost for the mine. Maintaining consistency of the binder flow rate and orifice size at the mixing tank allows the required binder content to mix with the tailings. When the required binder content is added to the tailings, the backfill material can achieve the required strength provided curing conditions are kept constant. The new technology allows the flow rates and relative density to be adjusted remotely which also improve consistency.

The optimum orifice size must be determined for both CCT and FPT plants to allow enough binder to mix with tailings. Binder flow rate is of most importance since the binder promotes the strength of the backfill material. When the binder flow rate is low, the backfill material will become weak and will be unable to carry the load exerted on the hanging wall. Both the binder and tailings flow rates must be monitored to avoid over-dilution and overconsumption of the binder.

The curing conditions affect the development of backfill strength and temperature affects the rate of strength development in the early stages. Maintaining curing conditions provide constant curing of backfill material which allows strength development to be constant throughout the curing period. Monitoring the conditions in the curing room will also help identify changes that can be used to justify any variability on backfill quality reports. A new heating system must be designed according to the standards, must provide constant atmospheric conditions in the curing room for all samples and be monitored during each shift. The curing room must be inspected and monitored regularly. Devices measuring temperature and humidity must also be inspected and calibrated to ensure accurate readings.

Sampling and testing backfill quality underground is very important. The backfill quality testers used on the surface plant can also be used to monitor backfill quality at placement. Recent devices used to test in-situ rock stresses could be used in backfill stopes and the data must be compared to the result obtained from slurry samples collected during placement. This data could assist the mine in optimising the backfill system, improve backfill performance and reduce binder costs.

Backfill quality control in the mine is very critical in ensuring that the required backfill quality is produced constantly. The mine must emphasize the importance of backfill quality control procedures at every phase in the backfill production. Backfill quality tests must be conducted regularly both on the surface and underground to monitor variations of quality parameters from the required limits. A backfill quality control team is very important in ensuring successful backfill performance. The team will monitor backfill quality, analyse the current performances, communicate effectively with the relevant departments and implement corrective measures relatively earlier in the process.

The factors identified in this research are solely applicable to the studied backfill operation and there might be other factors contributing to the variation of backfill strength results that may be different from the ones listed in this research. Quality control and quality assurance procedures must be adopted at the backfill plant to ensure that backfill samples collected are representative, cured at constant temperatures and tested according to the proposed standard. This would allow the mine to produce consistent quality of backfill and achieve consistent strength results. Understanding the impact of these factors on the quality of backfill can help backfill operations to optimise the backfill and reduce binder costs.

Inconsistent backfill strength in the stope can compromise the safety of personnel working underground, compromise overall mine stability and affect productivity. Consistent backfill strength ensures effective and efficient stope support, achieves sustainable long-term strength of backfill underground, improved mine stability and safety of employees. Consistency of backfill quality test results improves the reliability and confidence of the backfill system operations.

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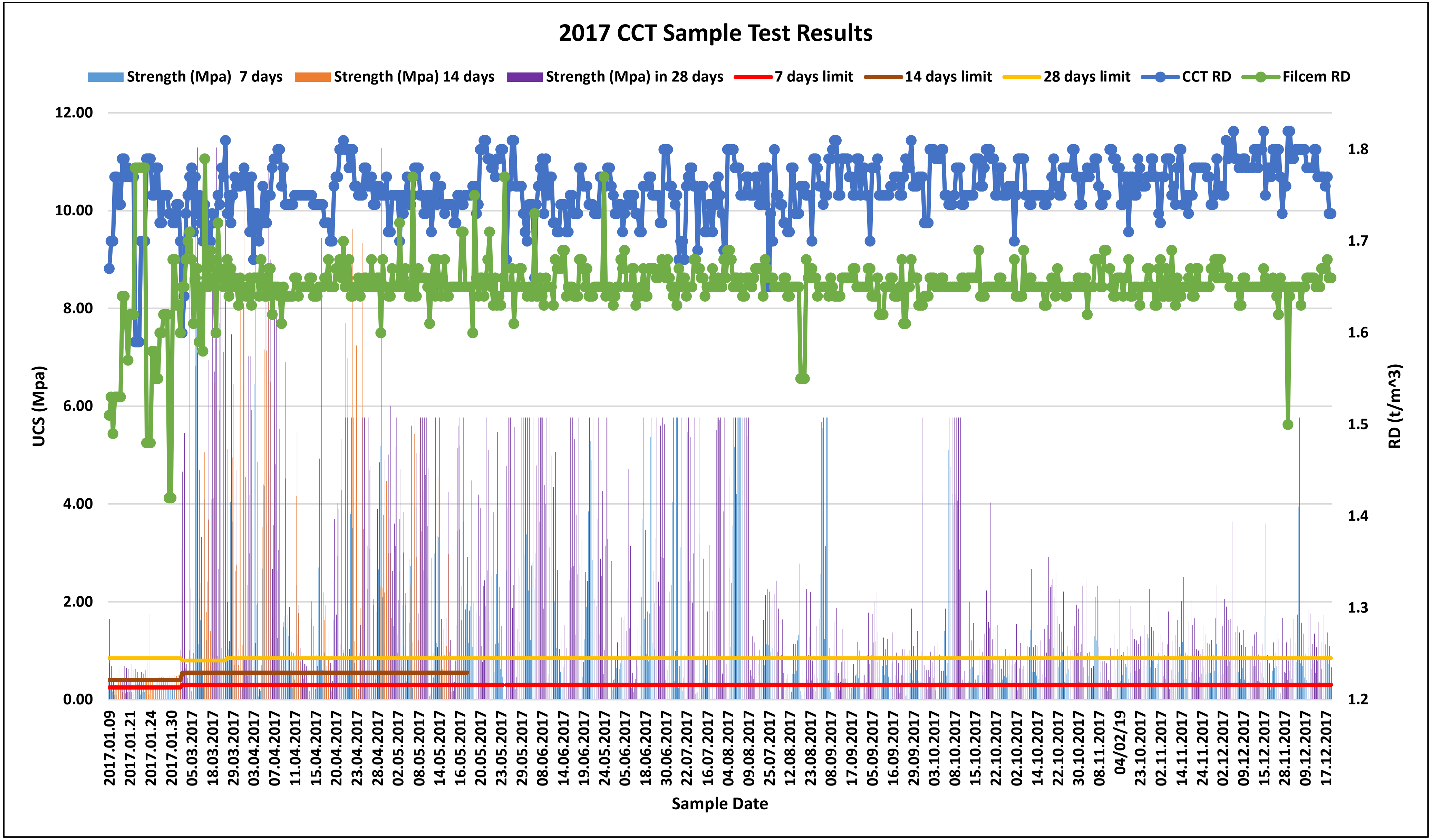
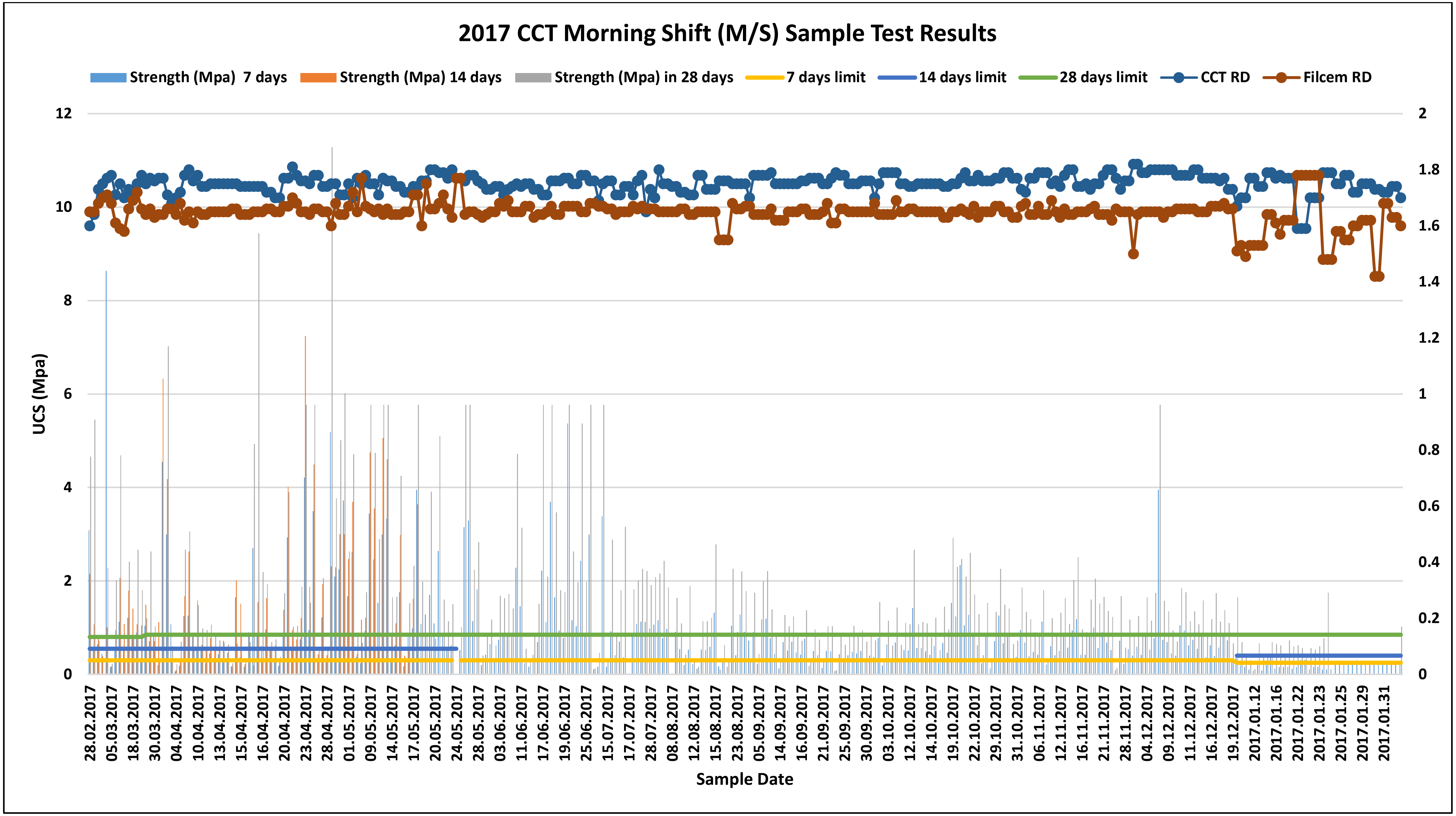
APPENDICES

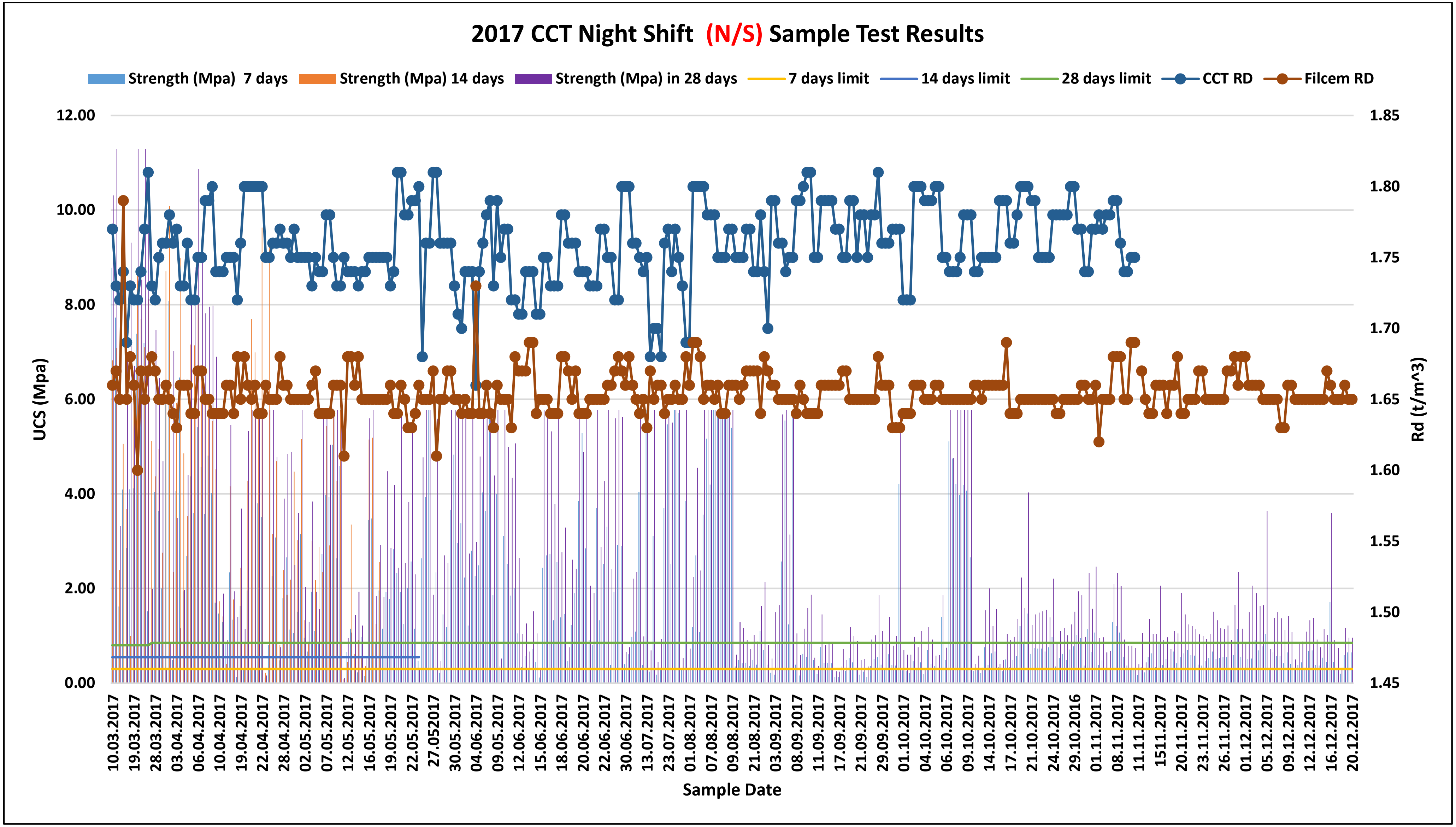
Appendix A: The 2017 Annual CCT sample test results.



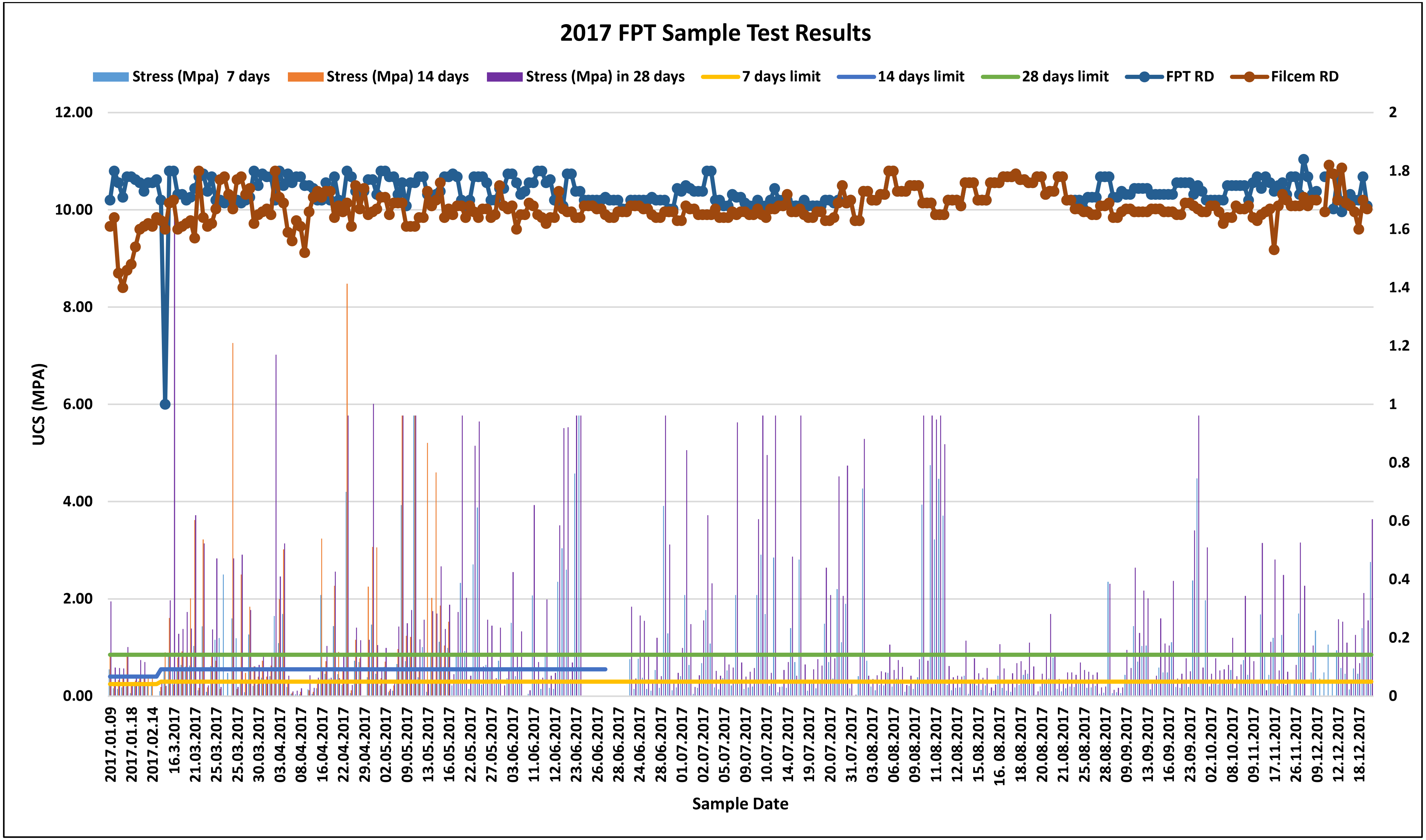
Appendix B: The 2017 CCT morning shift sample test results.



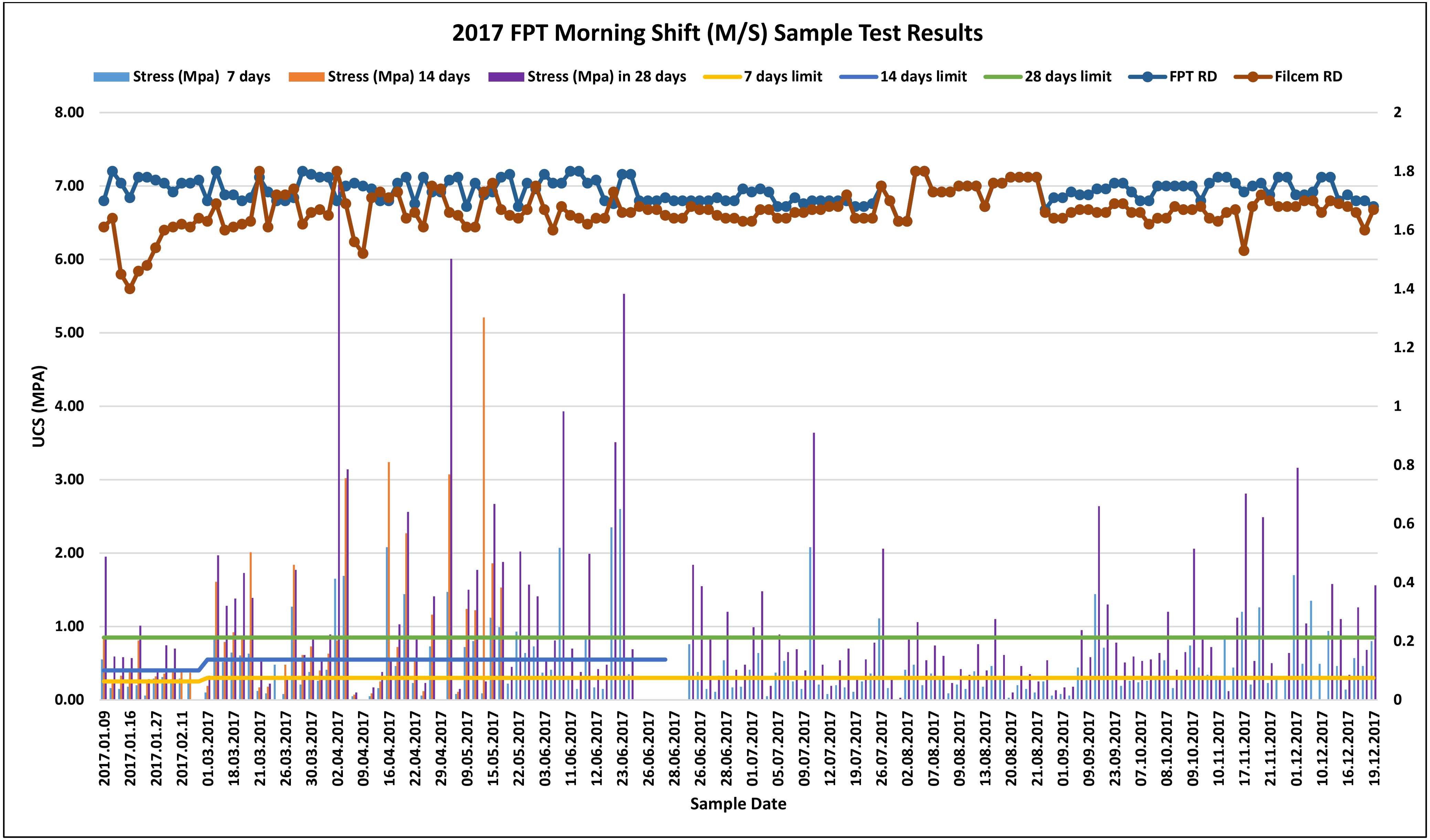
Appendix C: The 2017 CCT night shift sample test results.



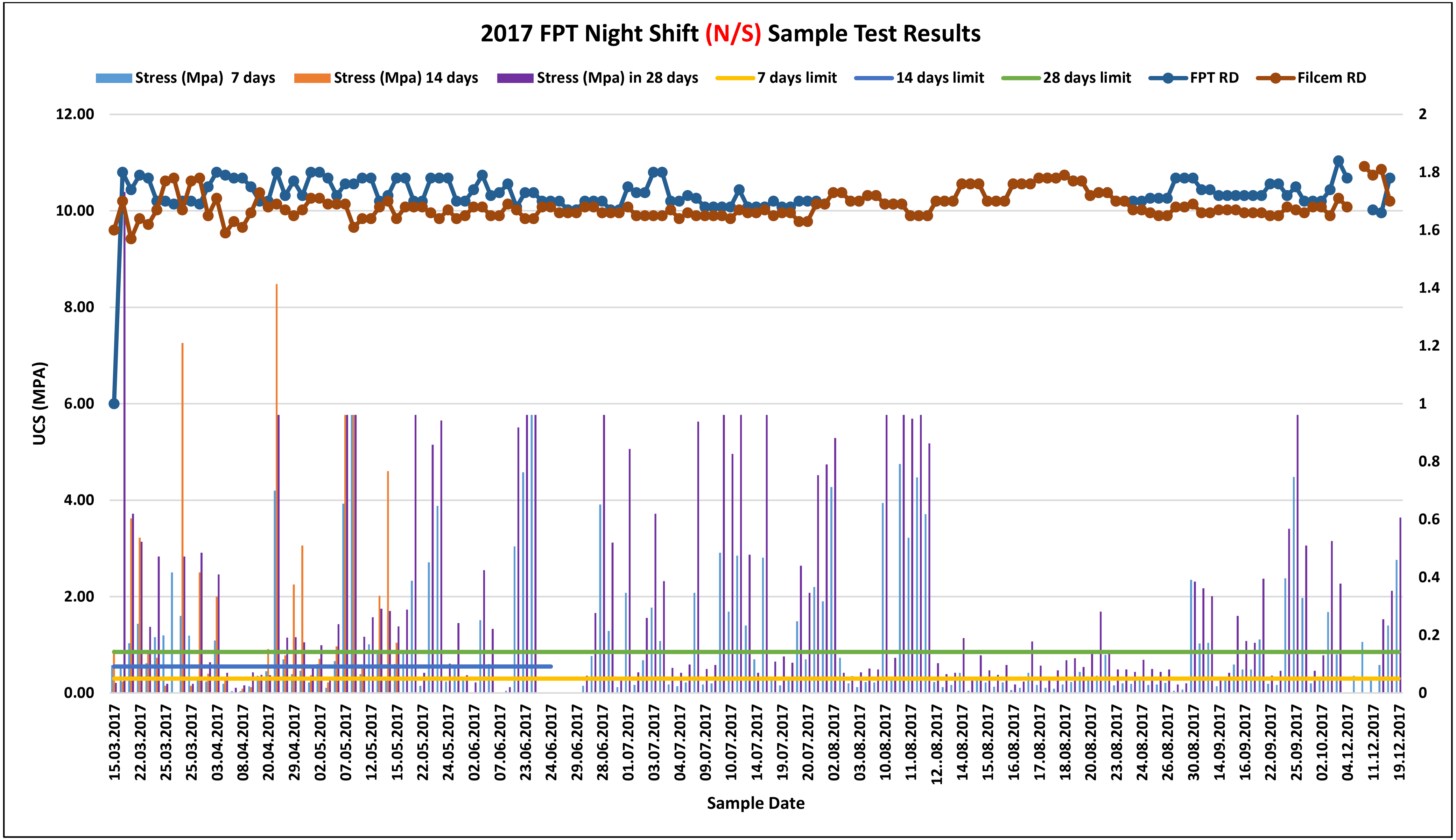
Appendix D: The 2017 FPT sample test results.



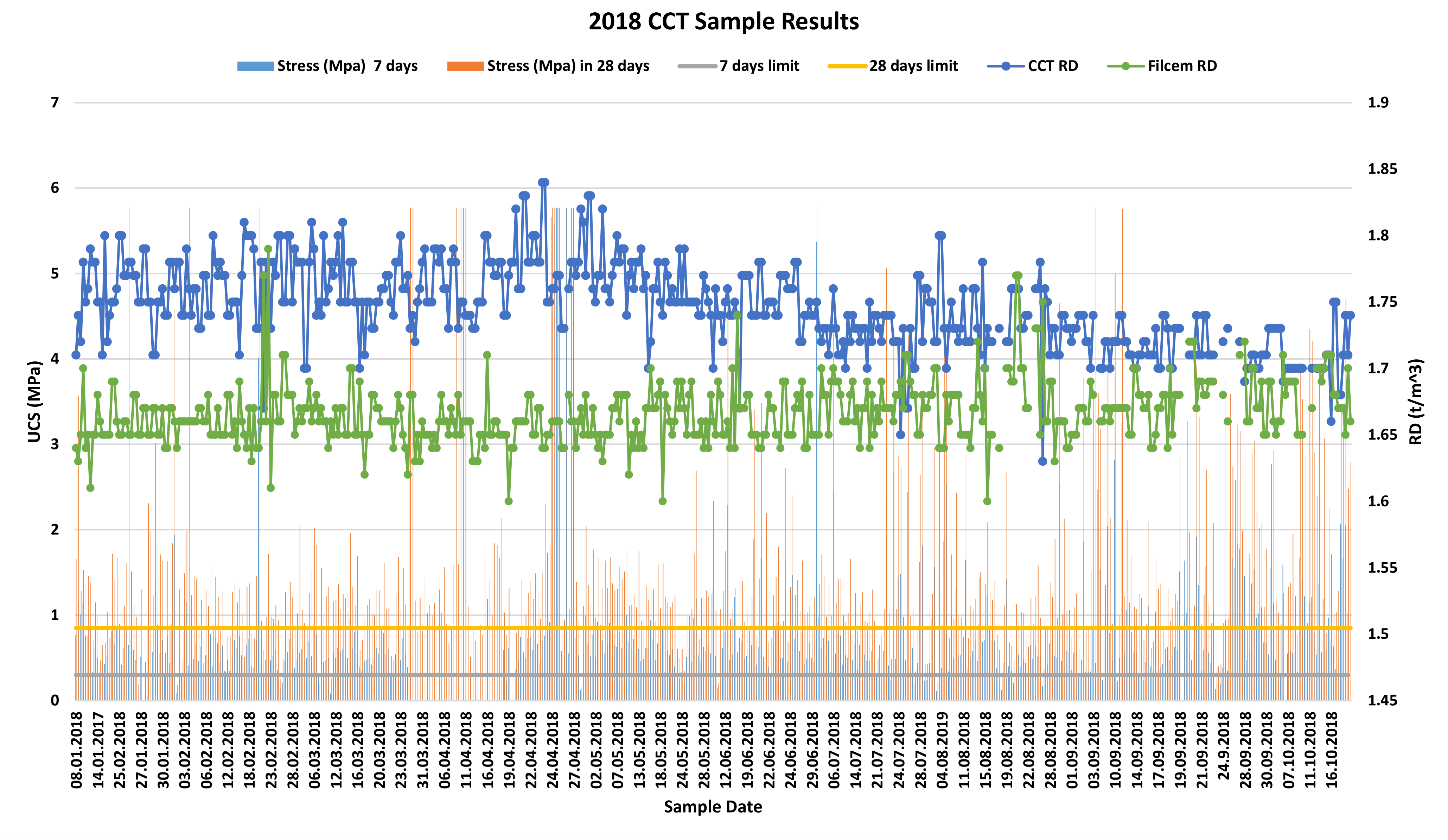
Appendix E: The 2017 FPT morning shift sample test results.



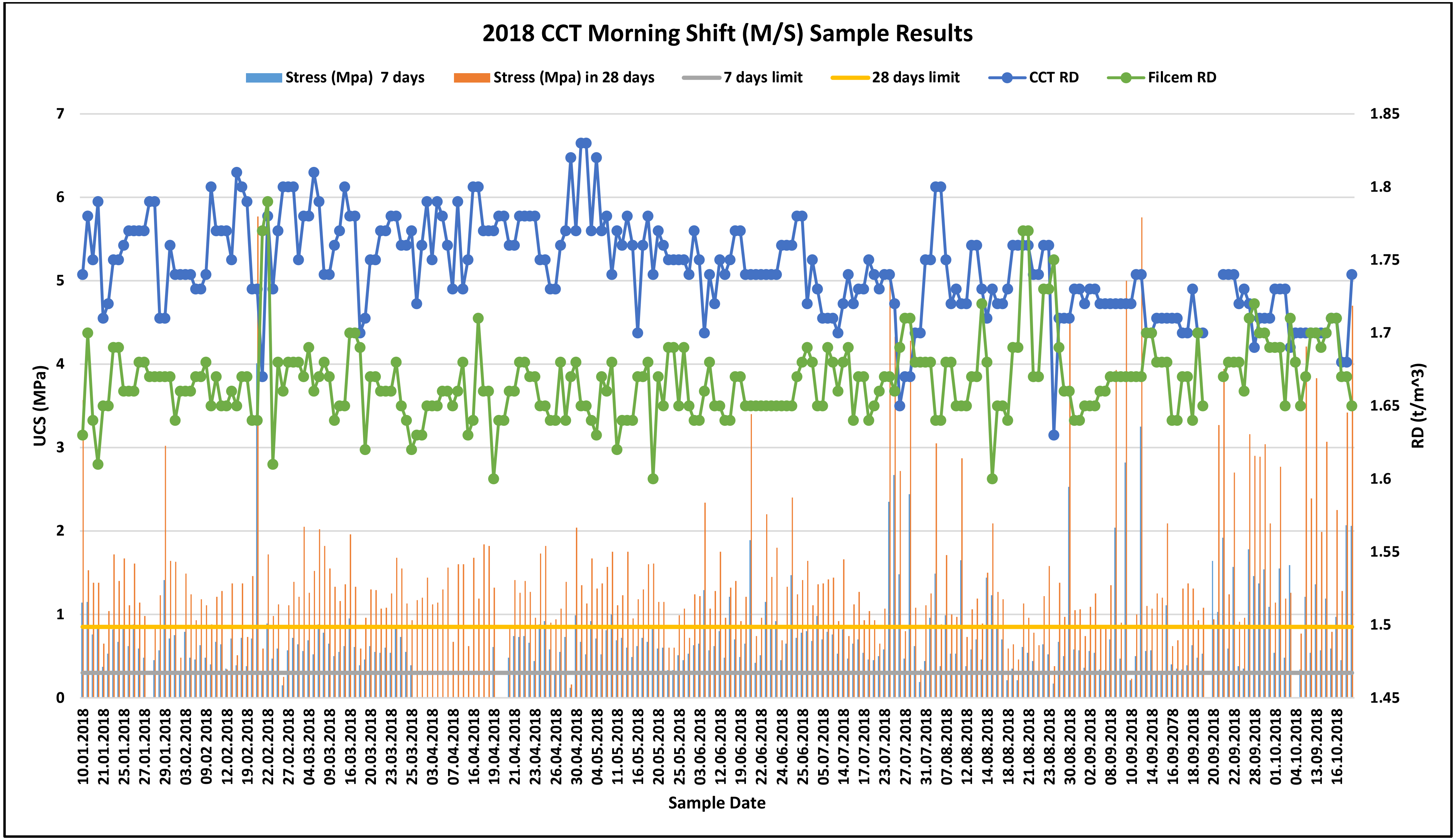
Appendix F: The 2017 FPT night shift sample test results.



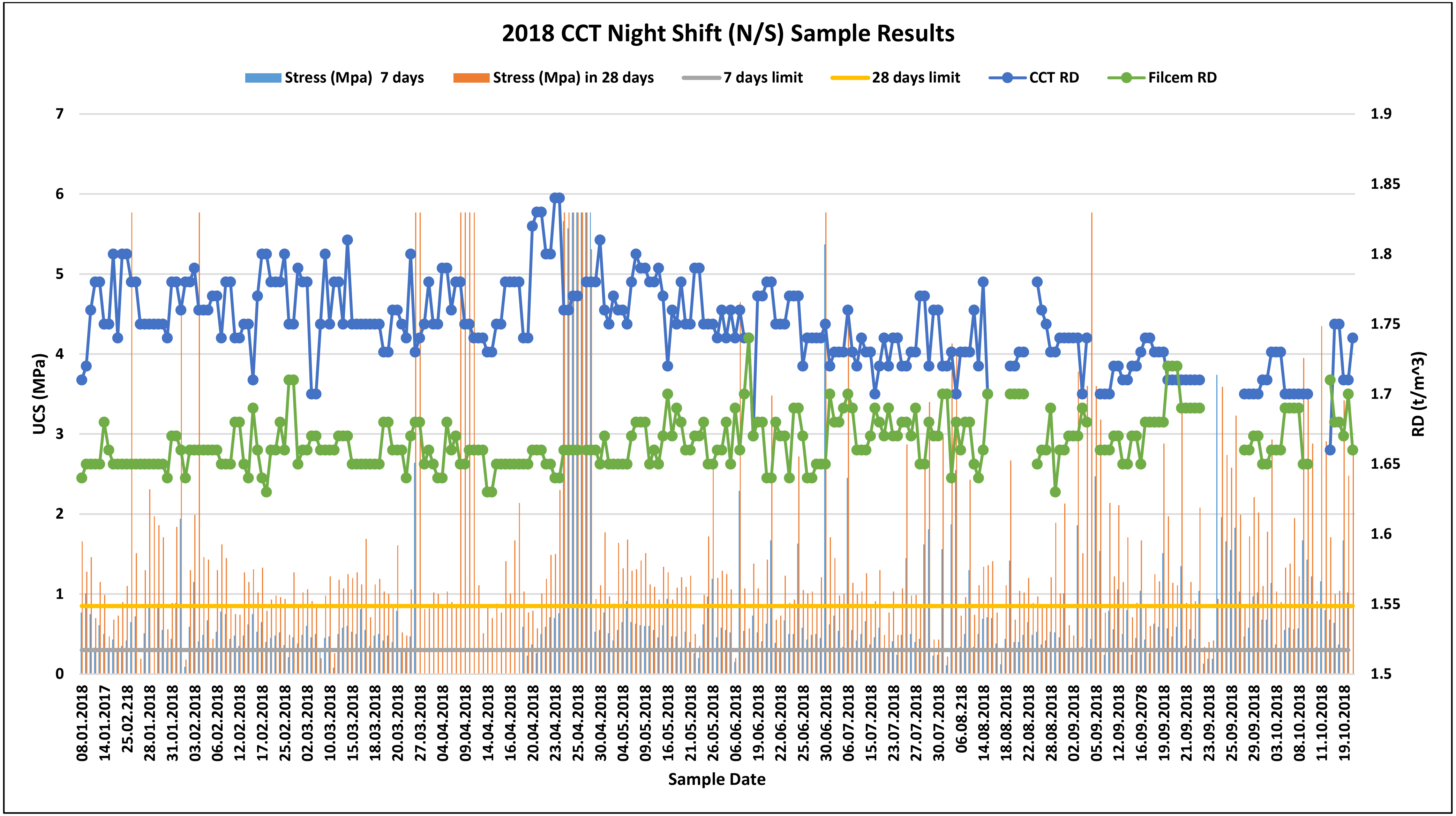
Appendix G: 2018 CCT Sample Results



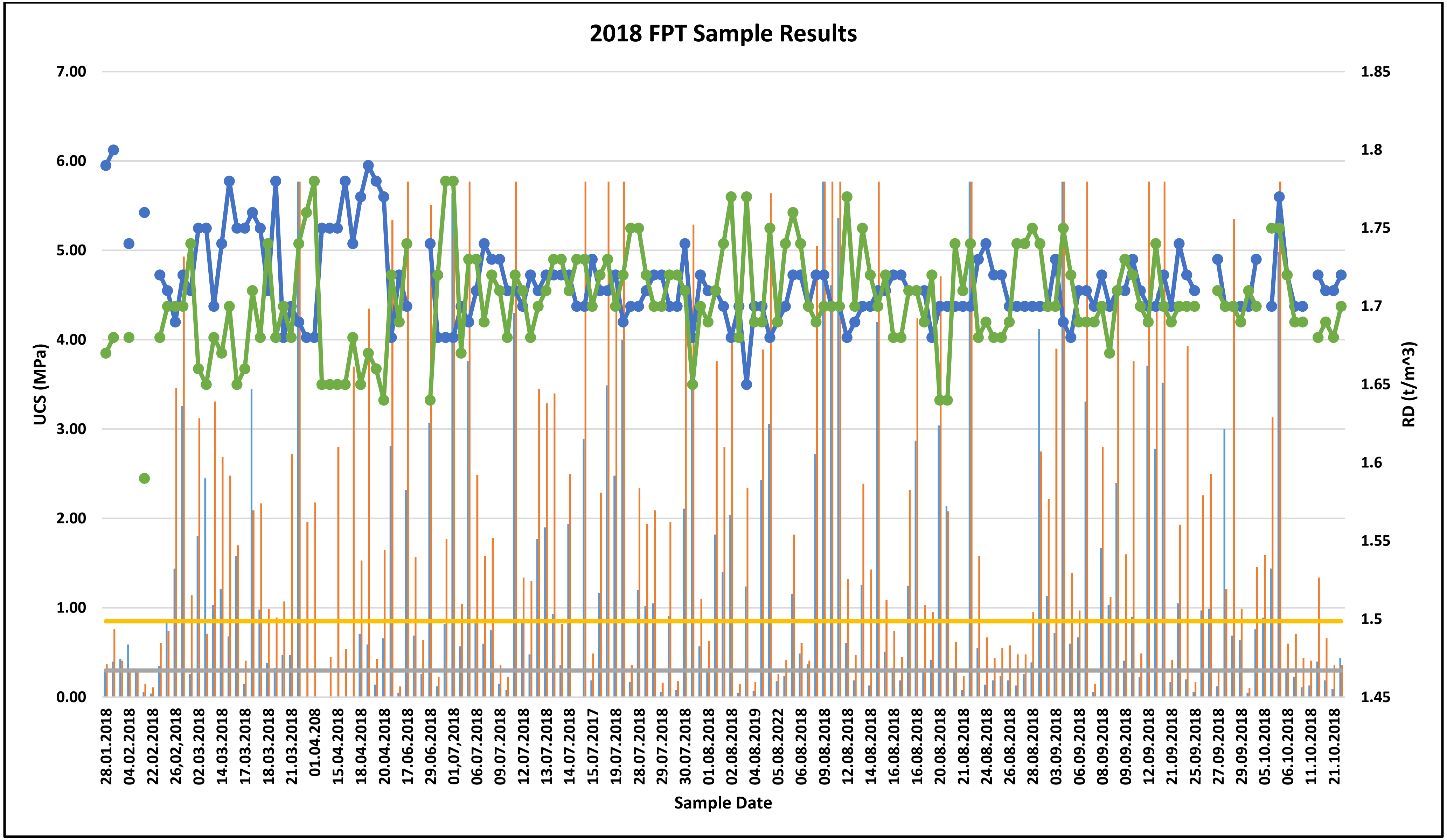
Appendix H: 2018 CCT Morning Shift Results



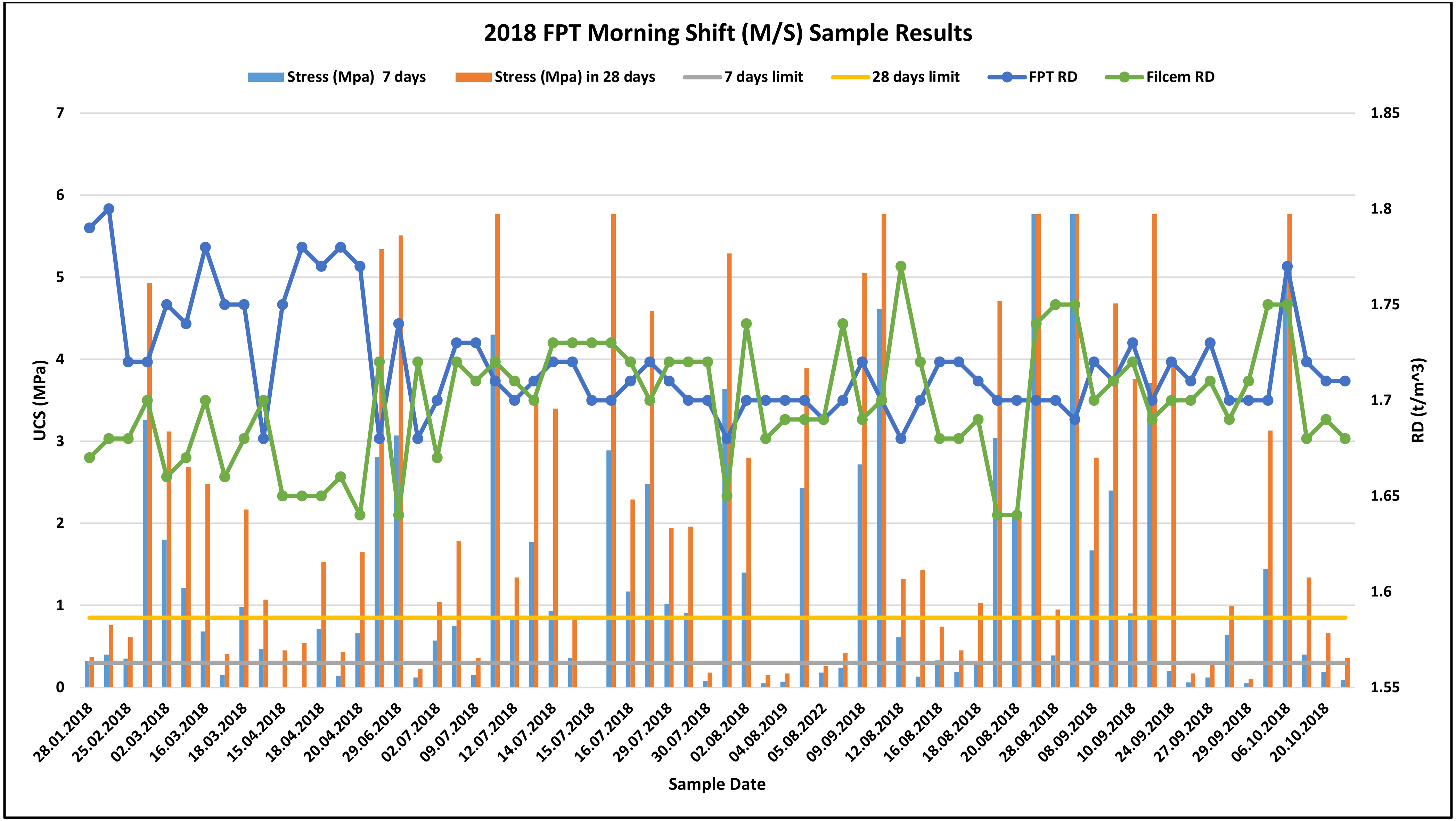
Appendix I: 2018 CCT Night Shift Results



Appendix J: 2018 FPT Sample Results



Appendix K: 2018 FPT Morning Shift Sample Results


2018 FPT Morning Shift (M/S) Sample Results
Stress (Mpa) 7 days
Stress (Mpa) in 28 days
7 days limit
28 days limit
FPT RD
Filcem RD
UCS (MPa)
0
1
2
3
4
5
6
7
RD (t/m^3)
1.55
1.6
1.65
1.7
1.75
1.8
1.85
28.01.2018
25.02.2018
02.03.2018
16.03.2018
18.03.2018
15.04.2018
18.04.2018
20.04.2018
29.06.2018
02.07.2018
09.07.2018
12.07.2018
14.07.2018
15.07.2018
16.07.2018
29.07.2018
30.07.2018
02.08.2018
04.08.2019
05.08.2022
09.09.2018
12.08.2018
16.08.2018
18.08.2018
20.08.2018
28.08.2018
08.09.2018
10.09.2018
24.09.2018
27.09.2018
29.09.2018
06.10.2018
20.10.2018
Sample Date

Appendix L: 2018 FPT Night Shift Sample Results.