Incorporation of basaltic aggregates from the Sibasa formation in shotcrete for potential use as support in underground mining

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Declaration

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vp mudau

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Dedication

This work is dedicated to my Parents **Rose Tshililo Mudau** and **Elijah Makondelele Mudau**, who have been my greatest support system and true cheerleaders. You have always pushed me to be the best.

Furthermore, I would like to devote this work to my husband **Matimba Maringa** and my daughter **Dakalo Rokunda Maringa**. They have been a source of motivation for me to reach my goals.

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ABSTRACT

The use of crushed basalt aggregates as an alternative to sand aggregates is gaining momentum. This is driven by efforts of ensuring sustainable developments in shotcrete production. The main objective of this study was to assess the suitability of basalt aggregates as sand replacement through aggregate physical characteristics tests.

To this end, shotcrete mixes of proportions 0%, 25%, 50%, 75% and 100% replacement of sand by basalt aggregates were prepared. The shotcrete mixes were then tested for compressive and flexural strengths over curing ages 7, 14, 21 and 28 days. Basalt aggregates used for the purpose were collected from the Sibasa Formation in Limpopo Province. They were subjected to crushing, milling and sieving to size of 425 µm as well as physical characterisation for fineness, water absorption, moisture content, specific gravity, bulk density, petrographic and geochemical properties. In addition to this, fresh mixes were evaluated for workability while hardened sand-based and basalt-based shotcrete mixes were studied for hardened density, compressive and flexural strengths.

Results indicated that basalt aggregates have favourable characteristics that influence the mechanical properties of shotcrete when compared to sand. Furthermore, fresh mixes with elevated basalt content exhibited higher consistency. Increased flexural and compressive strengths were also observed for shotcrete mixes at high basalt content. Conversely, lower compressive and flexural strengths were recorded for mixes at high sand content. Water immersion curing and curing age also contributed to a gain in strength for basalt-based shotcrete. Equally, basalt content and curing age were found to enhance shotcrete strength with notable interaction between the two parameters. Lastly, high deformations were observed for sand-based shotcrete compared to basalt-based mixes suggesting that basaltic aggregates lead to shotcrete of superior properties.

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List of abbreviation

ASTM	American Society for Testing and material
FOG	Fall of ground
SANS	South African National Standard
XRF	X-Ray Fluorescence
XRD	X-Ray Diffraction

List of symbols

A	Cross-sectional area
A_w	Water absorption
BC0	Control mix of sand aggregates
BC25	Basalt shotcrete mix with 25% sand replacement
BC50	Basalt shotcrete mix with 50% sand replacement
BC75	Basalt shotcrete mix with 75% sand replacement
BC100	Control mix of basalt aggregates
C_3S	Tricalcium silicate
C_2S	Dicalcium silicate
C_3A	Tricalcium aluminate
C_4AF	Tetracalcium aluminoferrite
CSH_2	Calcium sulphate dihydrate
F_C	Compressive strength

Chapter 1: Introduction

1.1. Background

For many decades, shotcrete has essentially been used to provide permanent support to infrastructures and rock masses in underground excavations. ACI (2005) defined shotcrete as mortar that is pneumatically projected onto a surface using wet or dry projecting methods. The two methods vary in mixing procedures. In the wet shotcrete method, water is mixed in the mixing chamber while the dry method mixes water with the other constituents at the nozzle during application. The use of wet shotcrete has gained popularity over the years compared to its dry counterpart. This is because it is environmentally efficient and does not create a lot of dust during application (Bernado et al., 2015). Shotcrete support system is usually applied in permanent openings and long-term excavations such as haulages, ramps, crusher chambers and shaft stations (Stacey et al., 2009). It is also used in production excavations that experience extreme ground deformation to prevent fall of ground. This has hence contributed to keeping underground excavations safe (Malmgren et al., 2005; Jolin et al., 2011). Furthermore, the industrial demand of shotcrete has increased enormously over the past decade, due to easy placement, rapid settling and lastly, its cost efficiency (Boniface, 2012).

The mix design of shotcrete generally consists of cement, aggregates, and water (Clements, 2003). Amongst these constituents, sand aggregates account for 60 to 80% of the mix (Neville, 2011). However, the depletion of sand reserves has led to an increase in the price of sand over the last 25 years. This situation has put a strain on the cost of producing shotcrete (Liew et al., 2017; Mohajerani et al., 2017; Kazmi et al., 2021). Removal of sand from beaches and wetlands leads to environmental concerns such as floods and natural disasters. Sonak et al. (2006) indicated that these environmental concerns would lead to the destruction of coastal communities. This predicament has led to seeking an alternative aggregate source to substitute for sand in the shotcrete mix design.

Moreover, shortcomings of shotcrete made with sand aggregates include cracking, scaling out and lack of adhesion (Malmgren, 2005). An ideal alternative replacement of sand aggregate in the shotcrete mix design should fulfil strength requirements and reduce underground structural failures. It is in this light that Kishore (2015) tested the incorporation of basalt aggregates to shotcrete as sand replacement. The motivation was to mitigate the use of costly sand and provide underground support at an inexpensive rate. Two other studies conducted by Ubi et al. (2020) and Leroy (2017) showed that basalt aggregates increase the mechanical strength properties of shotcrete.

Concordant studies have reported that the type of aggregates is essential to the strength of the shotcrete (Hassan, 2014; Aginam et al., 2013; Jimoh and Awe, 2007). Indeed, aggregates form the matrix of the shotcrete and act as a filling material. Aggregates sourced from excavated rocks improve the interlocking properties of shotcrete. Common types of excavated rocks used as aggregates include granite, basalt, marble and limestone. This subsequently results in improved compressive and flexural strengths. Due to the fact that aggregates take up to 60 to 80 % of the shotcrete mix, the effect of aggregates on the strength properties of shotcrete is pivotal (Neville, 2011). Amongst other factors, aggregates influence the successful application of shotcrete (Thomas, 2009).

Basalt is a fine- grained extrusive mafic igneous rock that forms from lava flows. Basalt aggregates are formed through crushing the basalt rock to the desired size (Swati et al., 2016). Incorporation of basalt aggregates in shotcrete mix design could potentially solve the largest problem of fall of ground and structural failure in underground mining. Properties that make basalt aggregates lucrative as an alternative aggregate source include chemical resistance, thermal resistance, mechanical resistance and ecological friendliness (Murray, 2019). An ideal shotcrete application is characterized by high strength, low absorption, resistance to physical weathering and chemical attack (Bernado et al., 2015; Choi et al., 2017).

Therefore, the idea of using basalt aggregates as a replacement of sand aggregates represent an environmentally friendly and inexpensive option for solving the problem of sand depletion. Basalt aggregates have been in road and building construction. However, there has been limited application of basalt aggregates as sand replacement in shotcrete.

In 2017, Department of Mineral Resources and Energy (DMRE) reported that there were 249 underground mines in South Africa. Underground mines experience high-stress level, this is due to mining at depth. This results to the development of induced stresses. Therefore, the stability of underground excavations becomes of paramount importance in ensuring a safe environment (Uotinen, 2011). The application of shotcrete in underground mines contribute actively towards the stability and strength of underground excavations. It is crucial to choose aggregate sources that will maximize the strength properties of shotcrete.

Several studies have demonstrated that shotcrete reduces the movements along joint planes from developing, which results in stabilizing the underground tunnel (Potvin and Hadjigeorgiou, 2008; Golser, 1976; Stacey et al., 2009). Basalt aggregates have abrasion resistance and high mechanical strength. This study aims to explore the possibility of using basalt aggregates in shotcrete as a replacement to sand.

1.2. Problem statement

Shotcrete is mostly applied in the cycle of the underground mine life. This implies that a large quantity of sand is always required in shotcrete mix design. Natural sand is generally regarded as a good quality aggregate for use in shotcrete mix design (Toderas and Danciu, 2020; Uotinen, 2011). However, due to environmental concerns caused by depletion of sand deposits, it has become imperative to look for an alternative source of aggregates (Choi et al., 2017). Indeed, the increased demand of natural sands has led to the increased industrial scale exploitation of available deposits generally found on riverbeds. The mining rate and depletion of these deposits have hence caused water pollution, bed erosion, decline in aquatic species, and increased costs of sand due to its scarcity (Kumar, 2019; Ubi et al., 2020). Strict environmental guidelines are now being enforced in various jurisdictions to limit the extraction rate of natural river sand (Suchithra et al., 2011; Pilegis et al., 2016; Vijaya et al., 2020). In reaction to this, the attention of the shotcrete industry is shifting towards alternative sources of aggregates. To put this into perspective, Pilegis et al. (2016) estimated that between 10 and 11 billion tons of sand aggregates are consumed annually. The search for suitable, inexpensive, abundant and eco-friendly substitute for natural sand therefore becomes an important undertaking. Scholars such as Lazutkin et al. (2003), Lesovik (2015) as well as Dvorkin and Stikowski (2017) reviewed the cost of natural sand in comparison to basalt aggregates. Their findings showed that the cost of natural sand is ($30 per ton) which is three times greater than the cost of natural crushed basalt ($10 per ton). In light of the cost implications, Kishore et al. (2015) explored the use of crushed rock aggregates as a replacement of sand on shotcrete mix design. The findings from their study indicated that crushed rock aggregates are a suitable replacement of natural sand in the shotcrete mix design. These findings have shown that basalt aggregates may potentially be utilized as an alternative aggregate source to maintain shotcrete production.

The Mineral Council of South Africa (MINCOSA, 2020) reported that fall of ground accounted for 60% of fatalities that occurred in underground mines. Fall of ground is defined as falling of a rock from the roof or the sidewall into a mine opening (MINCOSA, 2020). The occurrence of fall of ground in an underground mine can potentially be reduced through the application of shotcrete (Ubi et al. 2020). The application of shotcrete increases the load carrying capacity of the roof and sidewall in underground mines, which prevents the fall of key rock blocks. Again, Cebasek and Likar (2014) attested that shotcrete lining is crucial as a support system as it enables for greater yieldability, while securing a key rock block from falling to the ground. Yasmin et al. (2018) indicated that the addition of basalt aggregates in shotcrete mix can potentially increase the load carrying capacity of underground roofs and sidewalls, reducing the occurrences of fall of ground.

Basalt aggregates are non-flammable, with high thermo-durability and high chemical durability (Swati et al., 2016; Al-Bajait, 2012; Kubiszewski, 2012). Thompson et al. (2009) stated that shotcrete ground support strengthening could be installed in areas where there is cracking in high and low stress environments. This study brings forth the advantages of basalt aggregates and aims to use those as basis for their integration in shotcrete mix design.

1.3. Significance of the study

The Occupational Health and Safety Report (OHSR, 2017) declared that majority of the falls of ground that occurred in the past years in the Republic of South Africa were in medium to deep underground excavations. Several of these incidents led to fatalities. As a result, the Mine Health and Safety Council and the mining industry at large have aimed to transform the mining environment and achieve “zero harm” (OHSR, 2017; MINCOSA, 2020). The application of shotcrete is important in reducing the progression of rock deterioration, which can potentially lead to fall of ground. Figure 1.1 depicts the percentages of incidents that occurred in the Bushveld platinum underground mine. Fall of ground accounted for 37% of fatal incidences that occurred in the platinum underground mine (Seymour, 2011). The statistics depicted in Figure 1.1 have drawn attention and motive to reduce the number of incidences related to fall of ground. Furthermore, a solution of finding an alternative replacement to sand that can potentially lead to improved mechanical performance of shotcrete is deemed to be necessary.

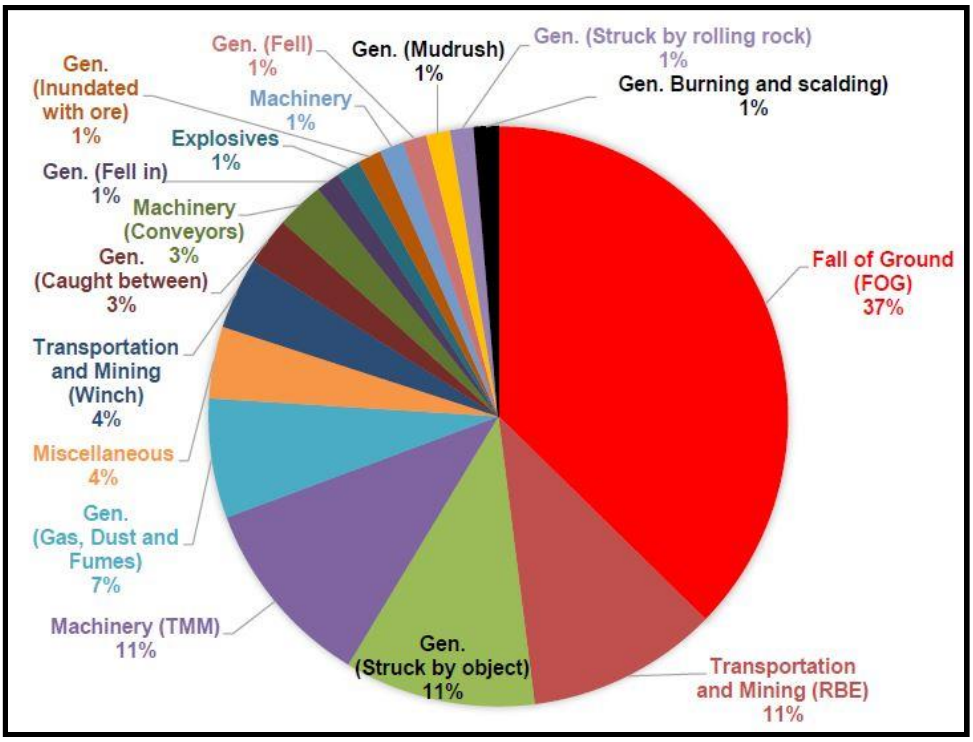

Figure 1.1: Statistical accountability chart of various incidences that occurred in the Bushveld Platinum underground mine (Seymour, 2011)

The projected outcome of the proposed study may potentially offer a solution of improving the mix design of shotcrete through the inclusion of basalt aggregates. A durable and serviceable shotcrete is crucial as it ensures improved safety of resources (human, machinery and infrastructure), through reducing the occurrences of fall of ground. Basalt aggregates are low-cost, sustainable, and environmentally friendly materials that could serve better in improving the mix design of shotcrete. The incorporation of basalt aggregates in shotcrete that will be used in underground mines for support can prove to be beneficial to the support engineering society. This knowledge can be beneficial to mining engineers, civil engineers, building agencies and, government institutions among others. Therefore, it is crucial to conduct this study to test the feasibility of using basalt aggregates derived from Sibasa Formation as an aggregate source in shotcrete mix design.

1.4. Aim and objectives of the study

Shotcrete primarily stabilises rocks and resists failure from the loads that these rock blocks generate (Saw et al., 2015). The mechanism of shotcrete failure is dependent on the strength of shotcrete which in turn is influenced by the ingredients in the mix design. The individual strength of each ingredient in the shotcrete mix design contributes towards the overall successful application of shotcrete (Bernado et al., 2015; Choi et al., 2017). This study presents the potential of using basalt aggregates from the Sibasa Formation as sand replacement in shotcrete mix design meant to support underground mines. One may argue that the use of basalt aggregates derived from Sibasa Formation in shotcrete is not common. The present study is meant to present the possibility of using basalt in shotcrete to improve the performance of shotcrete support system in extreme ground conditions.

In order to achieve the ultimate aim of the study the following objectives are set as follows:

- To assess the suitability of basalt as sand replacement in shotcrete mix design through aggregate physical characteristics tests;
- To determine the mechanical properties (compressive and flexural strength) of shotcrete with partial to full replacement of sand by basalt aggregates under water immersion curing over various periods; and
- To develop a predictive model of the performance of shotcrete mixes with partial to full replacement of sand aggregates by basalt aggregates in underground excavations.

1.5. Structure of the dissertation

Chapter 1 introduces the research topic, the motive behind the research, the problem statement as well as the significance and scope of the research.

Chapter 2 provides comprehensive review of the different aspects of shotcrete technology. This includes aggregate characteristics such as fineness modulus, porosity water absorption, moisture content, specific gravity, bulk density, petrographic and geochemical analyses. Fresh and hardened properties of shotcrete were reviewed. Furthermore, factors affecting the shotcrete strength and performance of shotcrete application.

Chapter 3 provides the laboratory test methods in this research. The physical aggregate tests conducted included fineness modulus, water absorption, specific gravity, moisture content, bulk density, petrographic and geochemical analyses. Fresh properties such as workability were measured. Also hardened density of mixes BC0, BC25, BC50, BC75 and BC100 are presented in this section. Lastly, flexural and compressive strength were also tested.

Chapter 4 presents results derived from the experimental tests conducted in Chapter 3. Physical aggregate characteristics such as fineness modulus, water absorption, moisture content, bulk density, specific gravity, petrographic and geochemical analysis. Results on the slump values of mixes BC0, BC25, BC50, BC75 and BC100 are presented in this section. Hardened properties of shotcrete such as hardened density, compressive and flexural strength are detailed in this section.

Chapter 5 presents the impact of basalt content as sand replacement on compressive and flexural strength of shotcrete over curing ages 7, 14, 21 and 28 days. Discussions of the outcomes in Chapter 4 are detailed in this section. Statistical modelling is conducted to assess the influence of mix types on compressive and flexural strength over curing ages. ANOVA two-way test is performed in order to test the influence of adding basalt aggregates into shotcrete mix on compressive and flexural strength over curing ages.

Finally, 2D deformational analysis model is modelled based on the compressive strength. The model took into consideration traditional shotcrete (BC0) and hybrid shotcrete (BC100). The findings of deformation along the x and y axis in underground mining is reported in this section.

Chapter 6 presents a summary of major findings and their relevance to the study. Also, areas that require further research are also identified.

Chapter 2: Literature Review

2.1. Introduction

Underground mining of economically endowed minerals such as diamond, gold, coal and platinum group elements (PGEs) is widespread in the Republic of South Africa (MINCOSA, 2020). The question of choosing rational, reliable and economical means of supporting underground mining becomes relevant. This is because the safety of employees and equipment is dependent on the stability of underground workings. The application of shotcrete contributes towards stabilising underground mines. It is important to further develop and improve the mix design of shotcrete, to ensure that the desired strength is achieved. A relevant development to the application of shotcrete in underground excavations would be the incorporation of basalt aggregates into the mix design of shotcrete. This is because the ingredients in the mix design of shotcrete plays a crucial role to its flexural and compressive properties.

Jager and Ryder (1999) formally defined shotcrete as a mixture of cement, aggregate and water, which is pumped pneumatically through a nozzle onto the wall of an excavation to form a bonded coherent layer. On the other side, Malmgren and Svesson (2003) defined shotcrete as mortar that is sprayed onto a surface to produce a compacted self-supporting and load-bearing layer. There are two types of shotcrete processes. In the wet shotcrete method, water is mixed in the mixing chamber while the dry method mixes water with the other constituents at the nozzle during application. The wet-shotcrete mix is preferably used in underground mines. An advantageous characteristic with the wet-mix is that the rebound of the product is reduced to 5 – 10%. While, for dry shotcrete the rebound of the product is 15 – 35%. An increased percentage (%) of rebound affects the effectiveness of the application of shotcrete. This implies that during the projection of shotcrete, most of the material will not adhere to the surface of application. Therefore, a reduced rebound is preferred to achieve successful application of shotcrete. As a result of the rebound characteristics, the review will focus on wet-shotcrete process. This is because wet shotcrete process was used in this study.

This chapter presents a detailed review of the development of shotcrete. This includes looking into gaps of innovative ways to improve the mix design of shotcrete. Firstly, physical properties of sand and basalt aggregates are reviewed. The review takes into consideration parameters such as specific density, grain size, water absorption, moisture content, fineness modulus, grain type, petrographic analysis and geochemical analysis.

Secondly, the parameters that contribute towards the strength development of shotcrete are reviewed. This section includes water to cement ratio, hydration reaction, curing method, curing period and shotcrete failure modes. In addition, fresh and hardened properties of shotcrete such as workability, hardened density, flexural, and compressive strengths are reviewed. The review looks into previous studies that have incorporated basalt aggregates in place of sand in shotcrete. This section of the review was conducted to provide merits to improve the mix design of shotcrete through the choice of aggregates.

Finally, the performance of shotcrete mixes with various proportions of sand and basalt aggregates was assessed. This section focuses on flexural and compressive strengths performance in underground mines. Furthermore, the successful and unsuccessful application of shotcrete in underground tunnelling is reviewed. The literature review discusses the abovementioned parameters, in efforts of proving the potential of basalt aggregates as sand replacement in shotcrete.

2.2. Mix design of shotcrete

Mix design is a process that involves selecting of suitable ingredients and determining their relative quantities (Mallikarjunar et al., 2013). The mix design is responsible for producing shotcrete with appropriate strength, workability, and durability (Mahar et al., 1975). A typical shotcrete mix design includes cement, water, and aggregates. These materials are mixed and fed into the shotcrete pump and conveyed through a pipeline to a nozzle (Mahar et al., 1975).

A typical example of wet-mix shotcrete is depicted in Figure 2.1. In this case, ingredients in the shotcrete mix design are loaded into the mixing chamber where there are rotating blades. Later on, the mix is rolled through the roller to the pumping tube. Lastly, the mix is projected through the nozzle where pressure is added to project the material onto the surface (Mahar et al., 1975).

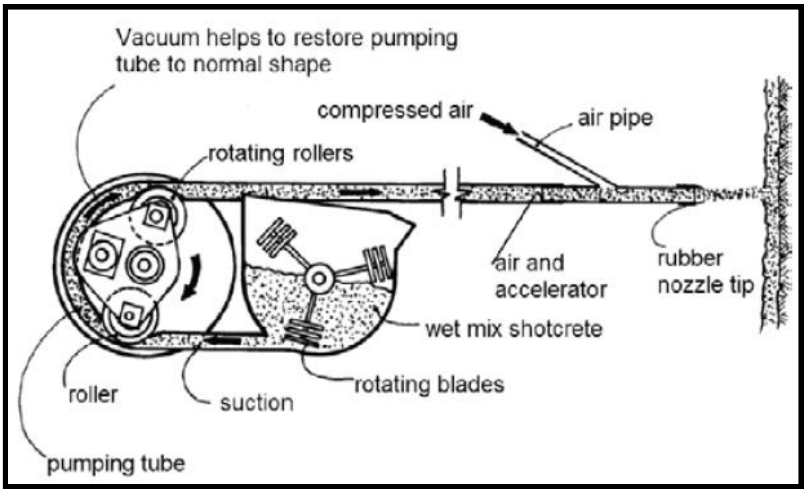

Figure 2.1: A typical type of wet-mix shotcrete (Mahar et al., 1975)

Amongst the mix ingredients of the wet shotcrete process, aggregates account for 60% to 80% of the mix design (Neville, 2011). Fine aggregates are preferred because they reduce the proportion of coarse aggregates in the mix. The reduction of coarse aggregates improves the pumpability of shotcrete, when it is projected onto the surface (Mamlouk et al., 2005; Monteiro and Mehta, 2006). Pumpability of shotcrete is defined as the capacity of shotcrete under pressure to be mobilized while maintaining initial properties (Jolin et al., 2006). It is deemed crucial that the ingredients of shotcrete not be altered during application. This is because the desired strength and durability may be compromised. It is essential to study and understand all the constituents in the shotcrete mixture. This allows for a comprehensive understanding of the mechanical and chemical behaviour of shotcrete upon application (Mamlouk et al., 2005). A typical traditional shotcrete mix consists of sand, water, cement, and aggregates (Clements, 2003). A traditional shotcrete mix does not consist of any additive such as steel fibres and silica fumes as depicted in Figure 2.2. It is shown in Figure 2.2 that sand aggregates take up a higher proportion of the shotcrete mix design compared to other constituents. Therefore, sand depletion adversely affects the production of shotcrete.

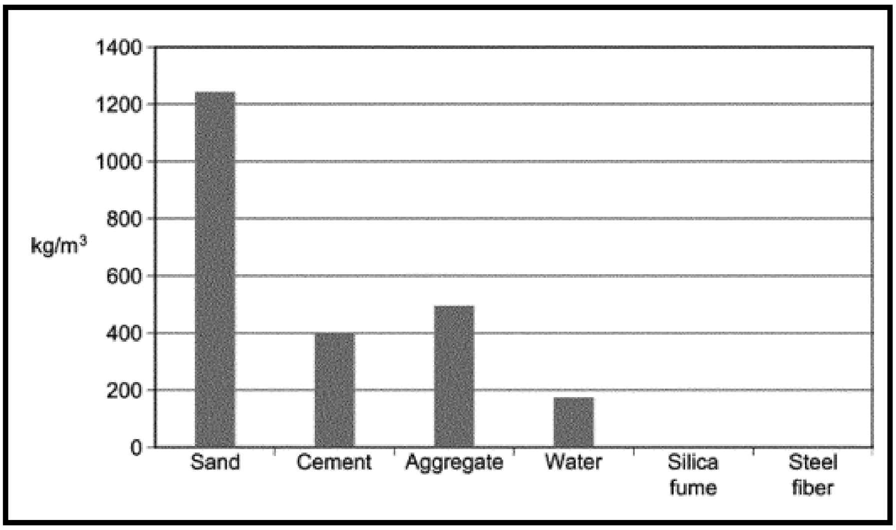

Figure 2.2: Typical composition of wet mix designed for underground mines (Clements, 2003)

2.2.1. Water

Water is a key component in the production of shotcrete. Water is the initiator of the hydration process. Hydration is a chemical reaction that occurs when water forms a chemical bond with major compounds in cement (Kosmatka and Wilson, 2011). During the hydration process, when water is mixed with cement it forms a paste that binds the mix constituents together. C_3S is a cement component that is mixed with water (H_2O), later forming a cement paste (C-S-H). A chemical reaction is denoted as follows (Soroka, 1979):

$$2(C_3S) \oplus 6(H_2O) \rightarrow C - S - H \oplus 3(CH) \qquad (2.1)$$

The hydration process is explored in detail in Section 2.2.2. Pure water is required in the mix design. Goodman (2009) stated that tap water or any potable water that is not contaminated can be used in the mix design. Pure water is used to prevent the incorporation of deleterious material that can affect the desired mix properties. The presence of deleterious material can interfere with the hydration process. This implies that side reactions can occur, reducing the chances of forming adequate paste that will hold together the mix constituents (Soroka, 1979). This may weaken the strength of shotcrete, due to decreased cohesion. Standards such as ASTM C1602/C1602M (1997) have been used to specifically guide the choice of quality water that needs to be used in shotcrete. This standard is discussed thoroughly in Chapter 3. Nikhil et al. (2011) conducted a study to assess the suitability of ground water, potable, and sewage water in shotcrete mix design. Shotcrete cubes were prepared with the incorporation of ground water, sewage water and potable water respectively. The three types of cubes were later cured using water immersion of pure water. The results of compressive strength after 28 days of curing were 22.50 N/mm^2 (potable water), 20.85 N/mm^2 (ground water), and 15 N/mm^2 (sewage water). The findings of flexural strength after 28 days of curing were 3.15 Nmm^2 (potable water), 3.00 N/mm^2 (ground water), and 2.80 N/mm^2 (sewage water). The findings from this study indicated that an increase in pH value, leads to a decrease in shotcrete strength. This is because elevated pH negatively affects (C-S-H) which is responsible for strength gain in shotcrete. This is a clear depiction of the influence of the type of water on the strength properties of shotcrete.

2.2.2. Cement

Cement is considered as a binder that sets, hardens, and binds the mix ingredients together. Ghiasi and Omar (2011) as well as Malmgren et al. (2005) reported that the binding properties of cement are crucial to ensure cohesion support in the mix design. The hydration reaction between water and cement forms hydrated cement paste. Various phases of the hydrated cement paste are depicted in Table 2.1. Note that the formulas given in Table 2.1 correspond to the shorthand notation commonly used in cement chemistry. The hydrated cement paste is responsible for the binding property of cement.

Table 2.1 Cement paste during the hydration process (Malmgren et al., 2005)

Cement phase	Chemical formula	Short notation
Tricalcium silicate	$3CaO•SiO_2$	C_3S
Dicalcium silicate	$2CaO•SiO_2$	C_2S
Tricalcium aluminate	$3CaO•Al_2O_3$	C_3A
Tetracalcium aluminoferrite	$4CaO•Al_2O_2•Fe_2O_3$	C_4AF
Calcium sulphate dihydrate (Gypsum)	$CaSO_4•2H_2O$	CSH_2

Paste agents include tricalcium silicate, dicalcium silicate, tricalcium aluminate, tetracalcium aluminoferrite and calcium sulphate dehydrate (Gypsum) (Malmgren et al., 2005). Characteristics possessed by the paste agents include setting and hardening. Exothermic reaction is responsible for developing hardening characteristics in shotcrete. The reaction is defined as heat generated during curing of shotcrete (Neville, 2011). This reaction promotes water loss and initiates hardening of shotcrete. Also, it should be noted that the rate of heat of hydration is not the same throughout the various cement phases. Table 2.2 summarises the heat released during hydration from the main chemical compounds in cement.

Table 2.2: Heat of hydration of the main chemical compounds in cement (Hasebo, 2003)

Chemical Compounds	Heat of hydration Cal g^{-1}
C_3F	120

C_2S	60
C_3A	525
C_3AF	100

The various phases differ in their rate of reaction as well as in their contribution towards strength development. As depicted in Table 2.2 chemical compounds that release high heat during hydration react rapidly. Each cement phase is discussed below in detail.

2.2.2.1. Tricalcium silicate (C_3S)

Tricalcium silicate (C_3S) is a cement phase in cement that is responsible for hardening of cement phase. It is formed during hydration whereby water reacts with calcium silicate, resulting to the formation of tricalcium silicate. C3S constitutes about 50% to 70% of cement by weight. It is the component most responsible for the formation of the calcium silicate hydrate gel (CSH). The hydrate gel is the principal product of hydration (Bullard et al., 2010). The reaction of C_3S with water occurs rapidly. The hydration reaction of C_3S is represented in a generalised form (Mamlouk and Zaniewski, 2005):

$$C3S \oplus (2.5 \oplus n) H_2O \rightarrow C1.5 \oplus mSH1 \oplus m \oplus n \oplus (1.5 - m) COH \qquad (2.2)$$

Where n is the amount of substance; m is the molar mass; C_3S stands for Tricalcium Silicate; H stands for Hydrogen dioxide; CSH stands for Calcium Silicate Hydrated; and COH stands for Calcium Hydroxide.

Previous studies conducted by Minard et al. (2007) and Bullard et al. (2011) have shown that cement phase (C_3S) lead to an optimum compressive strength of 25 MPa after 28 days of curing. Furthermore, the cement phase C3S is responsible for early strength development in shotcrete (Soroka, 1979; Bullard et al., 2011). Early strength development of shotcrete is one key factor that determines the quality and durability of shotcrete. In underground mines, early strength development is favoured (Mehta and

Monteiro, 2006; Minard et al., 2007). This is because it determines the duration of re-entry, which affects production and safety of workers.

2.2.2.2. Dicalcium silicate (C_2S)

Dicalcium silicate (C_2S) is responsible for the progressive strength gain of shotcrete. A higher percentage of C_2S results in prolonged hardening and elevated resistance to chemical attack (Taylor, 1998; Gartner et al., 2002). The reaction of C_2S is considerably slower compared to the reaction of C_3S as depicted in Table 2.2. The slow rate of C_2S reaction provides a platform for progressive strength gain of shotcrete. Also, the reaction between C_2S and water leads to the production of C-S-H gel (Gartner et al., 2002; Mehta and Monteiro, 2006). The C-S-H gel is gradually formed, the molar ratio increases from 1.65 to 1.80 over 12 months (Jawed, 1984; Taylor, 1997; Schindler, 2004). A generalised equation applicable to the hydration of C_2S is as follows:

$$C_2S \oplus (1.5 \oplus n) H_2O \rightarrow C1.5 \oplus mSH1 \oplus m \oplus n \oplus (0.5 - m) COH \qquad (2.3)$$

Where C_2S is dicalcium silicate; H_2O is water; CSH is calcium silicate hydrated; and COH is calcium hydroxide.

2.2.2.3. Tricalcium aluminate ($Ca_3Al_2O_6$)

Tricalcium aluminate ($Ca_3Al_2O_6$) is the most reactive component of the Portland cement. The reaction between $Ca_3Al_2O_6$ and water is responsible for consistency and strength development of shotcrete (Schindler, 2004; Saw, 2015). This reaction occurs rapidly, leading to the formation of hexagonal plate. These hexagonal plates consist of $4CaO.Al_2O_3.19H_2O$ and $2CaO.Al_2O_3.8H_2O$ (Taylor, 1997; Gartner et al., 2004). Over time these hexagonal plates increase in size and amount. They are responsible for reducing porosity and increasing compressive strength of shotcrete (Jawed, 1984; Saw, 2015). The complete hydration is represented by:

$$3CaO.Al_2O_3 \oplus 6H_2O \rightarrow 3CaO.Al_2O_3.6H_2O \tag{2.4}$$

2.2.2.4. Tetracalcium aluminoferrite (C_4AF)

Tetracalcium aluminoferrite (C_4AF) acts a filler on porous spaces in the cement matrix (Gartner et al., 2002; Bellmann et al., 2010). However, there is minimal contribution on the strength of shotcrete, although it hydrates rapidly. The reaction of C_4AF with water forms hexagonal plate crystals. The hexagonal plate crystals are denoted by the chemical formula C_3AH_6-C_3FH_6. These hexagonal plate crystals are responsible for filling up the porous spaces in the cement matrix (Bellmann et al., 2010; Saw, 2015). At complete hydration, the reaction can approximately be represented by:

$$4CaO.Al_2O_3.Fe_2O_3 \oplus 2Ca(OH)_2 \oplus 10H_2O \rightarrow 3CaO.Al_2O_3.6H_2O \oplus \oplus 3CaO.Fe_2O_3.6H_2O \tag{2.5}$$

2.2.2.5. Calcium sulphate dihydrate (Gypsum) (CSH_2)

The main purpose of gypsum is to slow down the hydration process of cement when mixed with water (Bellmann et al., 2010; Saw, 2015). This reaction results to the formation of calcium sulphoaluminate hydrate. The chemical formula of the calcium sulphoaluminate hydrate is ($3CaO.Al_2O_3.3CaSO_4.32H_2O$). Furthermore, gypsum is considered as retarding agent of cement, as it regulates setting time of cement (Gartner et al., 2007; Saw, 2015).

The reaction of Gypsum and water is shown by (Saw, 2015):

$$3CaO.Al_2O_3 \oplus 3CaSO_4 \oplus 31H_20 \rightarrow 3CaO.Al_2O_3.3CaSO_4.3H_2O \tag{2.6}$$

2.2.3. Aggregates

Aggregates constitute about 60 – 80 % of the shotcrete matrix (Neville, 2011). As such, the ability to choose durable and suitable aggregates cannot be overemphasized. The role of aggregates is fundamental to freshly mixed and hardened properties of shotcrete (Alexander and Mindess, 2010). The workability and cohesiveness of freshly mixed shotcrete is influenced by aggregates (Neville, 2011; Kosmatka and Wilson, 2011). Large size of the aggregates can cause nozzle blockage and reduce the workability of fresh shotcrete (Malmgren et al., 2005). Meanwhile, small sizes improve the workability and do not cause nozzle blockage upon application. This goes to show the importance of choosing the appropriate size of the aggregate. Conversely, aggregates influence strength, density, and durability of hardened shotcrete (Neville, 2011; Kosmatka and Wilson, 2011).

Malmgren et al. (2005) indicated that materials that are fit to be used as aggregates include sand, gravel, and crushed rocks. These aggregates when mixed with the binding agent, should be able to produce mortar. Aggregates reduce the amount of the cement paste required in the mix; therefore, they act as a fill-up in the production of shotcrete. Kosmatka and Wilson (2011) reported that aggregates occupy a greater volume in shotcrete matrix and are considered cheaper than cement. Physical and mechanical properties of aggregates influence the strength of shotcrete.

This section comparatively looks into the characteristics and influence of basalt and sand aggregates on fresh and hardened properties of shotcrete.

2.2.3.1. Aggregate type

Sand aggregates have been used for decades in the mix design of shotcrete (Ozer et al., 2016; Bajad and Sakhare, 2018). The application of sand aggregates on shotcrete mix design was initially introduced in the early 1900’s (Abrams, 1918). It has proven to be a vital material because of its high strength, good bonding ability and durability (Uddin et al., 2020; Ponnda et al., 2020). Chotaliya et al. (2020) defined sand as a continuously graded unconsolidated material that results from the natural disintegration of sedimentary rocks. While crushed basalt is derived from manually crushing basalt to the desired grain size. Sand and basalt aggregates are depicted in Figure 2.3. Alsadey and Omran (2021) mentioned that sand aggregates are chemically inert and durable. Other benefits of sand aggregates are that they have less clay and silt and that their grains are rounded. On the other hand, basalt aggregates are durable, chemically and physically inert, and strong which enable for adequate packing density in the shotcrete matrix (Al-Baijat, 2008). Basalt aggregates have low absorption which increases the compressive strength of the mortar mixes (Kishore et al., 2015). The rationale of looking into alternative aggregate sources that have improved mechanical properties has generated interest over the past years (Ozer et al., 2016; Bajad and Sakhare, 2018; Uddin et al., 2020). Other factors such as specific gravity, bulk density and aggregate shape contribute to the strength properties of shotcrete. These factors are discussed in the following section.

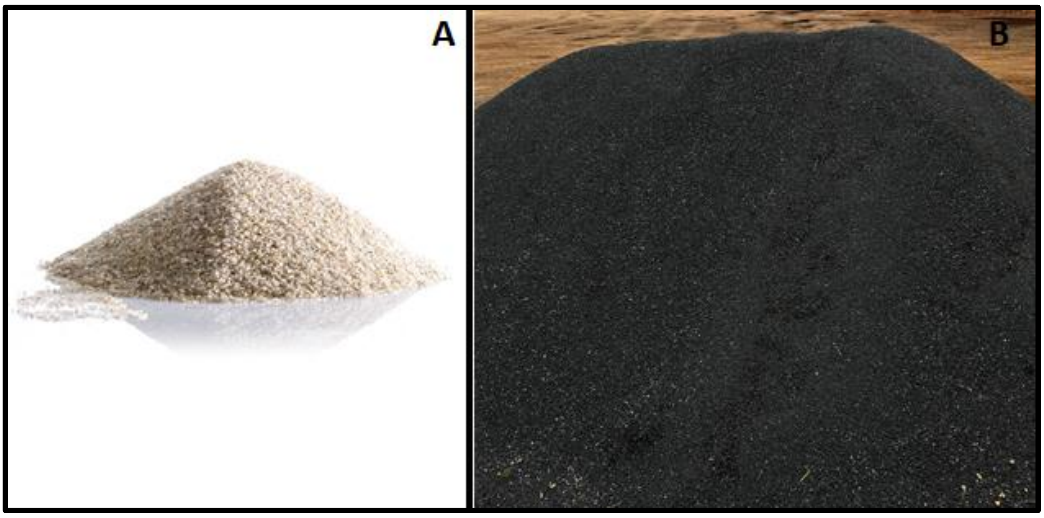

Figure 2.3: (A) Silica sand and (B) Crushed basalt aggregates (Alsadey and Omran, 2021; Al-Baijit, 2008)

2.2.3.2. Aggregate size

Subash et al. (2016) explained that few coarse aggregates (10 mm) and lots of fine aggregates (> 5 mm) are generally required for shotcrete. This is because fine aggregates result in drying shrinkage and coarse aggregates result in the high rebound. Therefore, a balance should be maintained between coarse and fine aggregates. The ACI 506R (2016) has suggested that aggregates used in shotcrete should be graded evenly (coarse and fine), to avoid drying shrinkage and high rebound. Fine and coarse aggregates should also conform to either grading No. 1 or grading No. 2 (refer to Table 2.2) to ensure accurate shotcrete placement. Grading No.1 is meant for fine aggregates while grading No. 2 is meant for coarse aggregates. Shotcrete mix design, consists of fine aggregates (< 4.75mm) and coarse aggregates (10 mm). The proportions of fine aggregates must always exceed the proportions of coarse aggregates. This is meant to promote cohesion, bonding and pumpability. It is depicted in Table (2.2) that the proportion of fine aggregates (grading No. 1) is higher than the proportions of coarse aggregates (grading No. 2) (ACI 506R, 2016). For example, if fine aggregates take up to 80%, then 20% should be taken up by coarse aggregates, in the aggregate proportion of the mix design. This mix proportions promotes interlocking and reduce void spaces in the shotcrete mix.

Table 2.3: Aggregate gradation of fine and coarse aggregates (ACI 506R, 2016)

Sieve size		Percent weight passing individual sieves	
U.S. standard square mesh	Metric	Grading No.1	Grading No.2
3/4 in.	19 mm	-	-
1/2 in.	12 mm	-	100
3/8 in.	10 mm	100	90 to 100
No. 4	4.75 mm	95 to 100	70 to 85
No. 8	2.4 mm	80 to 98	50 to 70
No. 16	1.2 mm	50 to 85	35 to 55
No. 30	600µm	25 to 60	20 to 35
No. 50	300 µm	10 to 30	8 to 20
No. 100	150 µm	2 to 10	2 to 10

Yazici and Mardani-Aghabaglou (2022) argued that the ratio of coarse and fine aggregates is crucial to the framework of shotcrete mix design. The two authors stated that the ratio of coarse-to-fine aggregates represents the aggregate packing density. Several authors (Arumugam, 2014; Mishuk et al. 2015; Aygar, 2020) conducted a study that assessed the influence of packing density on compressive strength of shotcrete. Shotcrete cubes were casted using coarse aggregates (10 mm) and fine aggregates (5 mm). These two mixes were subjected to 7 and 28 curing days. In this work packing density and compressive strength were correlated. Correlation coefficient of 0.953 and 0.998 were reported for coarse aggregate and fine aggregate mix respectively. It can be deduced from these studies that high packing density is experienced with fine aggregate mix. Furthermore, the higher degree of packing density leads to minimum voids in the shotcrete matrix. This subsequently implies that compressive strength of fine aggregate mix is higher than that of coarse aggregate mix. The effect of the fine aggregates on mechanical properties is discussed next.

2.2.3.3. Fineness modulus

Grieve (2009) defines the fineness modulus as a parameter that describes the average particle size of aggregates in terms of how fine or coarse they are. It is crucial to consider fineness modulus when designing shotcrete mix. This is because the average particle size of aggregates has an effect on several properties of shotcrete. Donza et al. (2002) conducted a study to assess the influence of fineness modulus on durability of shotcrete. The aggregates had a fineness modulus of 2.3. The findings indicated that the shotcrete was easy to place during application. This is because fine aggregates have high cohesion than coarse aggregates (Purwandito et al., 2018). Concordant study was conducted by Usman et al. (2015). This study looked into the influence of fineness modulus on compressive strength. The fineness modulus of the aggregates was 2.4. The findings indicated that shotcrete made with fine aggregates experiences early strength gain. In other words, compressive strength is elevated in shotcrete with increased fine aggregates.

The set of fineness moduli of aggregates used in shotcrete range from 1.2 to 3.5 (ACI 506R, 2016). A low fineness modulus (< 3.5) implies that the average aggregate particles are fine. Conversely, a high fineness modulus (> 3.5) indicates predominantly coarse particles in the sample. Karpuz et al. (2017) reported that shotcrete prepared using a low fineness modulus of aggregates requires additional cement which in turn increases water demand. On the other hand, coarse aggregates produce a shotcrete mix that is susceptible to segregation and is difficult to place upon application. Yun et al. (2015) also showed that aggregates with a fineness modulus ranging between (2.2 – 3.15) yield shotcrete that is less likely to crack. In addition to this, the range of fineness modulus (2.2 – 3.15) produces shotcrete with good strength and workability.

To sum this up, the fineness modulus is a good prediction of workability, finish ability, shrinkage, porosity, tendency to crack, and strength. All these properties are essential in the production of shotcrete mix design. The influence of specific gravity on the strength properties of shotcrete is discussed in the next sub-section.

2.2.3.4. Specific gravity

The specific gravity of an aggregate is indirectly considered as the measure of the strength of shotcrete. This influence will later be discussed in this section. Specific gravity can be defined as the ratio of the weight of a given volume of aggregate to the weight of an equal volume of water. ASTM C128 (2001) stated that the specific gravity of aggregates that are used in shotcrete ranges from about 2.5 to 3.2.

Studies indicate that the strength of shotcrete is influenced by the specific gravity of aggregates (Neville, 2000; Ryu and Monteiro, 2002; Al-Oraimi et al., 2006; Grieve, 2009). A directly proportional relationship has been reported between the specific gravity of aggregates and the compressive strength of the resulting shotcrete. This means that an increase in specific gravity leads to a corresponding increase in compressive strength.

Tooley (1989) reported that the specific gravity of sand aggregates ranges from 2.65 to 2.67. On the other hand, Ubi et al. (2020) found that the range for basalt aggregates is 2.7 – 3.3. It can therefore be noted that basalt aggregates are generally denser than sand aggregates. This could potentially imply that shotcrete with basalt aggregates will have higher compressive strength compared to shotcrete with sand aggregates. Indeed, few studies seem to support this; for example, Kandhal and Lee (1970); Ryu and Monteiro (2002); Al-Oraimi et al. (2006); and Neville (2011). Moreover, specific gravity is a proxy for the water absorption of aggregates. This is because aggregates with high specific gravity tend to be less porous and permeable. Schmidt and Graf (1972) indicated that less absorptive aggregates tend to be more resistant to mechanical forces of weathering. As such, shotcrete derived from less absorptive aggregates tend to be durable and mechanically sound (Smith and Collis, 1993; Korkanç and Tuğrul, 2004; Neville 2011).

In summary, the specific gravity of aggregates contributes towards the density of the hardened shotcrete. As such, bulk density of aggregates is pivotal to the quality and durability of shotcrete. The influence of bulk density on shotcrete is discussed next.

2.2.3.5. Bulk density

Bulk density measures the volume that graded aggregate occupies in the shotcrete matrix (Grieve, 2009). It is considered an indirect measure of void content, grading and shape characteristics of aggregates (Al-Baijat, 2008; Grieve, 2009; Vaniya et al., 2016). The bulk density of fine aggregates ranges from 2000 – 2700 kg/m^3 (Sri Ravindrarajah and Lyte, 2003). Neville (2011) reported that high bulk density reduces the void content of the shotcrete matrix. This subsequently promotes compressive strength of shotcrete. Vaniya et al. (2015) noted that sand has a bulk density of 2520 – 2680 kg/m^3. Basalt aggregates, on the other hand, has a bulk density ranging between 2565 kg/m^3 and 2800 kg/m^3 (Al-Baijat, 2008). Bulk density depends on how densely the aggregates are packed, which also depends heavily on the shape, distribution, and size of aggregates. High bulk density is indicative of the reduction in voids present in the shotcrete matrix. Bulk density can therefore be used as an indicator of void spaces in the shotcrete matrix. Although bulk density serves this purpose, it is equally important to assess the porosity of aggregates. This is discussed below.

2.2.3.6. Porosity of aggregates

The porosity of aggregates refers to the void or pore space in a matrix (Grieve, 2009). A correlation exists between the porosity of aggregates and the durability of shotcrete produced from the aggregates. Grieve (2009) observed that the lower the porosity of the aggregates used in the shotcrete mix, the more tightly packed the intrinsic framework is. This subsequently result in increased mechanical strength.

The porosity of aggregates also influences the durability and service life of shotcrete. Walker (2013) explained that the objective of low porosity is to reduce water ingress. This effect of low porosity limits the ability of water to penetrate the shotcrete especially if the water contains deleterious constituents. This type of water can react with the shotcrete, changing its chemical composition, and causing the internal framework structure to collapse. Porosity of aggregates is an indirect measure of water absorption and moisture content of aggregates. The influence of these two factors on shotcrete is discussed next.

2.2.3.7. Water absorption and moisture content

Water absorption of an aggregate is defined as the amount of water that an aggregate can absorb (Grieve, 2009). The water absorption of aggregate used has a significant effect on the water content of the shotcrete mix. This is because water content is responsible for workability of fresh state of shotcrete and strength of hardened state of shotcrete. The water absorption of an aggregate is set at a specific limit of 0.5% to 2.0% (ASTM C127, 2001). A higher water absorption is considered to be > 2% (Grieve, 2009). The usage of aggregates with water absorption that is > 2% can lead to shrinkage of shotcrete during drying. Furthermore, this shotcrete may be deemed unsuitable for support because it is susceptible to freeze thaw cycles. Such that when the temperature decreases, water will freeze in the pores, resulting to expansion of pores. All in all, this will lead to crack development in shotcrete. Water absorption is indirectly related with moisture content of the aggregate because they assess the water requirement in the shotcrete mix.

Moisture content is defined as the amount of moisture that can be retained by aggregates (ACI, 2006). Moisture content can cause major inconsistencies on shotcrete. Furthermore, moisture content can have dramatic effect on the compressive strength and durability of shotcrete. ACI (2006) has set specific limits of moisture content of aggregates to be between 0.2 wt% and 2 wt%. Increased moisture levels reduce the durability of shotcrete. An increase in moisture content, leads to an increase in void spaces (Lee et al. 2013). These voids are filled with air after the moisture evaporates. This results in inadequate compaction reducing the shotcrete`s strength gain period. Shotcrete with trapped air levels as little as 10% experiences reduction in strength (ACI, 2016). For the production of shotcrete that has high strength and durability, it is advisable to use aggregates with less moisture content. The interest in aggregates stems from their physical and chemical characteristics. More information can be derived about the nature of aggregates from their mineral constituents. In the subsequent section, petrographic analysis of major minerals that are included in sand and basalt aggregates are assessed.

2.3. Petrographic analysis

Petrographic characteristics of aggregates exhibits significant bearing on physical and mechanical characteristics of shotcrete. It is essential to use non-reactive aggregates in shotcrete (Mishuk et al., 2015). This is because they do not contribute towards side reactions that weaken the shotcrete mixture (Mehta and Monteiro, 2006). Conversely, reactive aggregates form part of side reactions that are destructive to the matrix of shotcrete (Liew et al., 2017; Mohajerani et al., 2017). Neville (2011) affirmed that aggregate chemistry, can significantly affect the durability and service life of the shotcrete mixture. This section focuses on the mineralogy of sand and basalt aggregates.

2.3.1. Mineralogy of sand aggregates

Sand aggregates are defined as unconsolidated sedimentary rock, with grain sizes between 2 mm and 63 µm (Herrick, 1990). The abundant mineral in sand aggregates is quartz. The quartz grains are considered to be highly pure with grain sizes that are rounded to sub-angular. The presence of quartz contributes towards the hardness and chemical structure of sand aggregates. Quartz is considered as a durable mineral that hardly weathers. Howari (2015) elaborated that sand consists of 98% of quartz, the remaining 2% constitutes of minor traces of carbonates and dark minerals. Howari (2015) conducted an XRD analysis on sand aggregates to assess the major mineral components. The major constituent of sand aggregates is quartz as depicted in Figure 2.4.

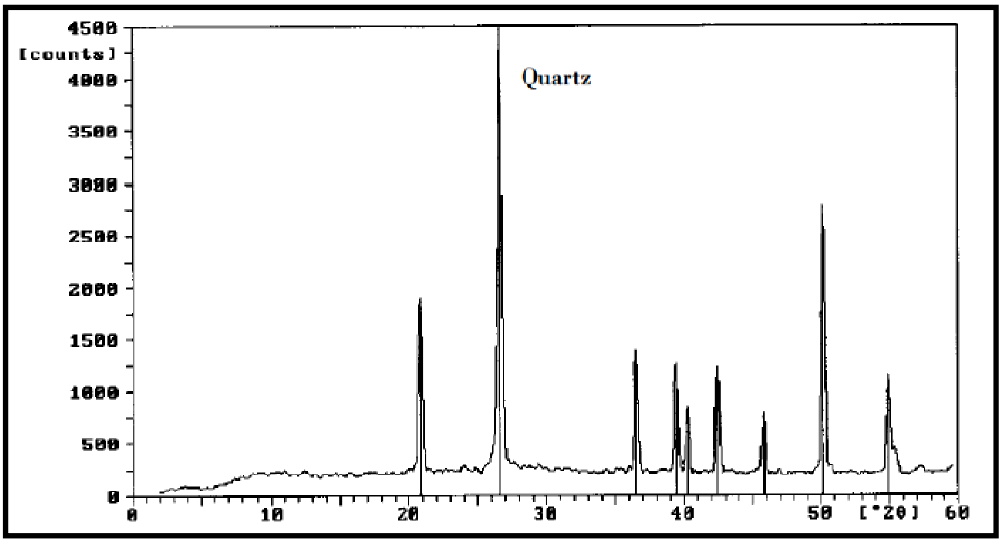

Figure 2.4: XRD analysis of silica sand (Howari, 2015)

The chemical formula of quartz is (SiO_2), which implies that silicon and oxygen are present. Note that silica is hard, has high melting point, and high resistance to chemical weathering. These characteristics are attributed to the microscopic bond that exists between the bonds of silicon and oxygen (Jung et al., 2014). Also, Herrick (1990) conducted an XRF analysis on the major mineral constituents depicted in Table 2.4.

Table 2.4: XRF analysis of silica sand (Herrick, 1990)

Mineral constituents	%
SiO_2	99.7
Fe_2O_3	0.007
Al_2O_3	0.07
TiO_2	0.021
$K_2O + Na_2O$	0.02
CaO+ MgO	0.03
LOI	0.03
Total	99.9

Although SiO_2 takes the highest portion, there is a minimal value of minerals such as Al_2O_3, Fe_2O_3, MgO and K_2O. These minerals (Al_2O_3, Fe_2O_3, MgO and K_2O) contribute towards resistance in aggressive media, thermal conductivity and corrosion (Sharma, 2016). However, in sand aggregates those minerals occur in small quantities. The XRF analysis showcases the minerals that contribute towards durability of shotcrete. It can be summarised that mineral characteristics affect the fresh and hardened properties of shotcrete. It is crucial to also look into the mineralogical characteristics of basalt aggregates to enable a comprehensive comparison. Section 2.3.2 assesses the mineralogy of basalt aggregate and their influence on mechanical properties of shotcrete.

2.3.2. Mineralogy of basalts aggregates

Basalt aggregates are derived from crushing of basaltic igneous rock into the preferred size (Murray, 2019). Dominant mineralogy includes plagioclase feldspar, pyroxene, and olivine (Crow and Condie, 1990). Bumby (2000) conducted an XRF analysis to investigate the major minerals present in basalt aggregates. Findings indicated that major minerals included Al_2O_3, SiO_2, Fe_2O_3 and MgO as depicted in Table 2.5. These minerals contribute towards tensile properties, thermal conductivity, resistance to aggressive mediums and corrosion (Sharma, 2016). These characteristics influence engineering properties of shotcrete. The incorporation of these aggregates to shotcrete mix design leads to the formation of high strength performance and durable shotcrete.

Table 2.5: XRF analysis results of the basalt from the Sibasa Formation (Bumby, 2000)

wt%	Sample 175 **23°06.73'S; 28°47.61'E**	Sample 177 **23°07.10'S; 28°50.10'E**	Sample 208 **23°07.30'S; 28°54.70'E**
SiO_2	49.05	50.84	48.56
TiO_2	1.27	0.93	1.96
Al_2O_3	13.45	14.13	14
Fe_2O_3	13.8	11.83	16.31
MnO	3.59	6.25	5.42

MgO	12.12	9.33	6.92
CaO	0.16	1.95	3.83
K_2O	3.68	1.49	0.048
P_2O_5	0.14	0.09	0.25
Cr_2O_3	0	0.01	0.02
NiO	0.01	0.02	0.01
LOI	1.44	2	2.54
Total	98.97	99.12	100.62

The presence of these minerals has contributed towards the advantageous characteristics of basalt aggregates over sand aggregates. The application of shotcrete in underground mines encounters challenges pertaining the suitable temperature range for shotcrete material. This is because temperature in underground mines can become excessively high or low. Therefore, a thermo-durable aggregate source would be advantageous in such conditions. ACI (2016) stated that the application of shotcrete in an underground setting with a temperature of below (5°C) could affect the adhesion of shotcrete to the area of application. This may cause some challenges during the setting and strength development of the shotcrete.

Kubiszewski (2012) reported that basalt is thermodynamically stable, they are non-reactive toward frost and elevated temperature. This is because melting range of basalt is at 1250 – 1500°C. The presence of plagioclase in basalt aggregates ranges from the form of albite to anorthite (Wu et al., 2013). This implies that sodium and calcium can be mutually substituted in the crystal lattice that forms them. Wu et al. (2013) stated that the significance of calcium is that it promotes cohesion in the shotcrete mix.

Basalt aggregates are non-combustible and explosion-proof (Iyer et al., 2015). When basalt aggregates are in contact with other chemicals, they produce no chemical reaction that may incur health or environmental damages. Lee et al. (2013) reported that during the production of shotcrete, factors such as corrosion risk, sustainability and environmentally friendliness are important. Wu et al. (2013) stated that basalt aggregates have resistance against an alkaline environment with the capability to withstand pH range of up to 13 – 14. Furthermore, basalt aggregates have strong resistance against the action of fungi and micro-organisms (Murray, 2019). The chemical composition and mineralogical features of basalt define its ability to be a suitable aggregate source in shotcrete. Overall, the mineralogical composition of aggregates influences the strength properties of shotcrete. Hence, Section 2.4 presents the effect of aggregates on water-to-cement ratio and strength properties of shotcrete.

2.4. Factors affecting the shotcrete strength

The strength of shotcrete is mainly affected by water-to-cement ratio, quality of mix ingredients, curing age, curing method and temperature amongst other factors. These factors contribute immensely to the production of the desired shotcrete that will suffice as support in underground mining. This section reviews these factors. Furthermore, fresh and hardened properties of shotcrete, performance of shotcrete and mechanical strength properties of shotcrete are reviewed.

2.4.1. Water-to-cement ratio

Water-to-cement ratio (w:c) is considered an important factor in the successful application of shotcrete. It is also considered as an indicator of the compressive strength.

In 1918, Duff A. Abrams investigated the relationship between compressive strength and water-to-cement ratio (Figure 2.5). He noted that as the water-to-cement ratio increases, the compressive strength decreases. Duff's water-to-cement rule resulted to an equation which can be expressed as follows (Duff, 1918; Jankovic et al., 2011):

$$F_c = \frac{k_1}{k_2^{w:c}} \qquad (2.7)$$

Where k_1 and k_2 are empirical constants.

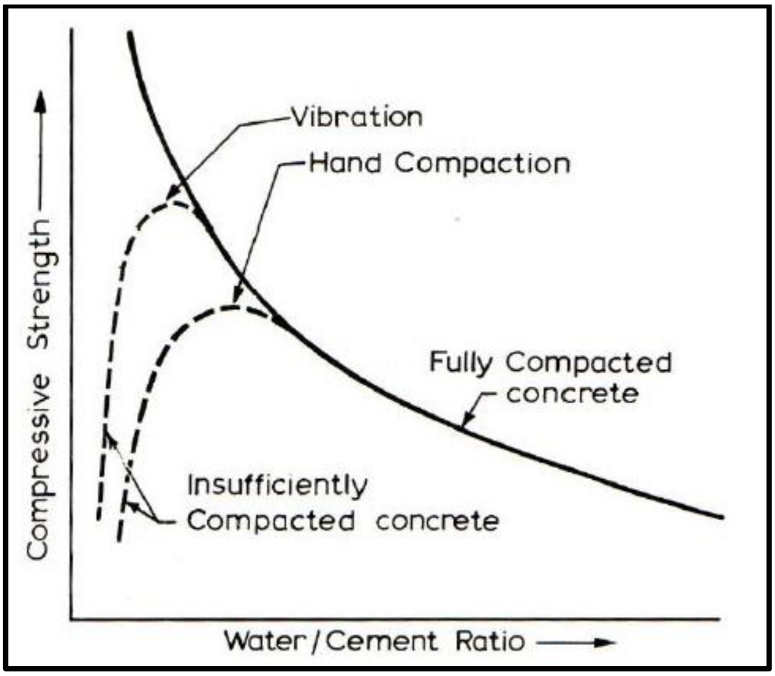

Figure 2.5: Influence of water to cement ratio on compressive strength (Neville, 2011)

The decrease in compressive strength with an increase in water-to-cement ration is due to the voids that form in the shotcrete matrix as a result of excess water. These voids increase porosity subsequently dropping the compressive strength of shotcrete.

Figure 2.5 also shows that excess water in shotcrete mix design is not desirable due to its weakening effect on the compressive strength. It is therefore advisable to regulate the water-to-cement ratio in order to acquire the desired compressive strength. It is a recommendation from ACI (2016) that the required water-to-cement ratio of shotcrete mix design ranges between 0.3 – 0.4. However, the incorporation of naturally crushed rock aggregates requires a water-to-cement ratio of 0.4 – 0.6 (Kosmatka et al., 2003; Mehta and Monteiro, 2006). Practical observations have justified the range 0.4 – 0.6 to ensure that the mix can be workable and easy to flow upon placement. Indeed, adequate water content will initiate hydration thereby allowing the mix design to gain the desired strength adequately.

Water-to-cement ratios of 0.6 have also been reported to produce a shotcrete mix that is resistant to corrosion (Ahmad and Shabir, 2005; Waziri et al., 2011; Shamsai et al., 2012). This can lead to the production of economical shotcrete mix. Adequate water-to-cement ratio also ensure pumpability and workability of shotcrete as is discussed next.

2.4.2. Workability

Workability is defined as the ease of mixing, transporting and placing of shotcrete without segregation of its constituents to produce full compaction of shotcrete (ACI, 2016). Jolin and Beaupré (2000) indicated that slump required for pumping shotcrete is typically between 75 and 150 mm. The workability of shotcrete mix design can be affected by water-to-cement ratio and particle size. Rooney (2002) showed that high water content results in greater workability. However, caution must be granted during the addition of water to avoid decreasing the compressive strength or leading to segregation of shotcrete. In terms of particle size, Koehler (2003) indicated that fine aggregates (> 300 µm) require a high water-to-cement ratio which leads to greater workability.

All in all, the addition of water should be carefully done to achieve adequate hydration. This will ensure that the shotcrete mix is workable and easy to place. In the end, good workability guarantees the successful application of shotcrete. After the placement of shotcrete, curing takes place immediately. Curing is recognized as a very important process to achieve strength gain of shotcrete. The impact of curing is discussed next.

2.4.3. Curing

Curing of shotcrete is essential in preventing the premature drying out. It also plays a major role in the development of the strength and hardness of shotcrete. Adequate development of strength and hardness leads to improved durability and performance of shotcrete.

Common methods used in curing shotcrete include water sprinkling and water immersion. Ogah (2016) assessed the effectiveness of various curing methods. He found from his study that water-sprinkling and water immersion were the most effective, producing a high compressive strength after 28 days of curing. In addition to this, Sharma and Sood (2017) reported that immersion curing is the best method of curing shotcrete cubes. This is because immersion curing was found to encourage the development of maximum compressive and flexural strength to take place as summarised in Table 2.7.

Table 2.7: Development of flexural strength under various curing methods (Sharma and Sood, 2017)

Curing method	Flexural strength (kN/mm^2)			
	7 days	14 days	28 days	56 days
Immersion curing	3.84	3.90	**4.37**	4.56
Air curing	1.56	1.72	1.96	2.01
Wet covering curing	2.86	2.91	4.12	4.30
Plastic films curing	2.54	2.86	3.92	4.02
Sprinkling curing	2.84	2.94	3.30	3.76
Membrane curing	3.02	3.06	3.38	3.58

Water immersion curing also produced the highest compressive strength in comparison to other methods, see Table 2.8.

Table 2.8: Development of compressive strength under various curing methods (Sharma and Sood, 2017)

Curing method	Compressive strength (kN/mm^2)			
	7 days	14 days	28 days	56 days
Immersion curing	21.92	28.78	**33.20**	35.56
Air curing	13.25	21.92	18.93	18.94
Wet covering curing	21.72	27.74	31.86	33.54
Plastic films curing	17.92	25.86	27.85	29.04

Sprinkling curing	11.88	24.28	25.68	29.26
Membrane curing	18.24	23.88	28.22	29.74

Various studies concurred with the fact that water immersion curing is advantageous over other curing methods (Princy and John, 2015; Usman and Isa, 2015). Furthermore, immersion curing has been found to be effective not only at developing shotcrete strength, but also at achieving good shotcrete properties (Safiuddin and Raman, 2007; James, 2011; Abalaka and Okoli, 2012; Al-Bakri et al., 2013).

The reduction of pore space is paramount during the hydration process and compressive strength development. Atoyebi et al. (2020) conducted a comparative study of the effect of different curing methods on the development of compressive strength. As shown in Table 2.9, it can be seen that the use of sprinkling and ponding methods (water immersion) gave higher compressive strengths. Therefore, depending on resources available, water immersion, sprinkling method and membrane method may prove to be beneficial on the compressive strength of shotcrete cubes. Although water immersion curing produces good compressive and flexural strengths, it is difficult to apply on the site and is limited to flat surfaces (Olofinnade et al., 2017). However, practical laboratory testing prefers water immersion curing. Various factors that contribute to compressive strength are discussed in Section 2.4.4.

Table 2.9: Mean compressive strength of various curing methods (Atoyebi et al., 2020)

	Mean compressive strength (kN/mm^2)				
Curing days	Open-air curing	Sprinkling method	Ponding method	Membrane method	Earthing method
7 days	5.34	6.68	8.32	7.79	7.23
14 days	5.80	7.01	9.95	8.80	7.97
21 days	6.43	7.47	11.50	11.09	8.93
28 days	7.84	8.08	11.66	11.08	10.82

56 days	12.61	14.12	19.10	13.09	11.15

2.4.4. Compressive strength of shotcrete

The compressive strength of shotcrete is its ability to keep rocks intact in underground mining. ACI (2016) reports that the compressive strength at 28 days is supposed to be 30 – 40 MPa. However, for special applications such as permanent tunnel lining, the compressive strength is expected to be 40 MPa at 28 days (SANS: 5863, 2006).

In practical terms, the strength of shotcrete can be defined as the force per unit area required to cause disintegration. Equation (2.8) provides a practical formula for calculating the compressive strength (ACI, 2016):

$$F_c = \frac{P}{A} \tag{2.8}$$

Where F_c represents the compressive strength in MPa

P is the load at failure (kN)

A is the cross-sectional area in mm^2

Compressive strength of shotcrete is an important parameter for engineering design of support. Shotcrete should have resistance to fracturing (Cebasek and Likar, 2014). This is to ensure that it maintain stability and integrity of underground excavations. Compressive strength is also used as an indicator of the performance and quality of shotcrete (Neville, 2011). Shotcrete design takes into consideration this important property.

Al-Swaidani et al. (2015) assessed the compressive strength of shotcrete cubes made with the incorporation of basalt aggregates and later immersed in an alkali aggressive media. Shotcrete cubes (150 mm x 150 mm x 150 mm) were prepared and cured in a media with 10% NaOH. The cubes developed an average compressive strength of 40 MPa, which still falls within the acceptable range recommended by ACI. The ability of basalt aggregates to withstand harsh conditions also enabled for the adequate development of compressive strength. Indeed, Tsado (2013) reported that volcanic rocks are reactive to alkali-silica reaction; however, basaltic aggregates typically show low reactivity. Similarly, Ubi et al. (2020) tested the efficacy of basalt in shotcrete mixes. The compressive strength of cubes (150 mm x 150 mm x 150 mm) was measured after 28 days of water curing and found to be 36.39 MPa. This is close to the 40 MPa reported by Al-Swaidani et al. (2015).

Bhuvaneswari et al. (2015) studied the development of the compressive strength of mortar cubes that incorporated sand aggregates. Shotcrete cubes (150 mm x 150 mm x 150 mm) were subjected into a media with 10% NaOH. After 28 days, the average compressive strength was found to be 32.2 MPa. Compared to the findings by Al-Swaidani et al. (2015) presented above, it can be deduced that shotcrete cubes with basalt aggregates are more durable than those with sand aggregates. A factor that could have contributed to the findings is the porosity known to be high in sand than in basalt aggregates (Rameshwar and Shrikant, 2017).

Al-Baijat (2008) conducted a laboratory experimental test of compressive strength on shotcrete cubes with sand and basalt aggregates respectively. Various proportions of sand and basalts were used (0%, 25%, 50%, 75%, and 100%). These proportions imply the following (0% basalt and 100% sand); (25% basalt and 75% sand); (50% basalt and 50% sand); (75% basalt and 25% sand); and (100% basalt and 0% sand). The shotcrete cubes were cured under water immersion for the duration of 28 days. The results indicated that the increase in basalt content enhances the mix strength over curing days (Figure 2.6). Optimal compressive strength was noted on the mix proportion of (50% basalt and 50% sand) and (100% basalt and 0% sand). It can be deduced that incremental addition of basalt improves the compressive properties of shotcrete mixes. This is because basalt is denser, more durable and less water absorbing compared to sand. It can therefore be concluded that an increase in basalt content in the shotcrete mix tends to enhance the strength property.

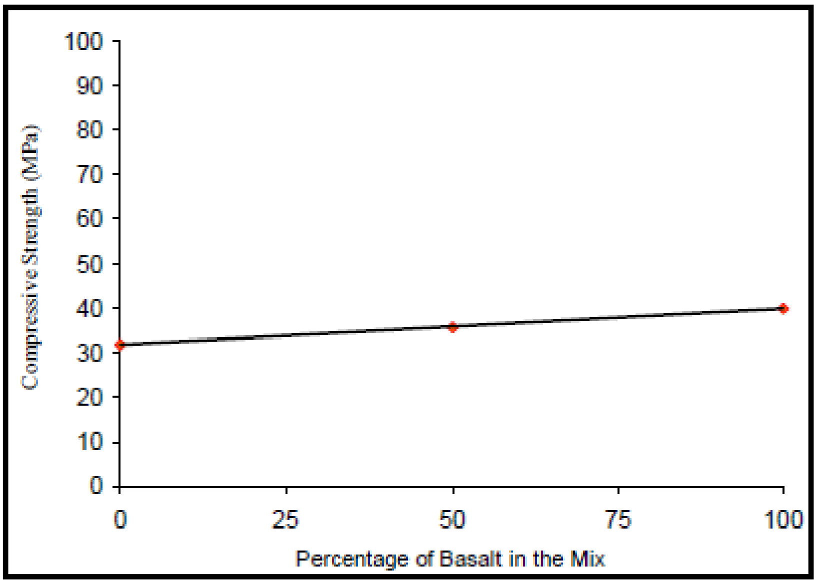

Figure 2.6: Compressive strength of concrete mixes inclusive of various proportions of basalt and sand aggregates (Al-Baijat, 2008)

Yang et al. (2020) conducted a comparative study of the effect of aggregate types on compressive strength. The study focused on four kinds of aggregates; namely, syenite, sandstone, marble, and basalt. The shotcrete cubes made with these aggregates were cured under water sprinkling method. Curing was done over the duration of 7, 28, 90 and 180 curing days.

The results illustrated in Figure 2.7 depicted that compressive strength of syenite-based shotcrete cubes were the lowest. Meanwhile basalt-based mortar cubes were the highest. This high compressive strength is attributed to the hardness of basalt aggregates in comparison to these other aggregates. The findings of the compressive strength of shotcrete cubes are related to the hardness property of the aggregates. The order of hardness of these aggregates type corresponds to the findings of compressive strength of this study. Donza et al. (2002) reported that the hardness of basalt ranges from (6 – 7); sandstone (4 – 5); marble (4 – 5); and syenite (3 – 4). Therefore, compressive strength gain corresponds efficiently with the hardness of the aggregates.

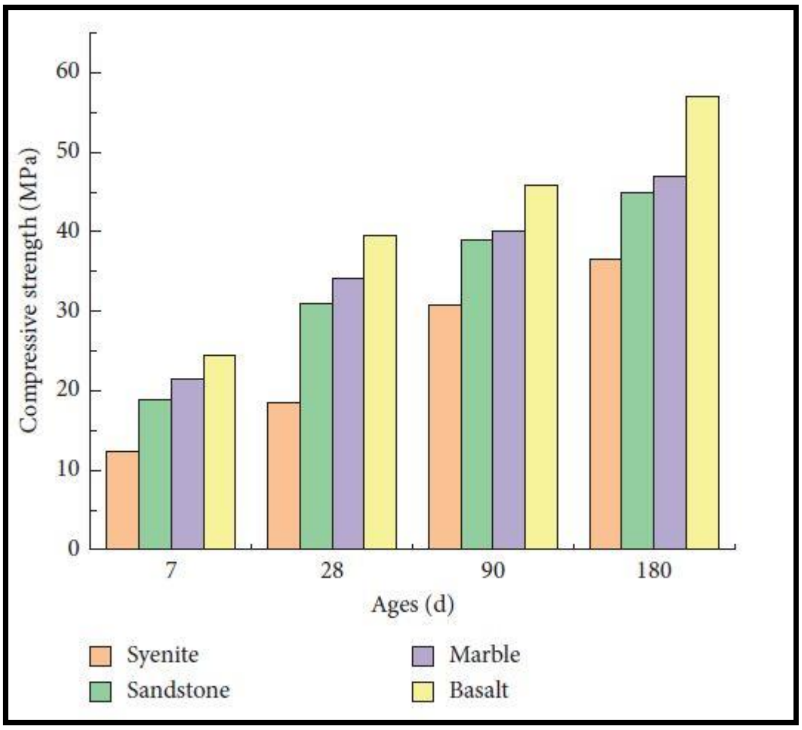

Figure 2.7: Compressive strength of concrete cubes made from four types of aggregates that are cured over the duration of 7, 28, 90 and 180 days (Yang et al., 2020)

Luc Leroy et al. (2017) compared the strength of shotcrete made from sand and crushed basalt. Shotcrete cubes (150 mm x 150 mm x 150 mm) were prepared and cured for a period of 90 days. Shotcrete mixes made from crushed basalt recorded a compressive strength of 34 MPa at 28 days. Conversely, the shotcrete mixes made with sand yielded a compressive strength of 24 MPa at 28 days. The presence of hard minerals such as olivine, clinopyroxene and plagioclase in basalt aggregates was argued to have a bearing on the results. In view of this, it may be concluded that crushed basalt aggregates offer more resistant shotcrete mixes compared to sand aggregates.

Jha et al. (2016) conducted an experiment aimed at assessing the durability of basalt aggregates in shotcrete mixes. Durability is defined as the ability to withstand pressure, damage and wearing out (Murray, 2019). Two shotcrete mixes were prepared, with the following mix proportions (50% basalt and 50% sand) and (70% basalt and 30% sand). The durability of these mixes was assessed through shotcrete cubes (150 mm x 150 mm x 150 mm). The findings indicated that high compressive strength was found in the mix proportion (70% basalt and 30% sand) than in (50% basalt and 50% sand). The compressive strengths were 36.39 MPa and 32.45 MPa respectively. The compressive results were attributed to the fact that basalt aggregates are less permeable, this increases their resistance to compressive forces.

Underground mining presents various challenges including seismically hazardous regions. Adejuyigbe (2019) affirmed that this can be combated by using basalt aggregates because they have impact-resistance. This reduces the rate of damages that can be caused by seismic activities such as stress waves generated from blasting. Indeed, shotcrete can provide support to a key block as illustrated in Figure 2.8. This ensures that there is no fall of ground during the transmission of stress waves due to blasting (Malmgren, 2001).

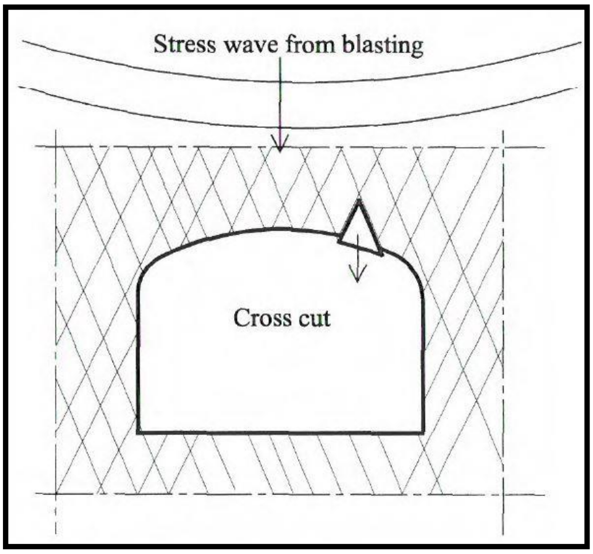

Figure 2.8: Transmission of stress wave from blasting to rooftop of underground mine (Malmgren, 2001)

Compressive strength is widely considered to be the most valued property of shotcrete (Al-Baijat, 2008; Murray, 2019; Luc Leroy et al., 2017). Chiemela (2015) reported that compressive strength gives a clear indication of the quality of shotcrete. Studies reviewed in this section have shown that shotcrete mixes with crushed basalt aggregates generally show high compressive strength compared to sand-based mixes. Other properties include grain size, durability and permeability. However, another pivotal mechanical characteristic that is necessary to assess in shotcrete is the flexural strength. Relevant work published around the flexural strength is covered in the next section.

2.4.5. Flexural strength

Flexural strength is widely regarded as a measure of shotcrete to withstand bending stress. According to ASTM C 293 (2010), the expected flexural strength of shotcrete at 28 days ranges between 0.6 MPa and 8.0 MPa. The flexural strength (in MPa) can be estimated as follows:

$$F = \frac{3PL}{bd^2} \tag{2.9}$$

Where P is the failure load (kN);

L is the effective span of the beam (mm);

b is the breadth of the beam (mm);

d is the failing point depth (mm)

Ubi et al. (2020) studied the flexural strength of shotcrete mixes with basalt aggregates. Shotcrete beams (210 mm x 150 mm x 300 mm) were casted for the purpose of testing flexural strength and cured for 28 days. The flexural strength was measured to be 8.3 MPa. In another study, Al-Baijat (2008) measured the flexural strength of shotcrete mixes prepared using basalt aggregates of different proportions (0%, 25, 50%, 75% and 100%). These proportions imply the following (0% basalt and 100% sand); (25% basalt and 75% sand); (50% basalt and 50% sand); (75% basalt and 25% sand); and (100% basalt and 0% sand). Shotcrete beams (20 cm x 25 cm x 310 cm) were also casted and tested for strength. The findings revealed an increase in flexural strength as the proportions of basalt aggregate in shotcrete mixes increased (see Figure 2.9). It can be concluded that the increase in basalt content in mortar mixes tend to enhance the mechanical properties of mixes.

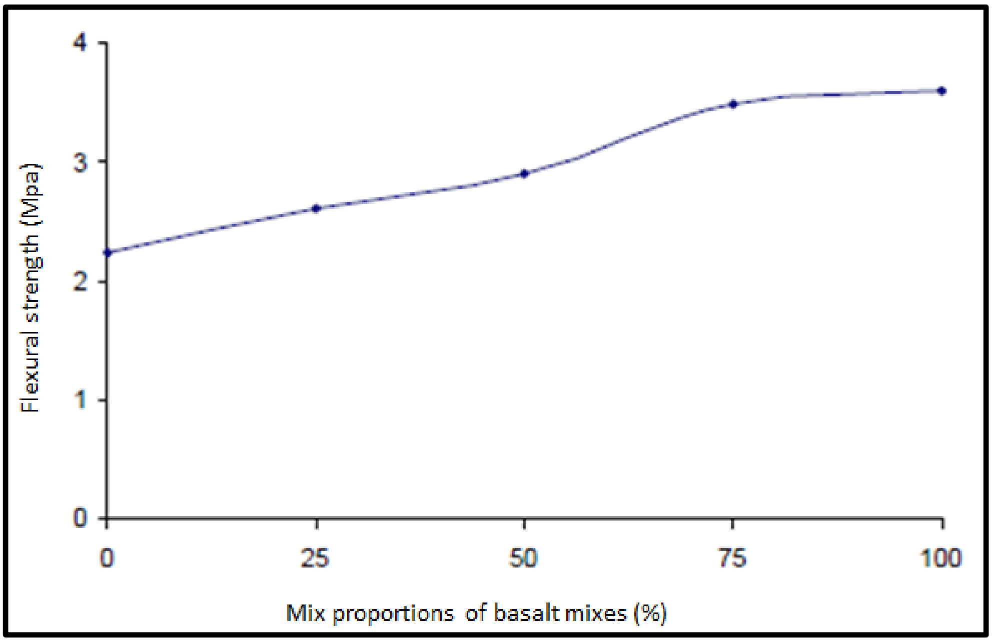

Figure 2.9: Flexural trends of concrete mixes with various proportions of basalt and sand aggregates (Al-Baijat, 2008)

Jha et al. (2016) investigated the flexural strength of basalt aggregates in shotcrete mixes. Shotcrete cylinder (150 mm x 300 mm) of two shotcrete mixes were prepared. The shotcrete mixes included the following mix proportions (50% basalt and 50% sand) and (70% basalt and 30% sand). From the findings it was indicated that the flexural strength was 5.13 MPa and 5.07 MPa respectively. It is clear that an increase in basalt aggregates leads to a considerable increase in flexural strength of the shotcrete mixes. The intent of the study was to show the importance of looking into the incorporation of basalt aggregates as a potential aggregate source of shotcrete. In this case, it can be summarised that the use of basalt aggregate in shotcrete mixes presents advantageous characteristics. The use of basalt aggregates in shotcrete mixture is a field with much potential. Hence, the current study focuses on the potential incorporation of basalt aggregates in shotcrete to improve the strength of the shotcrete mix design. Bakyalakshmi et al. (2017) set up an experimental study to assess the flexural strength on shotcrete cubes with basalt aggregates. A (150 mm x

300 mm) shotcrete cylinder of was prepared with the inclusion of (50% basalt and 50% sand), cement and water. The findings after 28 days were reported to be 3.27 MPa. Compared to other studies (Jha et al., 2016; Ubi et al., 2020; Al-Baijat, 2008), this flexural strength is relatively low. This is attributed to the low chemical composition of Al_2O_3 which is responsible for flexural properties. The presence of Al_2O_3 in these basalt aggregates was recorded as 9.45 wt%. Meanwhile, the normal range of Al_2O_3 is at 13.46 – 14 wt%. The reduced amount of Al_2O_3 is likely due to the fact that these basalts are derived from a low-alkali magma (Crow and Condie, 1990).

Satheesh and Rajasekhar (2018) assessed the flexural performance of sand on shotcrete mixes. A (500 mm x 100 mm x 100 mm) beam was prepared and subjected to water sprinkling curing over 28 days of curing. The flexural strength was found to be 6.74 MPa. On the other hand, Pachipala (2017) assessed the flexural strength of sand. A beam (500 mm x 100 mm x 100 mm) was prepared. After 28 days of curing, the shotcrete beam developed a flexural strength of 8.07 MPa. The difference in flexural strength between the aforementioned studies can be ascribed to the source region of sand aggregates. Indeed, sand aggregates leading to high flexural strength shotcrete generally have high quartz content. This is due to the fact that quartz improves the resistance to break when incorporated into shotcrete mixes (Vaniya, 2015; Permual and Sundarajan, 2003).

Past studies reviewed in this section have highlighted that shotcrete mixes with crushed basalt aggregates generally show high flexural and compressive strength compared to shotcrete mixes with sand aggregates. Although strength properties of shotcrete are critical to its successful application, it is equally important to consider the failure modes of shotcrete and its interaction with rock surface. The application of shotcrete in underground mines are therefore discussed next in view to understand the importance of shotcrete mix design in combating some failure modes.

2.5. Importance of shotcrete in underground excavations

High quality shotcrete should exhibit good adhesion with the surface of application. The bond strength of shotcrete with various rock surfaces, is crucial to the performance of shotcrete. Bond strength is defined as the ability of joining two materials together (Malmgren et al., 2005). Holmgren (1998) stated that bond strength depends on parameters such as the homogeneity of the shotcrete and conditions of the rock surface of application. Certain rocks form better bonds with shotcrete resulting in effective support (Clements, 2003). Meanwhile, some rocks form weak bonds with shotcrete, in such a case, shotcrete is deemed as an unsuitable support system. For example, strong and intact rocks that generally show effective bonding with shotcrete include sandstone, quartzite and chromatite (Wakizaka, 2000). In contrast, rocks such as weathered friable shale and soft mudstone hardly bond with shotcrete (Golser, 1976). Failure modes of shotcrete usually occur because of de-bonding. Section 2.5.1 explores various possible failure modes experienced in underground mining.

2.5.1. Failure modes

Possible failure modes include adhesion loss, punching shear, direct shear, compressive failure, flexural failure, and tensile failure. These possible failure modes can decrease the effective support of the shotcrete. Therefore, these failure modes of shotcrete are pivotal, hence they are discussed in detail below.

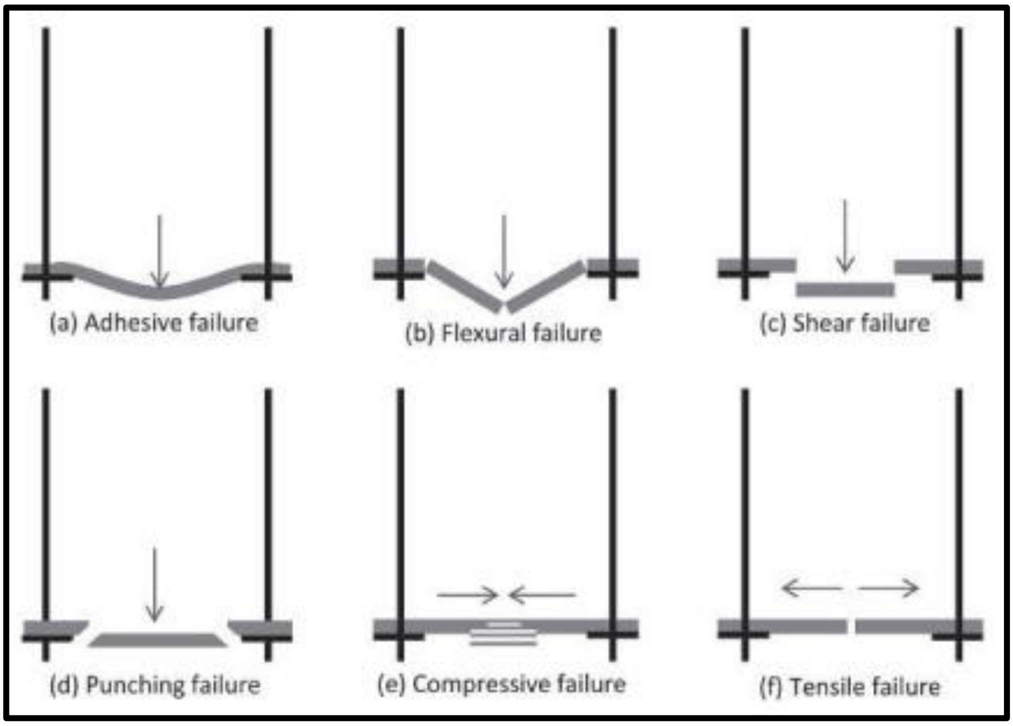

Figure 2.10: Six failure modes of shotcrete (adopted from Kong and Garshol, 2015)

2.5.1.1. Adhesive loss failure

Failure ascribed to adhesive loss occurs due to loss of adhesion between the rock surface and shotcrete. Malmgren and Svensson (2003) as well as Kuchta (2002) pointed out that adhesive failure occurs when the shotcrete-rock bond strength is weak relative to the dead weight of the shotcrete. This subsequently results in the shotcrete falling. As shown in Figure 2.10(a), the fallout of the shotcrete is indicative of the poor adhesion due to the tension perpendicular to the surface.

According to the evidence validated by the Chilean Institute of Occupational Health and Safety (OCHS) and other organisations around the world, at least 12.6% of mining accidents are related to FOG (Oraee-Mirzamani, 2011). Thus, shotcrete has an important role to play in preventing accidents. Therefore, choosing durable material that counteract the effect of de-bonding is crucial.

2.5.1.2. Flexural failure

Flexural failure occurs once adhesion between the rock and the shotcrete is lost. This is where the shotcrete bends so much, such that tensile cracks open up at the mid span and cracks grow through the shotcrete (Uotinen, 2011). This initiates cracks at the surface between the rock and the shotcrete as depicted in Figure 2.10(b). It is hence crucial to assess the flexural strength of aggregates to combat the flexural failure upon application of shotcrete.

2.5.1.3. Direct shear failure

Direct shear failure occurs when a differential load acting on the shotcrete layer exceed the shear strength of the rock-shotcrete bond (Uotinen, 2011). This results in shotcrete sharply breaking off from the rock surface as depicted in Figure 2.10(c). Displacements in shotcrete associated with direct shear failure are derived from geological discontinuities.

2.5.1.4. Punching shear failure

The failure of punching shear arises when a concentrated load is applied to a small area of shotcrete-rock interaction. The small area of load application consists of fractures as depicted in Figure 2.11. The rock and shotcrete interaction may consist of fractures that may be caused by geological discontinuities or blasting induced fractures. These fractures contribute towards punching shear failure. This type of shear failure propagates along these fractures. Eventually resulting to sliding failure of shotcrete-rock layer depicted in Figure 2.13. This type of shear failure has no warning, as it just suddenly happens. Hence, it is necessary to determine the weight of the rock surface that can sufficiently be supported by shotcrete. This is done in efforts of preventing this type of failure from occurring.

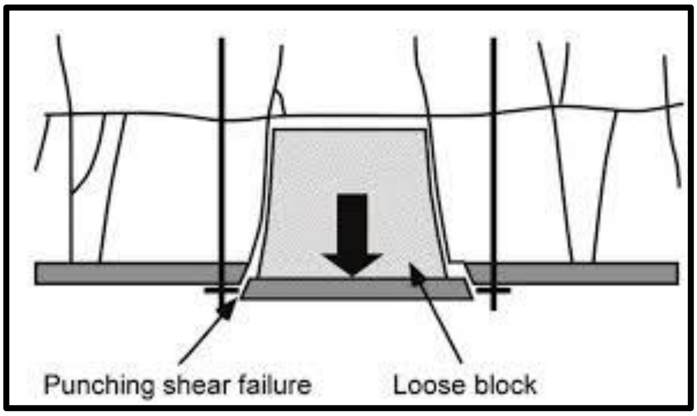

Figure 2.11: Punching shear failure mode of shotcrete-rock layer (Barret and McCreath, 1995)

2.5.1.5. Compressive failure

Shotcrete experiences compressive failure when it is subjected to high stress concentrations tangential to the excavation surface as depicted in Figure 2.10(e). Principal high stress concentrations are sub-horizontal, leading to shortening of the shotcrete application (Stacey, 2009). Furthermore, compressive failure may also occur during sudden violent rock mass failures which generate low energy demand (< 5kJ/m^2) on the shotcrete layer (Uotinen, 2011).

This mode of failure is most prevalent in three instances. Firstly, it is most likely to occur in the shoulders and roof of the excavation. Secondly, compressive failure is usually visible when shotcrete is applied too close to the end of the tunnel. Thirdly, compressive failure is experienced when there is continuous load bearing across the shotcrete layer which generate fractures. The successful usage of shotcrete takes into consideration all these types of failure modes. This is to ensure that fatalities and effective support is provided in underground excavation.

2.5.1.6. Tensile failure

The failure of tensile in shotcrete occurs due to effective pulling stresses across the plane. When the pulling stresses exceed a critical limit of pulling, tensile failure occurs as depicted in Figure 2.10(f) (Uotinen, 2011). Tensile failure in shotcrete is common in wide span excavations and at the apex of intersection of underground pillars. However, this failure is quite rare in underground excavations.

2.5.2. Reducing FOG through shotcrete application

The use of shotcrete as ground support is effective in reducing fatalities and injuries caused by FOG accidents. Shotcrete in conjunction with other support elements can provide early and effective ground support. The primary focus in underground support is to ensure that workers are safe and therefore there is a need to provide immediate and effective shotcrete support. A thin layer of shotcrete is applied as surface control to prevent the rock from unravelling. This thin layer of shotcrete stabilizes the newly exposed surface and prevents very small rock and debris from falling. Furthermore, this prevents air slacking and dehydration of the rock material exposed in the cracks.

Several scholars have highlighted the importance of shotcrete as support in underground mining (Golser, 1976; Potvin and Hadjigeorgiou, 2004; Stacey, 2009). Shotcrete minimizes movements along joint planes. This stabilises the tunnel surface. Shotcrete smoothens the sharp corners of a tunnel. As a result, stress concentrations are eliminated. Shotcrete also acts as a strengthening outer layer to the rock. Due to adhesion, the rock and shotcrete then acts as a unit with enhanced strength. Another benefit of shotcrete is that it prevents the rock from weathering by insulating it from moisture, air and running water. This in turn prevents the reduction in strength of the rock. Shotcrete also prevents the additional loosening of the rock mass and penetrates into joints and cracks to produce a wedging effect like mortar in a wall or arch.

Stacey (2009) indicated that shotcrete provides support to the rock mass through sealing the dilated fractures. In this case shotcrete acts a sealant support, filling up the fractures. This is done with the aim of reducing the propagation of fractures. It can be summarised that fractures are the primary causes of most of these shotcrete failures. These failures should be studied thoroughly prior to the application of shotcrete. This is because shotcrete failure modes affect the performance of shotcrete. Section 2.6 assesses the general performance of shotcrete upon application in underground excavations. This section also addresses successful and unsuccessful application of shotcrete and possible causes.

2.6. Performance of shotcrete

The primary goal of shotcrete is to aid rocks around the tunnel to self-support. Factors such as bond strength, temperature and the rock mass itself affect the performance of shotcrete. In some instances, shotcrete is not feasible as the sole support system amongst others. This section therefore discusses the effect of temperature on shotcrete performance. Secondly it presents the characteristics of shotcrete that govern its adhesion to the rock surface. Lastly, case studies on successful and unsuccessful application of shotcrete are presented.

2.6.1. Shotcrete and temperature

The temperature of the environment in which shotcrete is applied plays a crucial role as it affects the structural components of shotcrete. High temperatures have been known to accelerate the deterioration of shotcrete, subsequently compromising its performance (Yun, 2015; Zhu et al., 2017; Chen, 2017; Zhang, 2019). In a case study, Brook (1998) reported a temperature of 65°C of underground rock at the Mponeng Gold Mine in South Africa. The exposure of shotcrete to this temperature led to progressive water loss. This can then cause the expansion and disruption of shotcrete and ultimately lead to what is known as spalling of shotcrete.

Various studies have been conducted to assess the influence of high temperature on the mechanical properties of shotcrete. Lee et al. (2013) and Yang (2013) for example studied the variation of shear strength of shotcrete applied on granite with surface roughness under the influence of temperature. Shear strength is defined as the strength of a component against yielding over a shear load (Zhu et al., 2017). Lee et al. (2013) indicated finding that shear strength was 0.23 MPa which is relatively low. Meanwhile Yang (2013) indicated that the shear strength was 0.25 MPa. The normal range of shear strength of shotcrete lies within 0.3 – 0.5 MPa. The relatively low shear strength is indicative of the negative impact of high temperature on shear performance of shotcrete.

Cui et al. (2013) investigated the effect of temperature on the bond strength of shotcrete and rock surface. The bond strength initially increased at elevated temperatures and later decreased. At a later stage the bond strength decreased by 36.7% from 999.74 kPa. It was however, indicated by Zhang (2019) that high temperature affects the effectiveness and feasibility of shotcrete. Therefore, the use of thermo-durable material in the mix design of shotcrete, is advantageous. More especially in cases where shotcrete is applied in high temperature areas.

In another study, Dong et al. (2017) investigated the fracture process of the interface between shotcrete and rock under high temperature. The findings indicated that the structure of shotcrete develops fractures rapidly under high temperature.

Ping et al. (2019) conducted some tests to determine the effect of temperature on the compressive strength and the splitting tensile strength of shotcrete. Shotcrete was applied on a gneiss rock surface and cured under water immersion. The temperature of the water was constantly increased from 0°C to 100°C. During the increase in temperature compressive and split tensile strength were assessed. The experimental results depicted that both the compressive and tensile strength increased with curing age at an environmental temperature of 40°C. This is because 40°C is considered as an acceptable temperature range that can still provide the optimum compressive and tensile strengths. Also, at the temperature of 65°C compressive and tensile strengths decreased with curing age as depicted in Figure 2.12. The trends depicted in Figure 2.12 is indicative of the fact that high temperature > 65°C negatively affects the tensile and compressive strengths of shotcrete over various curing age.

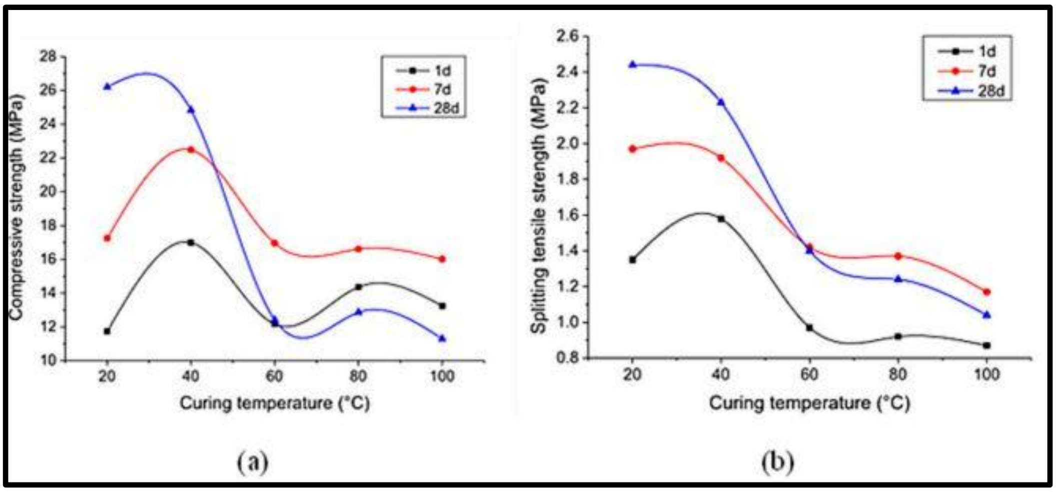

Figure 2.12: Mechanical properties of shotcrete for selected curing ages and under various curing temperatures: (a) Compressive strength and (b) Splitting tensile strength (Ping et al., 2019)

Zhu and Zhao (2016) also assessed the influence of temperature on early strength development of shotcrete. Shotcrete was applied on a granite rock surface and cured under water sprinkling. The temperature of water that was sprinkled was increased from 40°C to 70°C. Meanwhile, observation of the effect on compressive and tensile strength were noted. It was reported from the findings that early strength development of shotcrete increases when curing temperature is at the range of 35 – 40°C. However, beyond this temperature range, compressive and tensile strengths decrease. Overall, the two experiments showed that compressive strength and splitting tensile strength decrease when the temperature is too high. The observation is believed to be due to shotcrete shrinkage thereby affecting the performance of shotcrete in underground excavations.

Shotcrete has been widely used particularly in deep mines prone to violent rock failure due to mining induced stresses (Villaescusa, 2014). Section 2.6.2 reviews few case studies that have led to recommendations for areas where shotcrete can be suitably applied.

2.6.2. Application of shotcrete – Case studies

The last two decades have seen a substantial increase in the application of shotcrete and particularly in Canadian hard rock mines (Wu et al., 2013; Subash et al., 2016). Bryne (2014) advised that shotcrete should be applied immediately after blasting activities has taken place. This is meant to prevent fallout of smaller blocks and secure the arch shape of underground tunnel. It has been noted by Bryne (2014) that shotcrete support improves the capacity of the tunnel to carry the weight of the surrounding rock mass. The sealant effect of shotcrete provides support to the walls of underground tunnels (see Figure 2.13).

Figure 2.13: Application of shotcrete in underground mining to prevent rocks from FOG (Bryne, 2014)

Shotcrete in conjunction with other support elements such as rockbolts and wiremesh can provide effective ground support (Yugo and Shin, 2015). Aygar (2020) emphasized that the primary focus of underground support is to ensure safety of workers, uninterrupted production, and stable ground. Despite its anticipated benefits, shotcrete does not find use in all types of underground operations. Limitations to the applications of shotcrete are discussed next.

Venter and Gardner (1998) assessed the effectiveness of shotcrete application at Oryx Mine in South Africa. In this case, shotcrete was applied on a competent uneven granite surface. As the shotcrete mix was conveyed through the hose, there was segregation of the mix due to the long distance of application. As a result, there was poor quality application of shotcrete. This generally led to poor adhesion of the shotcrete to the rock walls. It was later noticed that in numerous places of application, shotcrete began to fall off from the rock wall. At this point, shotcrete application by itself is not a suitable support system. Further investigations conducted by (Bernardo et al. 2015; Bamigboye et al. 2018) revealed that the use of meshing and lacing as a support medium enhances the performance of shotcrete application.

Neuner et al. (2017) argued that underground mines do not depend on the sole support of shotcrete. However, rockbolts and wiremesh are support arrangements that are commonly used in conjunction with shotcrete. This is because several modes of support failure are predominant in areas where shotcrete is the only primary support (Bernado et al., 2015; Ajamu et al., 2012; Connor et al., 2016). Indeed, mineral exploitation activities such as blasting lead to the development of mining induced stresses. When subjected to high tangential stress, areas of thick shotcrete application can be prone to compressive failure (Connor et al., 2018). As a result, the failure mechanism may lead to violent spalling of shotcrete (Bryne, 2014). In this instance, it is advisable to install reinforcement such as rock bolts and wire mesh to improve the retention properties of shotcrete. Conversely, failure experienced when shotcrete is used as a sole support system, provides basis of incorporating other support systems. In addition to this, the shotcrete mix design can be altered to improve the mechanical performance of shotcrete. Moreover, adhesion loss contributes majorly to the failure of shotcrete application. The next section further elaborates on the importance of the adhesion characteristics of rock substrate and shotcrete. It also talks about how the adhesion characteristics contribute to the successful application of shotcrete.

2.6.3. Adhesion characteristics of shotcrete on surrounding rocks

The bond interface between shotcrete and rock surface has long been recognized as critical to the performance of shotcrete used as ground support. Ghiasi and Omar (2011) stated that the effectiveness of shotcrete as a structural support or as a sealant is strongly dependent on the bond between shotcrete and rock substrate. ACI committee 506.5R (2006) highlighted the importance of surface preparation in ensuring adequate bonding between shotcrete and substrate. Surface preparation is meant to remove impurities such as dust and laitance that can affect the shotcrete-substrate bonding. Poor preparation will lead to inadequate bonding that can subsequently cause the shotcrete layer to spall or slough off the surface of application as depicted in Figure 2.14.

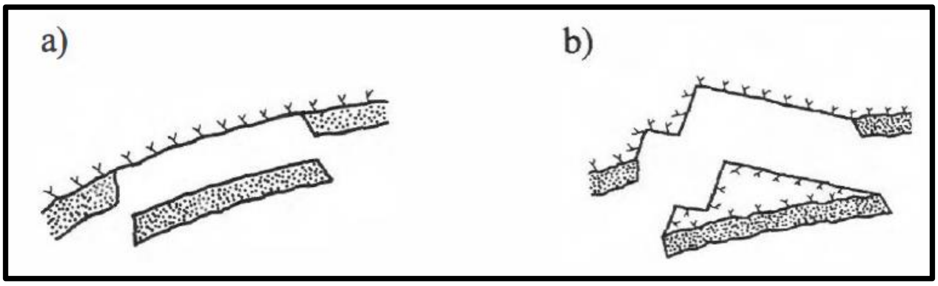

Figure 2.14: Fallout modes of shotcrete and rock: (a) fallout of shotcrete only and (b) fallout of rock and shotcrete (Malmgren and Svensson, 2003)

In summary, bonding strength is crucial to the performance of shotcrete (Malmgren et al., 2006; Ghiasi and Omar, 2011; Bryne, 2014). When shotcrete is well bonded to the rock surface, it can prevent the reduction in support capacity of the tunnel. Amongst other factors bond strength between rock surface and shotcrete is crucial for the successful application of shotcrete. Therefore, to achieve the required flexural and compressive strengths, shotcrete must be adequately bonded with the rock surface. The successful application of shotcrete provides underground excavations with support that can surely reduce incidences of fall of ground thereby keeping underground excavations safe. Section 2.7 summarises the major discussions of the review in light of various factors that contribute to the successful application of shotcrete.

2.7. Summary

Shotcrete is widely used in underground mining operations to provide support. Compressive strength, flexural strength, and bond strength are critical mechanical properties linked to the application of shotcrete as support. Various studies reviewed in this chapter have shown that curing method and age of shotcrete has an impact on the development of compressive and flexural strengths. Another factor that contributes to strength gain is the hydration reaction. During the hydration reaction cement phase (C_3S) lead to an optimum compressive strength of 25 MPa after 28 days of curing. Furthermore, the cement phase C_3S is responsible for early strength development in shotcrete. Strength properties of shotcrete determines the quality and durability of shotcrete. Also, the ingredients in the mix design contribute towards the desired mix that can meet the strength requirements.

The usage of basalt aggregates as a replacement of sand has presented improved strength properties. The performance of shotcrete cubes made from basalt aggregates proved to be improved compared to performance of shotcrete cubes with sand aggregates. It was summarised that the incorporation of basalt content improves the mechanical performance of shotcrete. This is because basalt aggregates offer a range of properties such as physical strength, thermo-durability and, resistance to chemical and physical weathering. These ranges of properties enable basalt aggregates to be a suitable alternative to sand aggregates. Furthermore, physical characteristics of sand and basalt aggregates were reviewed. This included bulk density, specific gravity, fineness modulus, water absorption, moisture content, size and shape. From literature review, it was deduced that basalt aggregates consist of high density and specific gravity compared to sand aggregates. This improves the compressive and flexural strength of shotcrete mixes with basalt aggregates. Meanwhile the size and shape of crushed rocks improves the interlocking matrix of shotcrete. Thereby improving cohesiveness of the shotcrete mix ingredients. Another contributing factor to the successful application of shotcrete include the bond between the rock surface and shotcrete. Major factor that can lead to de-bonding include temperature and type of rock surface. Elevated temperature affects the bond strength. It is therefore advantageous to have aggregates that are thermo-durable. Conversely, hard competent rock such as gneiss and granite provide good bond strength. While friable rock masses such as shale and mudrock hardly bond with the shotcrete layer. Previous studies (e.g., Al-Swaidani et al. 2015; Luc Leroy et al. 2017; Bakyalakshmi et al. 2017; Pachipala, 2017) have been conducted with efforts of showcasing advantageous characteristics of basalt over sand aggregates. These studies have proven that the incorporation of basalt aggregates in shotcrete presents minimal issues on pumpability during application. These findings demonstrated that crushed basalt aggregates may provide a greater benefit in shotcrete production in comparison to sand aggregates. The preliminary results derived from studies by Jha et al. (2016), Al-Baijat (2008) and Ubi et al. (2020) may serve as the basis to further verify the applicability of crushed basalt aggregates. It can be concluded that this type of research is crucial to identify the shotcrete behaviour with basalt aggregates. This literature review has highlighted advantageous characteristics of basalt aggregates. These characteristics qualify basalt aggregates to be incorporated in shotcrete that will be used in underground as support. The review also discussed the failure modes of shotcrete. It was quite clear that all failure modes that occur are initiated by de-bonding, through fractures or geological discontinuities. The shotcrete mix is designed to meet the strength and quality assurance standards, so that adequate support can be provided in underground excavations. The review has provided a platform of exploring shotcrete with basalt aggregates. This is done with the efforts of providing an alternative to sand aggregates while still providing shotcrete that is durable and serviceable in underground excavations.

Chapter 3: Experimental design and equipment used

This chapter provides relevant details about the experimental design plan, equipment used and standard operation procedure for the various strength tests conducted. The data collected and methodology are presented in accordance with the objectives that the dissertation is set to achieve. Lastly, challenges encountered during the experimental investigation and their implications on results are discussed.

3.1. Introduction

In order to respond to the objectives of the study, shotcrete prisms were used for the purpose. The shotcrete prisms were prepared using basalt and sand as the aggregate component of shotcrete. All the shotcrete prisms were subjected to water immersion curing for 28 days. The duration was divided into 7, 14, 21, and 28 days. For each mix type there were replicates making a total of (24 prisms), which were divided into 6 prisms. These 6 prisms per mix type were later subjected to compressive and flexural strengths tests over the various curing ages.

The following steps were executed in all tests: aggregate characterisation, X-Ray Fluorescence (XRF) analysis, preparation of shotcrete mix, curing and measurement of compressive and flexural tests. Detailed descriptions of each data collection and analysis procedure are documented in the subsequent sections.

3.2. Data collection and sampling

Bhardwaj (2019) defines a sample as an individual or group of individuals drawn from a large population. If variations between samples are negligible, then, the information obtained from the samples can be taken as representative of the population at large. In terms of a geological formation, primary sampling involves looking into individual points and localities to provide an overview of the entire formation.

Primary sampling was conducted at the Sibasa Formation, South Africa. The previous location points (i.e., 23° 06' 73''S; 28° 47' 61''E) noted by Crow and Condie (1990) informed the sample location of this study. In this study, the basalt rock samples were collected along the following coordinates (22° 59' 00''S, 29° 45' 50''E). This is still within the marginal lava flow of the basalt rock in the Sibasa Formation. Furthermore, Crow and Condie (1990) conducted an XRF compositions analysis. It is from the XRF analysis, that basalt was deemed as an acceptable aggregate source that can be used for shotcrete mix design. Rock samples were collected in the area of the Tshikweta village located proximal to Thohoyandou town as depicted in Figure 3.1.

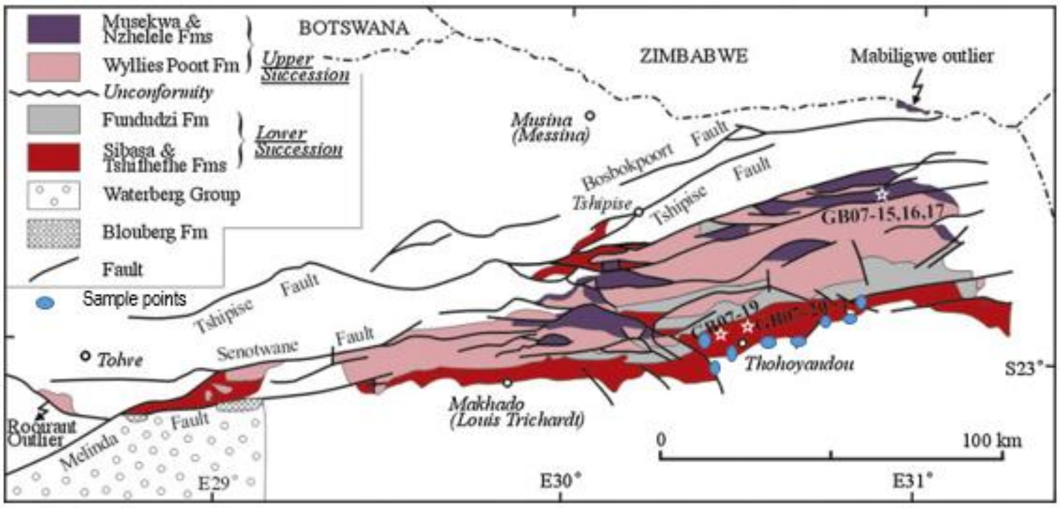

Figure 3.1: Location of Sibasa Formation that consists of basaltic rocks, that covers the lateral extent from Thohoyandou to Makhado Town, Limpopo (Adopted after Bumby, 2000).

Samples were found as an intact rock as shown in Figure 3.1. However, they had to be broken down using a sledgehammer to ensure that they are easily movable from the source point of collection to the transporting vehicle. Samples of basalt aggregates were also collected along the Sibasa Formation, as depicted in Figure 3.1. The samples were named L1, L2, L3, L4, L5, L6, L9 and L10, they were taken from 8 different locations. These samples were later subjected to petrographic and geochemical analyses, and the results are discussed in detail later in Section 4.2.

Figure 3.2: Basaltic rock sample that was broken down in the field (Own picture taken from Tshikweta village)

Sampling was followed by an on-site collection of basalt aggregates. In this regard, a detailed description of how each sample was collected is presented in the next section.

3.3. On-site collection of basalt aggregates

The lava flow within the Sibasa formation left several basaltic outcrops. These could be located at various source points in the Sibasa area and the Tshikweta Village. The whole rock sample was broken down into small pieces of rocks easy to carry as shown in Figure 3.3. The fragments of broken rock were filled in sample bags of 5 kg each.

Figure 3.3: Broken basaltic rock samples from the field (Taken from Tshikweta village)

Basalt aggregates used in this study were part of the Sibasa Formation which is a volcanic succession with sub-aerially extruded basalt. An example of amygdaloidal basalt found in Sibasa Formation is shown in Figure 3.4. Barker (1979) stated that basaltic rocks in the Sibasa Formation have sub-ophitic texture, amygdaloidal, massive and generally overlain by a thick layer of fertile soil. As time elapses, this layer erodes and leaves behind a reddish to brownish stain on top of the Sibasa basalt as depicted in Figure 3.4. Radiometric dating was used to date the Sibasa basalt. The Rb-Sr method of dating was used. The age of Sibasa basalt is between 1.9 – 1.8 Ga (Cheney et al.,1990).

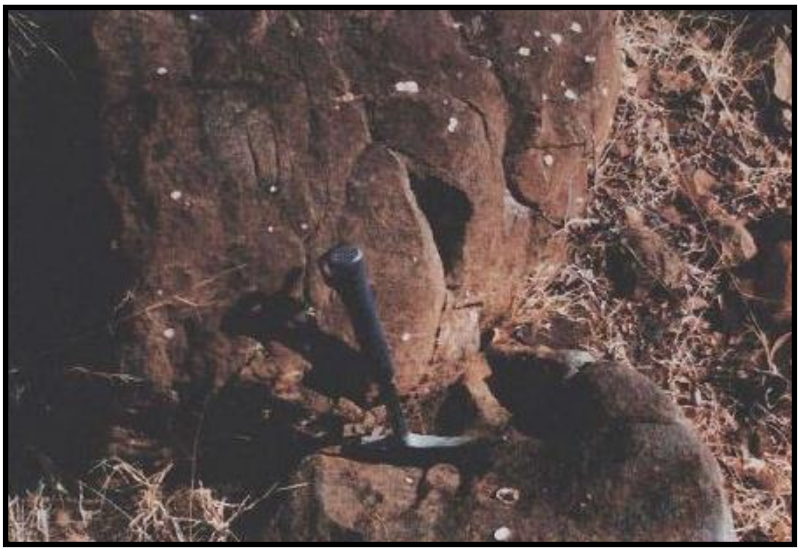

Figure 3.4: Amygdaloidal basalt of Sibasa Formation at 23°06.68'S; 28°52.32'E (Adopted after Bumby, 2000). The hammer is 30 cm long.

The mineralogy of basalt aggregates is a key component that influences its performance when used as an aggregate source in the shotcrete mix. In light of understanding the mineralogical contribution of basalt aggregates, its mineralogy is discussed in detail in the next section. Samples that were collected were subjected to various laboratory tests which include mineralogical tests (XRF). The details of these experiments are discussed next.

3.3.1. Mineralogy of Sibasa basalt

Sibasa basalts is categorised as a mafic extrusive igneous rock that was formed under rapid cooling of magnesium-rich lava. Basalt is classified as a mafic rock due to it being rich in magnesium (Mg) and iron (Fe) and poor in silica (SiO_2) (Bumby, 2000). Stepien and Kostrzewa (2019) elaborated that the presence of magnesium and iron offers beneficial physical qualities. These qualities include high resistance to chemical and mechanical weathering. Furthermore, basalt rocks exhibit a semi-crystalline structure. This means that these components are less reactive to amorphous substrates. The chemical inertness and abundance of basalt rocks makes it a lucrative aggregate source.

Chief mineral assemblages that are present in basalt include pyroxene, plagioclase and olivine (Klein and Dutrow, 2007). Ndung`u (2018) suggested that the presence of these mineral assemblages have contributed to chemical stability and resistance to corrosion. Sharma (2016) devised various effects of minerals on the mechanical properties of aggregates (Table 3.1). It can be summarised that shotcrete mix that has basalt aggregates will have mechanical advantageous characteristics.

Table 3.1: Minerals found in basalt and their mechanical properties (Sharma, 2016)

Minerals	**Factors affected by mineralogy**
Al_2O_3 and SiO_2	Tensile properties
Fe_2O_3 and FeO	Thermal conductivity
CaO, TiO_2, MgO	Water resistance and resistance to aggressive media
Na_2O and K_2O	Corrosion resistance in alkali-rich mediums

A detailed account of the characterisation is made in the next section. This entails crushing, splitting, milling and sieve analysis of the basaltic aggregates.

3.4. Characterisation of the aggregates

The main purpose of aggregate characterisation is to measure various physical attributes of aggregates. This is conducted to ensure that important information about aggregates is known during preparation of shotcrete mix. Furthermore, the preparation processes of basalt included crushing, milling, splitting and sieving. The processes of basalt preparation are discussed in detail in the next section.

3.4.1. Crushing

On-site samples of basalt rock fragments were sealed in plastic bags to ensure that there is no contamination during transportation. These bagged samples were later taken to the Council for Geoscience (CGS) in Pretoria for sample characterization. The rocks in the sample bags are subjected to a rock jaw crusher as depicted in Figure 3.5. A JC series Eurostar model jaw crusher was used. The jaw crusher had a capacity speed of 50 – 2700 t/h and a maximum feeding size of 1800 x 2100 mm. The operational phase of a jaw crusher consists of two crushing jaws, whereby one is stationary, while the other one is moving. The rock sample falls into the top of a crushing chamber. Then, it is squeezed between the two crushing jaws. The crushing jaws exerts compressive force to break down large material of rocks into smaller and more manageable sizes. At this stage, the aggregates are still coarse and requires further processing to reduce the aggregate size.

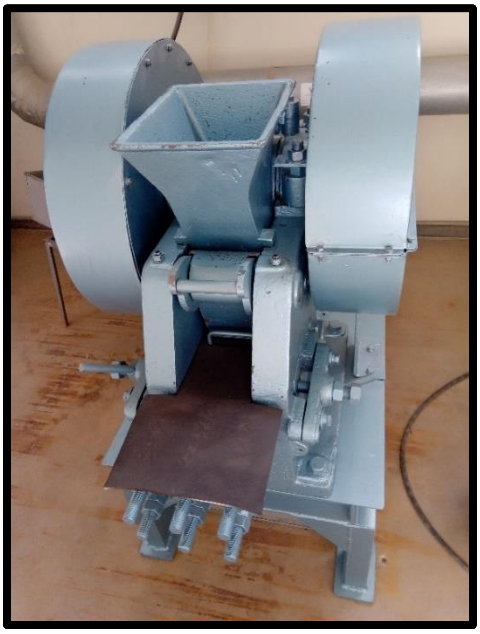

Figure 3.5: Jaw crusher (Council for Geoscience)

Pieces of rock samples shown in Figure 3.6(a) are product derived from laboratory jaw crushing process. This yielded a product made up of smaller aggregate fragments ranging in sizes of 2 mm to 3 mm as illustrated in Figure 3.6(b).

Figure 3.6: (a) Rock samples collected on site and (b) smaller size aggregates as the product of crushing

3.4.2. Splitting of aggregates

The next step after jaw crushing consisted of splitting the crushed product. Splitting is meant to reduce variability and acquire a representative sample of the aggregate between 400 g and 1600 g. The procedures followed for splitting coarse aggregates were in accordance with ASTM Practice C-702 (1998). Initially, a 5 kg bag of crushed rock was arbitrarily selected for reduction to a representative 500 g sample that was to be used at a later stage for XRF analysis. Following that, a fraction of the bag content was poured onto a receiving pan. The content of the pan was then poured into a Jones riffle shown in Figure 3.7(a). The splitter released the aggregates as two fractions of approximately equal mass into two chutes. The process was repeated numerous times until the content of the bag was emptied into the Jones riffle. One of the two fractions collected from the riffle chutes was further split through the riffle. The cycle was repeated with the product from one of the two receptacles approximately eight times until a 500 g sample was acquired. These samples as seen in Figure 3.7(b) were later subjected to the XRF analysis.

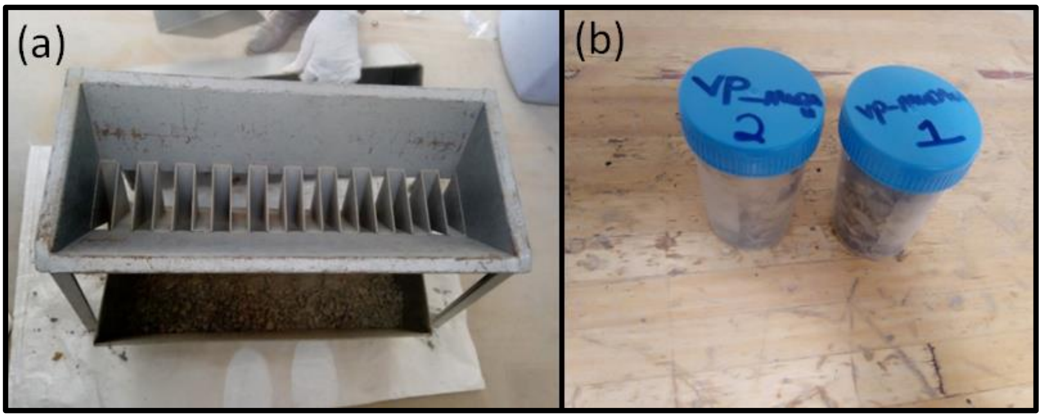

Figure 3.7: (a) Jones riffle for the splitting of aggregates into (b) representative samples

Representative samples from splitting were subjected to milling to further reduce their particle size. The process of milling is discussed next.

3.4.3. Milling of split aggregate samples

Milling or grinding is used to further reduce the size of the crushed aggregate samples (2 mm to 3 mm) into fine powder (≥ 500 μm). In addition to that, Kara and Budak (2015) mentioned that milling also removes contamination and moisture from aggregates.

Milling typically consists of two balls with size of 50.8 mm each. The ball mill has an open and close direction on the wheel as depicted in Figure 3.8. Opening the wheel means that rock samples of 3 mm can be crushed to medium grained sizes of 1.5 mm. Meanwhile, closing the wheel means that rock samples can be crushed to finely grained sizes. About 5 kg of crushed rock samples are placed onto the milling chamber and the wheel was open fully. The ball mill mechanically broke the crushed rocks from 3 mm to 1 mm. The wheels were turned three times to close, to ensure that the size is reduced. The milled samples were later placed onto the milling chamber and the grain size was reduced from 1 mm to 500 μm. A batch of 5 kg of crushed samples was subjected to the ball milling for 15 minutes at a time. The milling equipment was used to reduce the crushed basalt aggregates into finer particles as required. Although milling took place, however, to be precise of the grain size, sieving needed to be done. Sieving of the milled aggregates is discussed in the next section.

Figure 3.8: Ball milling equipment at the Council for Geoscience

3.4.4. Sieving

Aggregate sieving was conducted to ensure that the size of aggregates is precise. In this study, aggregate sieving was conducted in accordance with ASTM C33 (1999). The interest of this study falls within aggregates of grain sizes 425 µm, 250 µm, and 150 µm. These grain sizes are classified as fine-grained aggregates. Sieve pans that were used include 600 µm, 425 µm, 250 µm, 150 µm and a retaining plate. The vibrator on the sieving plate was set for 10 minutes at a speed of 1200 m/s. The material that amounted to 2.5 kg was subjected to sieving at a time. However, nothing was retained on 600 µm sieve pan. A portion of material was retained amounting to 18 kg of grain size 425 µm and 18 kg of grain size 250 µm. The material retained after the 150 µm sieve plate was combined with material found in the sieve pan 150 µm amounting to 25 kg. This is because the combination does not change the average grain size of 150 µm. The particle size distribution is used to extract two major properties of the sample material: grading, and fineness modulus. Figure 3.9 shows the sieve shaker for particle size analysis and the product of sieving which are 425 µm, 250 µm, and 150 µm.

Figure 3.9: (a) Sieve shaker and (b) sieved products (425 µm, 250 µm and 150 µm) of basalt samples

The physical characteristics of aggregates are important in assessing the suitability of an aggregate source. The next section focuses on physical characteristics of aggregates used in this study.

3.5. Characterisation of the physical properties of aggregates

Aggregates constitute an essential proportion in the preparation of shotcrete. They are mainly used to stabilize the shotcrete and limit the need for cement thereby reducing the cost of production of shotcrete. In terms of this research, the type and particle size of aggregates are essential to achieve malleable, cheap, workable, coherent, and high strength shotcrete. The characterisation of aggregates is important for the proper mix design of shotcrete. The properties include size, shape, bulk density, specific gravity, water absorption and moisture content of sand and basalt aggregates (Addis and Goodman, 2009). In this dissertation, the following properties of sand and basalt aggregates were measured: Fineness modulus, bulk density, density and specific gravity, water absorption and moisture content. Details of each property are presented in this section.

3.5.1. Fineness modulus

Fineness modulus is a measure of particle size distribution that quantifies the average size of the aggregates in a shotcrete mix. The size of particles greatly affects the workability, strength and durability of mortar once cured (Karpuz et al., 2017). That is why the determination of the fineness modulus is important.

In the context of the current study, fineness modulus was measured by standard sieving of the milled aggregates through the sieves of the following apertures: 7.10 mm, 5.00 mm, 2.00 mm, 1.00 mm, 0.60 mm, 0.30 mm, 0.15 mm, and 0.075 mm. The material retained in each sieve pan is converted into percentages. Sand and basalt aggregates were oven-dried at 105°C for 24 h to remove any trace of moisture that might lead to contamination. Then, a setup similar to Figure 3.10 was used for particle size analysis.

Figure 3.10: Shaker with stack of sieve used for the particle size analysis and the subsequent determination of fineness modulus (Subash et al., 2016)

A set of sieves were stacked as shown in Figure 3.10 from the coarsest sieve (i.e., 7.10 mm) down to the finest (0.075 mm). The nest of sieves covered with a lid was placed on a vibrating shaker for 2 min at a frequency of 1500 Hz. Milled sand and basalt aggregates were weighed respectively.

The masses of basalt and sand aggregates were 704.5 g and 743.3 g respectively. The difference in mass used is acceptable, however, it is not meant to exceed 50 g.

The mass of material retained on each sieve was carefully transferred into a pan and weighed on a scale. As per ASTM Standard (2001), sieves that were supposed to be used were meant to be between sieve sizes of 37.5 mm and 0.150 mm. However, sieve sizes above 7.10 mm were not used for this test because the fractions retained would be zero. After shaking for 2 min, the mass of particles retained on sieve sizes between 7.10 mm and 0.075 mm were finally recorded. These masses were later used to deduce the fineness and coarseness of both the sand and the basalt aggregates. The equation below is used to estimate the fineness modulus (CRD-C 104-80, 1980):

$$Fineness\ modulus = \frac{N(100) - Sum\ of\ total\ percent\ passing}{100} \qquad (3.1)$$

Where N is the number of sieves involved in the sum total of percent passing from the largest size.

Another important physical property of aggregates is bulk density. It is presented in the next section.

3.5.2. Bulk density

Bulk density measures the volume that graded aggregate occupies in the shotcrete matrix (Grieve, 2009). The bulk density was determined for sand and basalt aggregates in accordance with the ASTM C29 standard (1997). The apparatus used for testing consisted of a tamping rod, scoop and a 3-litre cylindrical metal measure with handles. Samples of mass 3000 g were prepared separately for the sand and basalt aggregates. Prior to measuring the bulk density, the aggregates were oven-dried overnight at 105°C. The weight of the cylindrical metal that was used for measurements is depicted in Figure 3.11. Sand aggregates were alternatively placed in the cylindrical metal in a sequence of three layers at a time. During the placement of the first layer at the bottom 25 blows were given to ensure that aggregates occupy all areas in the cylinder. This was repeated two more times. The same was also done for basalt aggregates. The surface of the cylindrical metal was levelled with the rod and cumulative weight of cylindrical metal and aggregates was determined. Through using the volume of the cylindrical metal and the weight of aggregates, the density was calculated.

Figure 3.11: Cylindrical metal and rod for measuring bulk density of sand and basalt aggregates (University of South Africa, UNISA)

The bulk density (kg/m^3) value was then calculated as follows (ASTM C29, 1997):

$$\text{Bulk Density (BD)} = \frac{M}{V} \qquad (3.2)$$

Where M stands for the weight of the measuring cylinder with aggregates (kg) and V stands for the volume of the measuring cylinder (m^3).

Although bulk density is needed in assessing the suitability of aggregates, it is crucial to look into specific gravity of aggregates. This is because specific gravity is a measure of strength and water absorption capacity of shotcrete. The specific gravity of aggregates is discussed in detail in the next section.

3.5.3. Density and Specific gravity

Density and specific gravity were measured in accordance with ASTM C128 (2001). The reference substance is usually pure water. The method of testing for specific gravity required one graduated pycnometer as depicted in Figure 3.12.

Figure 3.12: Graduated volumetric pycnometer containing water and sand sample (UNISA)

The volume of the pycnometer is at 950 cm^3. Initially 600 g of sand sample were oven-dried at 105°C for 24 h. After this, the sand sample were weighed again to confirm the mass. The dry sample of sand was placed into the pycnometer. Then, water was filled to the level of 750 cm^3. At this point the dry sand sample in the pycnometer is fully immersed in water. Following this, the pycnometer was rolled, flipped over and shaken. This is done to release and remove air bubbles. The pycnometer was then left to rest for 24 h. After 24 h, water was added up to the calibrated capacity of the pycnometer. Then, the total mass of the pycnometer containing the sand sample and water was determined. Lastly, the mass of the sand sample was subtracted from the total mass. The remaining mass from the total mass was assigned to be the mass of the pycnometer filled with water. The same methodology was used for basalt aggregates. From the mass values and volume obtained, the density and specific gravity were calculated using Equation (3.3) and (3.4) (ASTM C128, 2001):

$$\mathrm{RD}=\frac{M_{OD}}{M_{pyc+W+}M_{OD-}M_{pyc+w+sample}} \tag{3.3}$$

$$P_{aggregates}=1\ 000 \text{ x RD} \tag{3.4}$$

Where M_{OD} is the mass of oven dried (sand and basalt) (g)

M_{pyc} is the mass of pycnometers (g)

W is the mass of water (g)

$Sample$ represents the aggregates (g).

3.5.4. Water absorption

In terms of the test itself, 1 kg of sand and basalt respectively was soaked in water for 24 h. Water was dried from the surface of the aggregates after 24 h; then, the mass of the saturated surface-dry test sample was determined. The drying process required an oven as per standard ASTM C127 (2001). Water absorption expressed as a percent volume of voids was determined as follows:

$$\text{Void content}=\frac{bulk\ density-specific\ gravity}{specific\ gravity}\,x\ 100\% \tag{3.5}$$

Where M_{OD} stands for the mass of oven-dry specimen (g)

M_{SSD} stands for the mass of saturated surface-dry specimen (g)

M_{AW} stands for the mass of water that fully fills internal pores (g).

3.5.5. Moisture content

Moisture content was determined in accordance with the ASTM C566-13 standard (1997). A representative sample (500 g of basalt or sand) was placed into a clean dry container and weighed to determine the apparent mass of sample denoted as (M_A). The container was then oven-dried at 105°C for 24 h. Afterwards, the container was cooled down and its content was weighed again so as to determine the apparent mass of the dry sample denoted as (M_B). The moisture content (in %) could be estimated using this equation (ASTM C566-13, 1997):

$$W=\frac{M\_A-M\_B}{M\_B} \text{x } 100\% \quad (3.6)$$

where M_A is the mass of the sample (g) and M_B is the mass of the dry sample (g).

3.6. Petrographic analyses

Aggregate characterisation takes into consideration the physical properties of the aggregates. Petrographic analysis, on the other hand, provides the basis for understanding the mineralogical constitution of aggregates. This section presents the petrographic analysis that was performed as part of the experimental work underpinning this research study.

Petrographic analysis gives an in-depth investigation of the chemical and physical features of a rock sample. It is deemed critical in the microscopic investigations of the rock sample of interest. In this study, the XRF and thin section preparation have been conducted to analyse the basalt rock sample at a microscopic level.

3.6.1. X-Ray Fluorescence analyses

XRF analysis is conducted to understand the mineralogical composition of basalt aggregates. The analysis focuses on major constituents of the aggregates. It is important to determine the geochemical composition of aggregates as this affects the quality of shotcrete produced. To this end, two samples of basalt aggregates each weighing 5 g were submitted to the laboratory at Council for Geoscience. The basalt samples are depicted in Figure 3.13.

Figure 3.13: Two samples of crushed basalt aggregates, that are further subjected to the processing of XRF analyses performed at the Council for Geoscience

The basalt samples were air-dried in a clean place. The samples were later crushed and grinded. The grinded samples were subjected to sieving, through a sieve pan of 60 µm. Sieves that were used, were made of nylon. To avoid contamination by metals. It is necessary to sieve the samples into fine powder to minimize undesired particle size effects. The processing of making pressed pellets for XRF analyses requires fine particle sizes. These fine particles of basalt aggregates are pressed at a pressure of between 15 and 35T applied for 1 – 2 min. The XRF analyses machine is depicted in Figure 3.14 alongside with the location where the pressed pellet is inserted for further mineralogical analysis. The pressure applied to a sample should compress the sample completely. It is important that pellet samples are fully compressed so that no void spaces remain in the pellet.

Figure 3.14: Pressed pellet insertion location on the XRF instrument stationed at the Council for Geoscience

The diameter of the pressed pellet used in this study was 16 mm with a thickness of 3 mm. The thickness of the pressed pellet is important in achieving accurate XRF results. The pellet must be thick so that the X-ray beam can reach through all elements in a sample and that their quantity is accurately measured. X-ray produced in the sample is directed to the detector and is measured. A schematic depiction of the X-ray beam is shown in Figure 3.15 to enhance the understanding of how XRF results were generated.

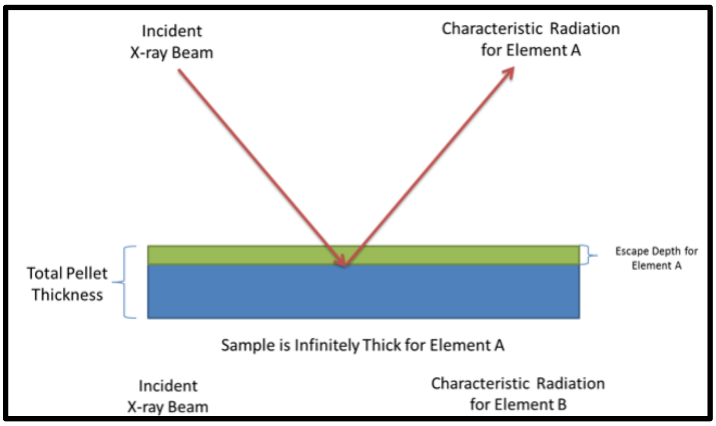

Figure 3.15: X-ray beam subjected to pressed pellet sample, to extract mineralogical characteristics through to a detector which measures the mineral quantity found in a sample (Herrick, 1990)

Results of major and trace elements found in the basaltic samples are later discussed in the next chapter. Furthermore, thin sections are prepared to assess minerals in the basalt aggregates. The following section covers the methodology of thin sections.

3.6.2. Preparation of thin sections

Thin sections help identify minerals in aggregates. Through providing transparency of mineral contents and quantity in aggregates. In addition to this, thin sections determine if the aggregate is appropriate for shotcrete. Some mineral contents in aggregate may cause deleterious reactions hence, they need to be identified through thin section. The thin sections were prepared by using a Struers Labotom-15 cutting saw. A 30 mm x 20 mm x 10 mm slab of basalt rock was cut and then glued onto a 26 mm x 42 mm glass slide. The glued basalt rock was then grinded to reduce its size using a Logitech lapping machine on 800 grit size. Silicon carbide powder is used to make slides thinner. The thickness of the thin section is approximately 30 µm.

After achieving the correct thickness, the thin section glass slides were polished using the Struers LaboForce-MI polishing equipment in order to attain a smooth reflecting surface. The quality of the slides was assessed using a BX-43 Olympus petrographic microscope in Figure 3.16. The microscope was loaded with the Stream Start and Essentials image analysis software used in conjunction with a dedicated camera to produce high quality images. A total of 8 thin sections were viewed under plain polarised light (PPL) and cross polarised light (CPX). From the thin sections viewed, the presence of 50% of minerals implies that the mineral content is predominant while 20 – 50% means that the mineral content is major. Furthermore, 5 – 20% implies that the mineral content is minor. Lastly, any mineral content < 5% is considered as a trace mineral.

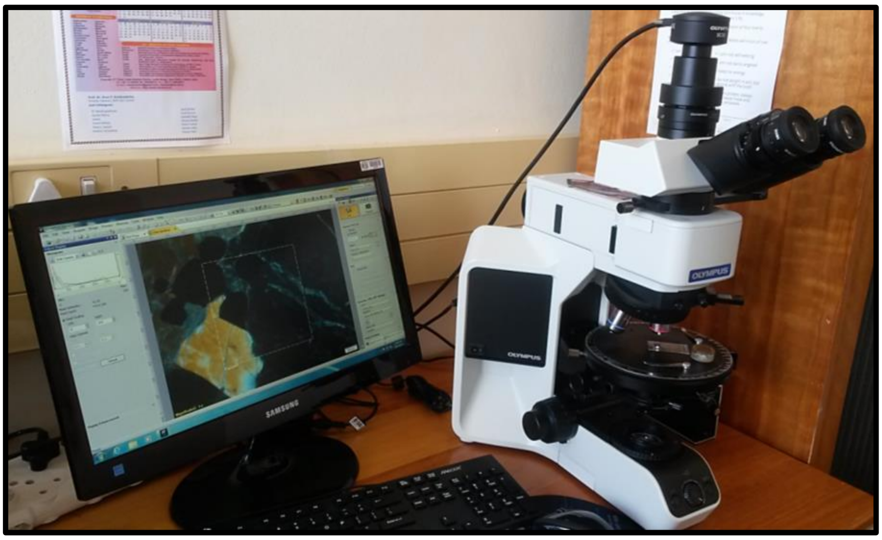

Figure 3.16: BX-43 Olympus petrographic microscope at the Council for Geoscience, South Africa

3.7. Shotcrete-making components

In this study, shotcrete mixes were designed following the method advocated by the ACI (2016). The adoption of the method was primarily motivated by the availability of all the required materials for the mix design which included sand, cement, and water. The mix design for shotcrete prisms was prepared with the view to have partial to full replacement of sand by basalt aggregates. The constituents were properly proportioned to meet the desired shotcrete characteristics and properties meant to support underground excavations.

This section discusses shotcrete ingredients such as sand, cement, basalt aggregates and water. The discussion entails the properties of each ingredient.

3.7.1. Binding agent

The Lafarge Portland cement all general-purpose in Figure 3.17 was used as a binding agent for the preparation of all the shotcrete samples. The selected hydraulic binder is type CEM II 42.5N. The acronym “CEM” stands for cement while “II” denotes the type of cement that contains silica fumes, pozzolanas, fly ash, limestone, alumina, iron oxide and calcium (Bullard et al., 2011).

Limestone and calcium are present to control the setting time of shotcrete. Lastly, 42.5 N refers to the Ordinary early strength of the cement. Furthermore, this class of cement, is able to withstand high pressure and loads (Schindler, 2004).

Figure 3.17: Lafarge Portland cement

Perhaps it is important to note that the Lafarge Portland cement used in this work offers a range of benefits for mortar works including resistance to sulphate attack. This is the primary reason for its use.

3.7.2. Sand

The silica sand used in this study was directly ordered from Sallies sand mine in the North-West Province of South Africa. Bags of silica sand weighing 40 kg each are shown in Figure 3.18 for reference.

Figure 3.18: Sallies sand

The sand is of high quality in terms of its chemical composition (Howari, 2015). This is because it is mined from a uniform quartzite ore body. The run-of-mine is then processed in a series of crushing and screening steps. The material then proceeds to washing and homogenization over various high frequency vibrating screens. The grain size used in this study was between the ranges of 3.0 – 4.8 mm. This grain size falls within the range of coarse aggregates, complimenting the fine basalt aggregates. This is the primary motive for its use. The primary characteristics of silica sand is that it is mechanically strong and chemically resistance to weathering.

3.7.3. Basalt aggregates

The basalt aggregates used in this study were directly collected from the Sibasa formation at the Tshikweta village as discussed in Sections 3.2 and 3.3. Local community members use basalt as a reinforcement to their walls to prevent cracks that develop as a result of heavy rainfall. The physical characteristics of basalt include black colour, fine-grained texture and partial surface erosion. Basalt aggregates were crushed, milled and sieved to 425 µm as shown in Figure 3.19.

Figure 3.19: Crushed -425 µm basalt aggregates

3.7.4. Water

Tap water was used as an initial mixing agent with the cement during the preparation of the shotcrete cubes. A similar approach was used by Nikhil et al. (2011) which was adopted for this research study and was deemed acceptable for the purpose. The same water from the tap that entered into shotcrete mixing was used for curing. However, the temperature of the water used for curing was monitored to be at a 25°C. The laboratory is regulated at a temperature of 25°C. The temperature was taken down every morning using a thermometer.

3.8. Material proportioning

Proportioning of shotcrete is the process of selecting the appropriate quantity of cement, aggregate and water to obtain the desired strength and quality of shotcrete. An accurate method of proportioning the materials is through measuring their weight. As a result, this section focuses on calculating the quantities of sand aggregates, cement and water used in the mix design of shotcrete.

3.8.1. Water and cement

Water requirements depend on the type and texture of aggregates as well as the required consistency or workability of the shotcrete. The required workability range of shotcrete is 118 mm and 142 mm (ACI, 2016). Successful proportioning of fresh properties of shotcrete is associated with sufficient workability. The amount of water used in the shotcrete mix affects the final product of shotcrete after placement in two ways. For example, if the amount of water is too much, the shotcrete may be too weak, therefore strength development may be compromised. Practical observations have justified that the ratio of 0.6 ensures that the mix with basalt aggregates is workable and easy to flow upon application (Mehta and Monteiro, 2006; Kosmatka et al., 2003). The water-to-cement ratio was deduced to be 0.60 to ensure a consistent and adequate workable shotcrete. The quantity of water was weighed using a graduated cylinder amounting to 270 g. This amount was deemed suitable as it reached the desired workability and strength during the assessment of trial mixes, which is discussed in later section. On the other hand, the amount of cement required was calculated as follows:

$$M_c = \frac{\text{Water content}}{\text{w:c}} \tag{3.7}$$

where M_c stands for the weight of cement (g) and w:c is the water-to-cement ratio.

From Equation (3.7), the calculated weight of cement was noted to be $M_c = \frac{270}{0.6}$ or 450 g. This is the proportion that was deemed suitable to reach the desired workability and strength properties of shotcrete. It can be summarised from the equation that cement content is governed by the mixing water requirement and water to cement ratio of 0.6. Although water and cement are crucial to the mix design, sand aggregates remain the major constituent of shotcrete. The following section discusses the proportioning of sand aggregates in the shotcrete mix design.

3.8.2. Sand aggregates

The sand content was calculated from the known fact that the sand constituent of the shotcrete must amount to 1350 g. This fact was devised in accordance with CEN Standard sand EN 196-1' which states that the mass of sand must be at 1350 g. The mix proportion of shotcrete include partial to full replacement of sand by basalt aggregates. Materials used to make the shotcrete prisms are depicted in Figure 3.20.

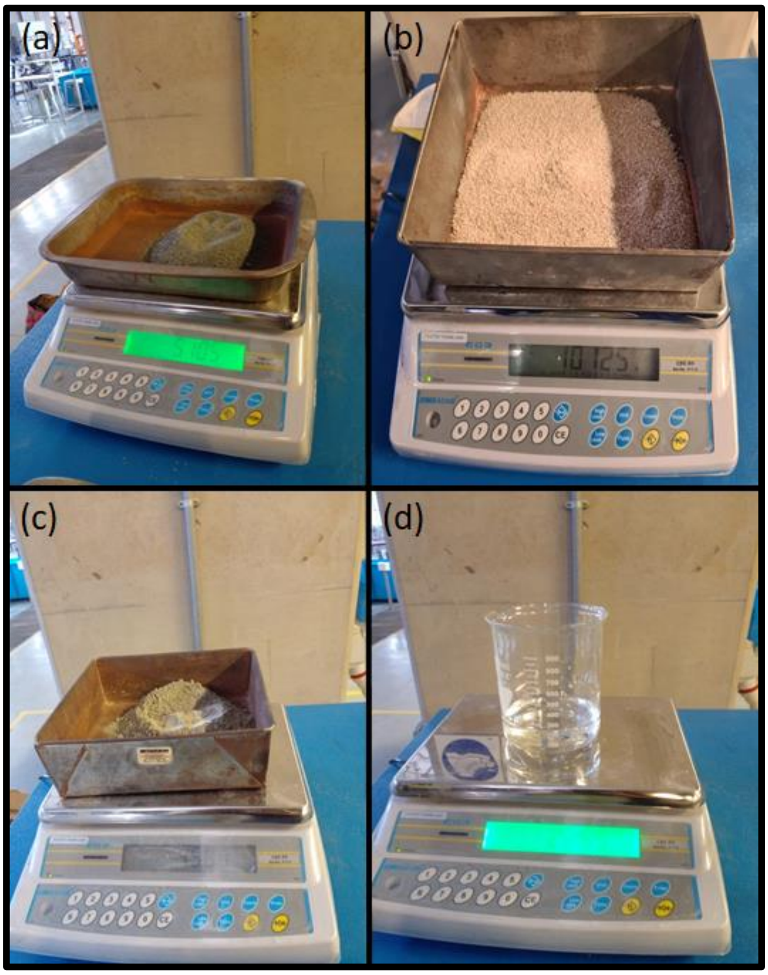

Figure 3.20: (a) Basalt aggregate, (b) Silica sand, (c) Cement, (d) Water

The proportion of sand aggregates differ in various mix design. The partial to full replacement of sand by basalt aggregates affects the proportioning. The proportioning of each mix is depicted in Table 3.2. These mix proportions were prepared to make 120 prisms.

Table 3.2: Mix proportions of constituents that were used in shotcrete prisms

Weight fraction of sand in shotcrete prisms					
Weight (%)	100%	75%	50%	25%	0%
Sand	1350 g	1012.5 g	675 g	337.5 g	0 g
Basalt	0 g	337.5 g	675 g	1012.5 g	1350 g
Cement	450 g	450 g	450 g	450 g	450 g
Water	270 g	270 g	270 g	270 g	270 g

The weight of cement and water remains the same throughout the mix proportions of 120 shotcrete prisms. Furthermore, the weight of sand and basalt changes for various mix proportions. To assess the feasibility of these mix proportions, trial mixes were prepared and assessed. The findings from the trial mixes are discussed in the next section.

3.8.3. Assessing trial mixes

High performance shotcrete starts with a great mix design. There are so many aspects to consider when designing a shotcrete mixture. A successful mix design should take into consideration aspects like workability, pumpability, long term durability and strength properties. To get the right mix, trials of various proportions of sand and basalt aggregates, water and cement were assessed. Three mix designs with different proportions of sand, cement and water were prepared. Proportioning of the mix ingredients was repeated three times with different water-to-cement ratios for a total of 15 trial shotcrete mixes. The water to cement ratio initially was 0.4, then, 0.5, and lastly 0.6. These mixes have informed the desired proportions of the mix ingredients used in this study.

Table 3.3: Shotcrete mix design for five types of mix proportions

Mix ID	No. of Samples	Sand (g)	Basalt (g)	Cement (g)	Water (g)	w:c
BC0	1	1350	0	450	180	0.4
	1	1350	0	450	225	0.5
	1	1350	0	450	270	0.6
BC25	1	1012.5	337.5	450	180	0.4
	1	1012.5	337.5	450	225	0.5
	1	1012.5	337.5	450	270	0.6
BC50	1	675	675	450	180	0.4
	1	675	675	450	225	0.5
	1	675	675	450	270	0.6
BC75	1	337.5	1012.5	450	180	0.4
	1	337.5	1012.5	450	225	0.5
	1	337.5	1012.5	450	270	0.6
BC100	1	0	1350	450	180	0.4
	1	0	1350	450	225	0.5
	1	0	1350	450	270	0.6

This mix proportions with water to cement ratio of 0.4 and 0.5 produced shotcrete that is stiff and hardly flows. Now, this presented a challenge of using this water to cement ratio for shotcrete. Because ACI (2016) has stipulated that shotcrete has to be workable, pumpable and easy to place. This mix design did not meet those requirements. Furthermore, it was deduced that the water to cement ratio of this mix design was too low, hence the mixture was too stiff. As a result of these fresh properties of shotcrete, trial mixes with water-to-cement ratio of 0.4 and 0.5 were deemed not suitable for use as shotcrete. The practical experiment excluded the use of mixes with these water-to-cement ratios. On the other hand, the use of a water-to-cement ratio of 0.6 produced shotcrete that was easy to place, workable, pumpable and had desirable strength properties. The cast mortar cubes were then cured under water immersion for a period of 28 days. To determine their flexural and compressive strengths after 28 days. The results of the compressive and flexural strengths to assess their strength properties (Appendix A). The results indicated that optimum results were found in mixes with a water-to-cement ratio of 0.6. ACI (2016) stipulated compressive strength to be at 30 – 40 MPa after 28 days of curing.

Meanwhile, the flexural strength is expected to be within the range of 0.6 – 8 MPa. This study was motivated to use the water-to-cement ratio of 0.6 due to the experimental findings.

3.9. Specifications of curing and compressive strength of shotcrete

According to the standard IS 9012 (1978), the compressive strength of shotcrete ranges from 20 MPa to 50 MPa at 28 days. Again, the standard ACI 506R (2006) reports that the compressive strength at 28 days is supposed to be 30 – 40 MPa. And for special applications such as permanent tunnel lining, a compressive strength of 40 MPa at 28 days is acceptable. The inclusion of basalt aggregates in shotcrete could potentially reach the target or exceed the strength standard set by ACI 506R (2006). In this case, this could imply that basalt aggregates can be a suitable replacement for sand aggregates in the shotcrete mix design.

Curing: A cumulative number of 120 shotcrete prisms were prepared with 24 prisms prepared per proportion. The number of prisms and curing methods are summarised in Table 3.4.

Table 3.4: Cumulative number of shotcrete prisms and curing method

Sample proportion	No of samples	Type of curing
100% basalt	24	Water immersion
75% basalt	24	Water immersion
50% basalt	24	Water immersion
25% basalt	24	Water immersion
0% basalt	24	Water immersion

Samples were cured in the laboratory by immersion in tap water for 28 days as shown in Figure 3.14. The temperature of the curing tank was maintained at 25°C and was measured every day in the morning. Curing by water immersion was carried out over a period of 7, 14, 21 and 28 days. After curing six prisms were removed from the water and left to dry at room temperature for a period of 24 h. For each mix proportion, there were six shotcrete prisms set to be tested for compressive strength during each curing interval. Compressive strength tests were carried out during the curing interval which are 7, 14, 21 and 28 days. Shotcrete is set to reach at least 80% of its final strength at 28 days (Mehta et al., 2006; Kosmatka et al., 2011; Neville, 2011). This informed this study to stop its curing duration at 28 days.

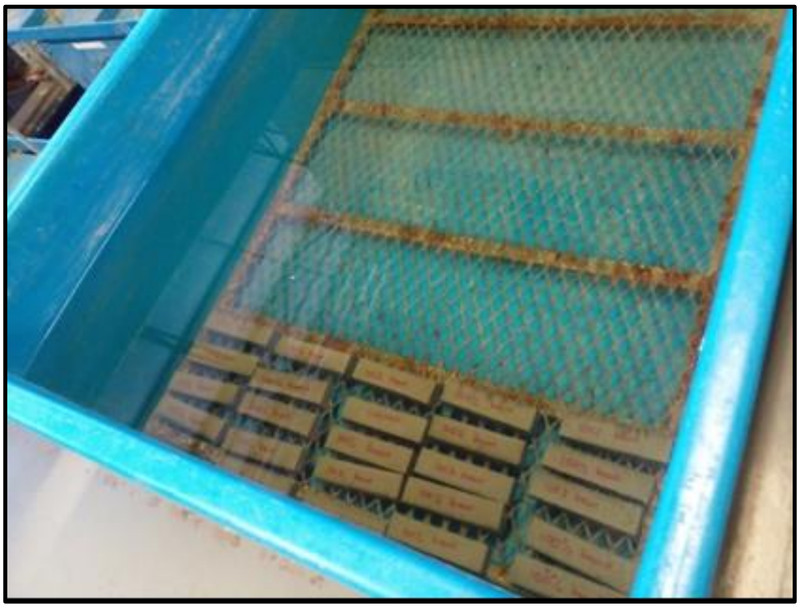

Figure 3.21: Curing tank holding shotcrete rectangular prisms immersed in water

It should be noted that samples with partial replacement of sand by basalt aggregates were subjected to compressive and flexural strength tests. These strength tests are covered in Sections 3.10.3 and 3.10.4 respectively.

3.10. Mechanical properties of fresh and hardened shotcrete

In this section, the performance of shotcrete is measured in terms of its mechanical properties, i.e., workability, compressive strength, and flexural strength. The experimental protocols for these tests and the standard practice are presented below.

3.10.1. Flow table test

The flow test was conducted in accordance with ASTM C230 (1997) to assess the workability and consistency of fresh shotcrete. The test assists in determining amongst others the volume of water required to ensure that shotcrete is workable. The flow table test was cleaned using compressed air and left to dry at room temperature of 25°C for over 2 h. The mould of dimension of (100 mm) was placed at the centre of the flow table. Then, a layer of shotcrete mix about 25 mm thick was placed on the mould reaching 7 mm and tamped 25 times with a tamper as shown in Figure 3.21(a). The tamping pressure must be sufficient to ensure uniform filling of the mould. The shotcrete was allowed to even out at the top through gently shaking the table. The excess shotcrete was wiped clean and dry using the paper towel. From there, the mould was lifted 1 min after completing the mixing. After approximately 15 s, the table was dropped 25 times. A meter ruler was used to measure the diameter of the shotcrete along four directions as depicted in Figure 3.21(b). The diameters were recorded.

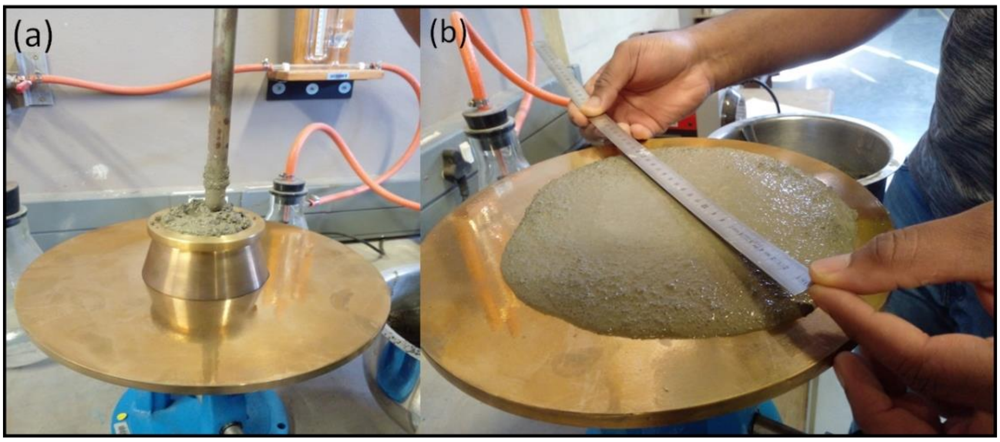

Figure 3.21: (a) Tamping rod on the mould and flow table; (b) Measurement of the diameter of the settled shotcrete

The calculations of the flow table test were conducted using the equation denoted below (ASTM C230, 1997):

$$Flow = \frac{Average\ of\ four\ readings\ (mm) - Original\ inside\ base\ diameter\ (mm)}{Original\ inside\ base\ diameter\ (mm)} \times 100\% \qquad (3.8)$$

3.10.2. Casting of prisms

After completing the flow tests, fleet line hydraulic oil was applied to the casting moulds to enable their easy de-moulding. Fresh shotcrete was then poured into a total of 120 prisms of 150 mm x 210 mm x 150 mm. The moulds were subjected to a vibrating compacting machine for 10 s as depicted in Figure 3.22(a). After 24 h of casting, the casted moulds were de-moulded (Figure 3.22b) and labelled appropriately in terms of the proportion of aggregates used (Figure 3.2c).

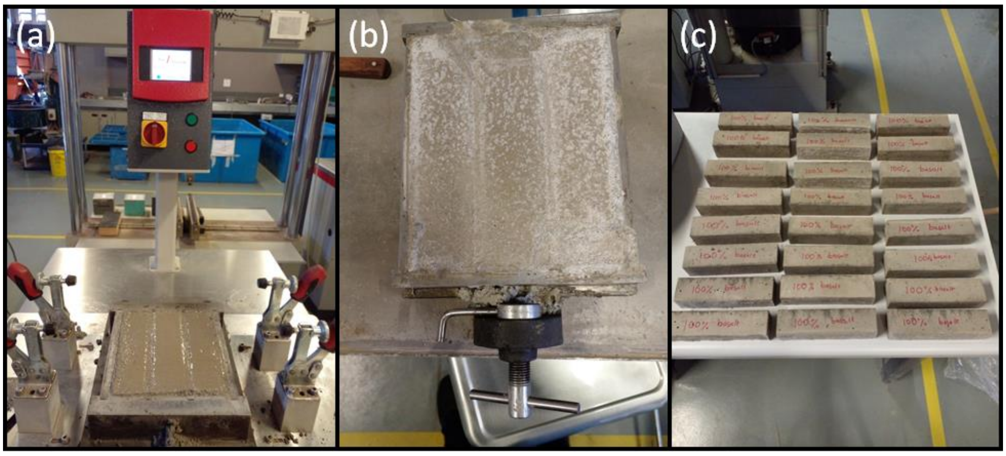

Figure 3.22: (a) Casted prisms on a vibrating compacting machine, (b) Cured prisms after 24 h of casting, and (c) De-moulded prisms

After the processing of de-moulding, it is important to subject these shotcrete prisms to compressive and flexural strengths. The next section focuses on compressive strength of shotcrete prisms.

3.10.3. Compressive strength and hardened density of shotcrete prisms

The casted shotcrete prisms were cured for 7, 14, 21 and 28 days, they were subjected to further testing. Two key properties that were measured included hardened density and compressive strength. The mass of shotcrete prisms was determined after the curing period. The compressive machine measures the mass, the load and compressive strength as shown in Figure 3.23. These masses were noted on a datasheet. Through using the volume of the shotcrete prisms after 28 days, the hardened density of each shotcrete prisms was calculated as follows:

$$D_{28} = \frac{W}{V} \tag{3.9}$$

where W is the mass after 28 days (g),

V is the volume after 28 days (mm^3), and

D_{28} is the density after 28 days (g/cm^3)

In accordance with SANS 5863 (2006), each cube specimen was placed under the compression machine (refer to Figure 3.23) at a loading rate of 325 kN/min and observed until it failed. The corresponding compressive strength (in MPa) was then determined as follows (SANS 5863, 2006):

$$C_{28} = \frac{P}{S} \tag{3.10}$$

where P = load (kN) and S = face area of the cube (mm^2)

Figure 3.23: Compressive testing station in the Civil Engineering laboratory at UNISA

Generally, the compressive strengths of 120 shotcrete prisms specimens were recorded over 7, 14, 21 and 28 days. It was deemed necessary to assess the gradual strength development. This was done to determine the curing age at which the shotcrete mixes reach the stipulated compressive strength. Another strength property that is crucial includes flexural strength. The conduction of flexural strength test is discussed in the following section.

3.10.4. Flexural strength tests

Flexural strength of shotcrete or any other material is also known as modulus of rupture. It gives the maximum load capacity prior to the shotcrete prisms breaking (Cebasek and Likar, 2014).

The five shotcrete mixes considered were used to prepare 120 prisms with 24 prisms designated to each proportion. From the 24 shotcrete prisms, six were cured for 7 days and then tested in accordance with ASTM C293 (2010). The same methodology was carried out for shotcrete prisms cured for 14, 21 and 28 days. The flexural strength test entailed using a beam to assess the flexural strength properties as illustrated in Figure 3.24.

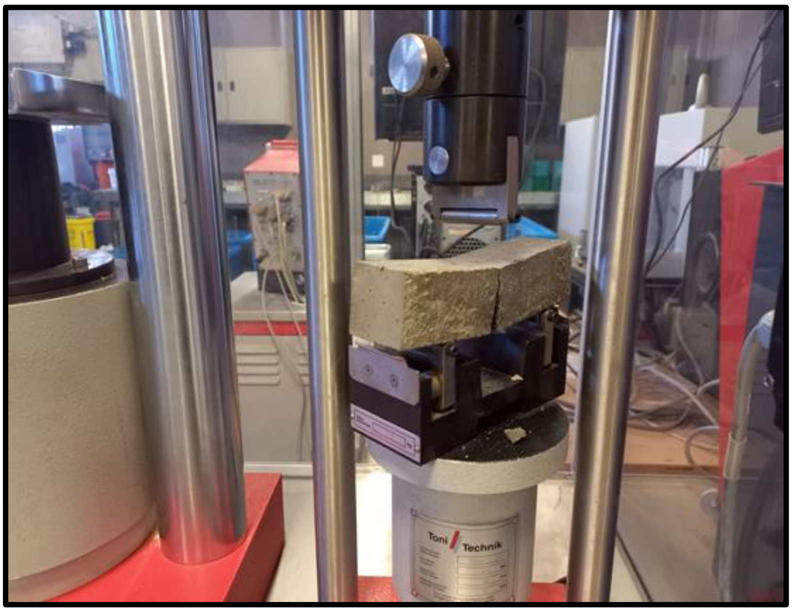

Figure 3.24: Three-point flexural testing machine at UNISA.

Flexural strength is estimated as follows:

$$F = \frac{3PL}{bd^2} \qquad (3.11)$$

Where F is the flexural strength in (MPa),

P stands for failure load (kN),

L stands for effective span of the beam (mm),

b represents the breadth of the beam (mm), and

d is the failing point depth (mm).

Although most of the properties that determine the quality of shotcrete were assessed, some experimental challenges were encountered. These challenges are discussed in the next section.

3.11. Challenges encountered

Basalt aggregate samples included grain sizes of 150 µm, 250 µm and 425 µm. These various grain sizes were included in shotcrete mixes. The mixes were duplicated according to each grain size. The water-to-cement ratio was set at 0.6 for all the mixes. While all the mixes were prepared at this water to cement ratio, mixes of 150 µm and 250 µm were considered too stiff to flow and lacked consistency as depicted in Figure 3.25.

Figure 3.25: Failed trial mix of shotcrete

Meanwhile, mixes of 425 µm were deemed workable and consistent. Furthermore, the mixes were subjected to the flow table test to assess their workability. The acceptable range of shotcrete according to ACI (2006) is 90 mm – 135 mm. Mixes prepared from grain size of 150 µm and 250 µm exhibited workability of 55 mm to 65 mm. On the other hand, mixes with 425 µm grain size had workability that ranges within 90 mm to 120 mm. This falls within the acceptable range of workability of shotcrete. Although the study was initially aimed at assessing the influence of various grain sizes, it was insignificant to continue with the other grain sizes. This is because the results derived would not be suitable for the practical application of shotcrete. A key parameter to the fresh properties of shotcrete is workability, consistency, and easy placement upon application. However, if these requirements are not met, such shotcrete cannot be considered as suitable for underground support. Generally, a decision was taken to only use 425 µm. The usage of 425 µm does not significantly change the results, because the grain size is still considered as fine. The decision to use 425 µm was to ensure that the shotcrete mix meets the minimum standard of shotcrete. Although challenges were encountered, however results that were pivotal to this study were achieved. These results are presented in the next chapter.

Chapter 4: Effects of the inclusion of basalt aggregates on the mechanical properties of shotcrete

4.1. Introduction

The experimental work described in Chapter 3 highlighted the experimental protocols that were followed, to assess the effect of basalt aggregates on mechanical properties of shotcrete. In light of this, physical characteristics of aggregates were tested. The tests conducted included fineness modulus, bulk density, hardened density, moisture content, water absorption, compressive and flexural strengths, petrographic, and geochemical analyses tests.

These tests were conducted to assess critical properties of sand and basalt aggregates that affect the performance of shotcrete. Five proportions of sand and basalt aggregates (i.e., BC100, BC75, BC50, BC25, and BC0) were prepared, and subjected to water immersion curing. The process of curing was conducted over 7, 14, 21, and 28 days. At the end of each curing interval, compressive and flexural strengths were measured on corresponding shotcrete specimens.

Shotcrete properties in both fresh and hardened states were reported. These includes workability of freshly prepared shotcrete and mass of the hardened shotcrete after curing periods were measured and recorded. Hardened properties include compressive and flexural strength tests. From these tests raw data of six replicates per mix design were collected after each curing interval. Outcomes of physical properties of basalt and sand aggregates used in this study are reported below.

4.2. Physical characteristics of aggregates

Aggregate characteristics tests performed include fineness modulus, bulk density, specific gravity, moisture content, water absorption, petrographic and geochemical analyses tests. The raw data was analysed through quantitative data analysis. This choice was motivated by the fact that quantitative data method is less prone to bias and is deemed suitable for large data collection (Saunders and Thornhill, 2012). Furthermore, quantitative analysis uses graphs and charts to exhibit correlation and comparison within variables. The results of this study are presented through graphs and statistical methods to generate better understanding. The influence of aggregate type on shotcrete mixes was assessed. The results were compared and correlated with findings of previous studies. Physical characteristics in this study provide an opportunity to assess the results and determine if whether basalt aggregates are a suitable replacement for sand. Results of physical properties of sand and basalt aggregates are provided in the subsequent sections.

4.2.1. Fineness modulus

Fineness modulus was measured for both sand and basalt as per equation in Section 3.5.1. The results are summarised in Table 4.1 which depicts the percent mass fraction retained on each sieve after sieving.

Table 4.1: Aggregate gradations of sand and basalt

	Cumulative mass retained (%)	
Sieve size (mm)	**Basalt**	**Sand**
7.10	0	0
5.00	0	16
2.00	0.5	80.0
1.00	28.7	4.0
0.60	80.0	0
0.30	98.9	0

0.15	99.3	5
0.075	100	0
FM	**3.07**	**3.99**

The purpose of calculating fineness modulus was to specify the proportions of fine and coarse aggregates when designing shotcrete mixes. A higher value of fineness modulus imply that aggregates are coarse. While a low fineness modulus mean that aggregates are fine.

The fineness moduli for basalt and sand aggregates samples tested were at 3.07 and 3.99 respectively. Although both aggregates are characterised as coarse based on their fineness modulus. However, sand is coarser compared to basalt. Several scholars have argued that fineness modulus between 2.22 and 3.15 of aggregates tend to yield shotcrete with the best workability and high compressive strength (Kalra, 2016; Karpuz et al., 2017; Adewuyi et al., 2017). It is therefore expected that basalt-based shotcrete would be of good quality as its fineness modulus is within the acceptable range. Other factors such as specific gravity and bulk density influence mechanical performance of shotcrete. These two factors are discussed in the next sub-section.

4.2.2. Specific gravity and bulk density

Specific gravity of an aggregate is considered as a measure of the strength and quality of the aggregate (Arumugam, 2014). Specific gravity and bulk density were measured for sand and basalt aggregates. Specific gravity (RD) was determined in accordance with ASTM C128 (2001) for the aggregates. Meanwhile, bulk density (BD) for each type of aggregate material was determined in accordance with the ASTM C29 (1997) standard. Two samples were submitted, one per aggregate type for the measurement of specific gravity and bulk density. Results are summarized in Table 4.2.

Table 4.2: Specific gravity and bulk density of basalt and sand aggregates

Properties	Sand aggregates	Basalt aggregates
Specific gravity	2.71	2.82
Bulk density, *BD* (kg/m^3)	2520	2720

The results of bulk density were noted in Table 4.2 as 2520 kg/m^3 and 2720 kg/m^3 for sand and basalt aggregates respectively. Bulk density is an indirect measure of void content and porosity (Al-Ghuri, 2015). An increase in bulk density generally implies that aggregates have low void content. Sand aggregates were found to have low bulk density in this study. Therefore, sand aggregates have high void content and porosity compared to basalt aggregates. It can be summarised that shotcrete mixes with elevated basalt content are less porous and would contribute towards high compressive strength compared to shotcrete mixes with elevated sand content.

Table 4.2 also shows that sand and basalt aggregates used are of specific gravity 2.71 and 2.82 respectively. According to ASTM C128 (2001) the specific gravity of aggregates used in shotcrete ranges from 2.5 to 3.2. Specific gravity has been widely reported to influence the mechanical properties of the shotcrete mix and those of the interface between shotcrete and rock mass (Neville, 2011; Arumugam, 2014; Bernado et al., 2015). In terms of the mechanical properties, Azunna and Okolo (2019) were able to show that shotcrete mixes made from aggregates with high specific gravity generally have high durability and are highly serviceable. An increase in specific gravity leads to a corresponding increase in compressive strength this will be covered in detail in Section 4.4. As a result, shotcrete mixes with elevated basalt content are expected to have high durability compared to shotcrete mixes with high sand content. Factors such as water absorbability and moisture content also affect the durability of shotcrete. Section 4.2.3 details the results of moisture content and water absorption.

4.2.3. Water absorption and moisture content

The water absorption was measured in accordance with ASTM C127 (2001) while moisture content was measured in accordance with ASTM C566-13 (1997). The results of water absorption and moisture content of basalt and sand aggregates are presented in Table 4.3.

Table 4.3: Moisture content and water absorption of the aggregates

Parameters	Basalt	Sand
Moisture content (wt%)	0.31	0.81
Water absorption (wt%)	0.66	1.30

The water absorption of an aggregate is set at a specific limit of 0.5% to 2.5% (ASTM C127, 2001). Meanwhile, ACI (2006) have set specific limits of moisture content of aggregates to be between 0.2 wt% and 2 wt%. Both sand and basalt aggregates fall within the specified limits of moisture content and water absorption. However, water absorption value of basalt is generally lower compared to sand aggregates. Same applies to moisture content value, the value of basalt is low compared to sand.

Concordant studies have shown that water absorption generally affects the mechanical strength and the durability of shotcrete (Smith and Collis, 1993; Neville, 2000; Korkanç and Tuğrul, 2004). Aggregates with low water absorption and moisture content are deemed suitable for use in shotcrete. As they tend to be resistant to mechanical forces and weathering. In the present research study, basalt aggregates used were found to be good for shotcrete production. This is because basalt aggregates have low water absorption, high specific gravity and low moisture content compared to sand aggregates. Results of the influence of these factors on mechanical tests are presented later in Section 4.4. Another important factor to consider is the chemistry of aggregates. This is because the geochemical and petrographic characteristics are largely responsible for the performance of the aggregates. The results of geochemical and petrographic properties are discussed in detail in Section 4.3.

4.3. Chemical properties of basalt aggregates

Aggregate mineralogy is a critical factor that influences the engineering properties of shotcrete such as compressive and flexural strength. The mineralogy of aggregates is a key component that influences the performance of shotcrete. The chemical composition of basalt aggregates influences physical and mechanical properties of shotcrete. Section 4.3.1 looks into the geochemical XRF data and petrographic analyses.

4.3.1. Geochemical analyses of the basalt aggregates from Sibasa Formation

Geochemical analysis provides an insight on the chemical composition of a rock and gives an indication of rock quality. The results of geochemical analyses presented in Section 3.6.1 are summarised in Table 4.4.

Table 4.4: XRF results of basaltic rocks taken from the Sibasa Formation (Council for Geoscience, South Africa)

Samples → / Major minerals ↓	**Sample L1** Lat:-22.93233 Long:30.5103	**Sample L2** Lat:-23.93237 Long:30.5104	**Sample L3** Lat:-22.93581 Long:30.5199	**Sample L4** Lat:-220053 Long:30.5218	**Sample L5** Lat:;23.93485 Long:30.52547	**Sample L6** Lat:-23.93405 Long:30.52547	**Sample L9** Lat:-23.63405 Long:30.50470	**Sample L10** Lat:-22.5049 Long:30.5228
SiO_2	49.21	48.78	47.02	48.05	47.49	47.34	49.42	49.40
TiO_2	1.33	1.39	1.36	1.24	1.35	1.38	1.42	1.36
Al_2O_3	14.32	14.18	14.90	15.16	14.78	14.76	14.45	14.70
Fe_2O_3(t)	13.94	14.44	14.53	13.25	14.68	14.57	13.94	13.40
MnO	0.208	0.197	0.200	0.177	0.215	0.230	0.197	0.192
MgO	6.59	6.38	6.53	5.24	6.57	6.89	6.65	6.42
CaO	9.79	9.25	9.79	11.55	8.21	8.67	8.15	8.46
Na_2O	2.07	2.17	2.61	2.60	2.14	2.52	2.56	2.49
K_2O	0.58	0.72	0.35	0.19	1.43	0.65	0.59	0.79
P_2O_5	0.140	0.140	0.150	0.140	0.150	0.160	0.160	0.150
Cr_2O_3	0.033	0.041	0.035	0.031	0.028	0.029	0.029	0.033
LOI	1.83	2.31	2.63	2.38	2.69	2.90	2.44	2.63
Total	100.04	100.00	100.11	100.01	99.73	100.10	100.01	100.02
H_2O^-	0.34	0.56	0.50	0.34	0.41	0.41	0.53	0.32

It can be seen from Table 4.4 that basalt rocks are mainly composed of silicon dioxide SiO2 (47.02 – 49.40 wt%), aluminium oxide (Al_2O_3) (14.18 – 15.16 wt%) and iron oxide (Fe_2O_3) (13.25 – 14.57 wt%). Lian (2011) indicated that silica contributes towards the enhancement of tensile strength by improving the bonding between the aggregates and the cement matrix. Interestingly, the presence of silica is greater in sand samples (generally at 98 wt%) compared to basalt samples (Herrick, 1990). This implies that shotcrete mixes with sand may exhibit high tensile strength compared to basalt aggregates.

On another note, the presence of iron oxides is known to affect compressive strength (Korkanç and Tuğrul, 2004; Karpuz et al., 2017; Kara and Mehmood, 2018). Table 4.4 shows that the iron oxide content in basalt is in the range of 13.25 – 14.57 wt%. This is high compared to the iron oxide content in sand aggregates, which has been reported to be around 0.007 wt% (Herrick, 1990). Elevated iron oxide in basalt aggregates affirms that these aggregates have high compressive strength compared to sand aggregates.

This is because iron oxides improve the microstructures of the shotcrete matrix through reducing porosity. The bond between cement matrix and aggregates grows stronger and translates into greater compressive strength (Kubiszewski, 2012; Satheesh and Rajasekhar, 2018; Najah et al., 2021). Another school of thoughts argues that the elevated proportions of iron oxides encourage the rapid consumption of $Ca(OH)_2$ that forms during hydration. This then leads to shotcrete which is more compact and stronger (Lian, 2011; Sharma, 2016).

The last note in Table 4.4 is the presence of aluminium oxide in basalt aggregates. Its concentration range is 14.32 – 15.16 wt% while it is around 0.07 wt% for sand aggregates. Ramesh (2014) and Sharma (2016) showed that an increase in aluminium oxide content improves the compressive strength and the corrosion resistance of shotcrete. Other researchers such as Herrick (1990), Howari (2015) and Lian (2011) also reported an increase in compressive strength in shotcrete mixes with basalt aggregates. They ascribed this to the high content of aluminium oxide in the basalt aggregates. Furthermore, the researchers explained that the aluminium oxides develop covalent bonds with other complexes and compounds in the shotcrete mix design. The shotcrete mixes with basalt used in this study is expected to exhibit some of the attributes mentioned above.

Major minerals that constitute these aggregates affects mechanical properties of shotcrete. This is because chemical reaction can occur between the surrounding rock mass and shotcrete. These reactions may cause cracking within shotcrete and eventually lead to failure of shotcrete support. Petrographic analysis assesses the occurrence of unsuitable minerals. For this reason, this study analysed the petrography of basalt, and the results are detailed in Section 4.3.2.

4.3.2. Petrographic characteristics of the basalt aggregates from Sibasa Formation

The purpose of this section is to indicate mineral constituents and basic petrographic descriptions of basalt aggregates. Petrographic examinations were conducted to assess the influence of petrographic characteristics on the durability and strength of shotcrete.

The submitted samples originate from the Sibasa Formation as discussed in Section 3.2. The thin section samples are presented in Appendix B. The hand specimen of basalt appears dull and dark shaded with a greenish grey colour. Furthermore, basalt specimens show white (silica) and dark (pyroxene) minerals with some revealing amygdaloidal texture. Gas bubbles filled with secondary minerals formed the amygdaloidal texture. However, it is difficult to distinguish minerals at this point by the naked eye alone, due to the fine-grained nature of these rocks. The basalt rocks appear hard and show no favoured planes of shortcoming nor zones of weakness. Table 4.4 illustrates eight basaltic rock samples used for XRF analyses and thin section preparation. The mineral constituents that are present in basalt specimen are depicted in Table 4.5.

Table 4.5: Mineral assemblages with their state of abundance and percentage of their presence in basalt specimen

Minerals	State of abundance	Percentage
Plagioclase	Predominant	~60%
Pyroxene	Major	~15%
Oxide (magnetite/ilmenite)	Minor	~5%
Zeolite/chlorite	Minor	~5%
Olivine	Trace	2%

The mineral constituents of these basaltic aggregates are moderately altered depicting intersertal texture. Plagioclase is the main constituent of the rock and occurs as large fine-grained lathes with interstitial pyroxene. Plagioclase feldspar commonly alters into clay minerals as well as pyroxene, see Figure 4.1. Cracks are also rare in basalt specimen.

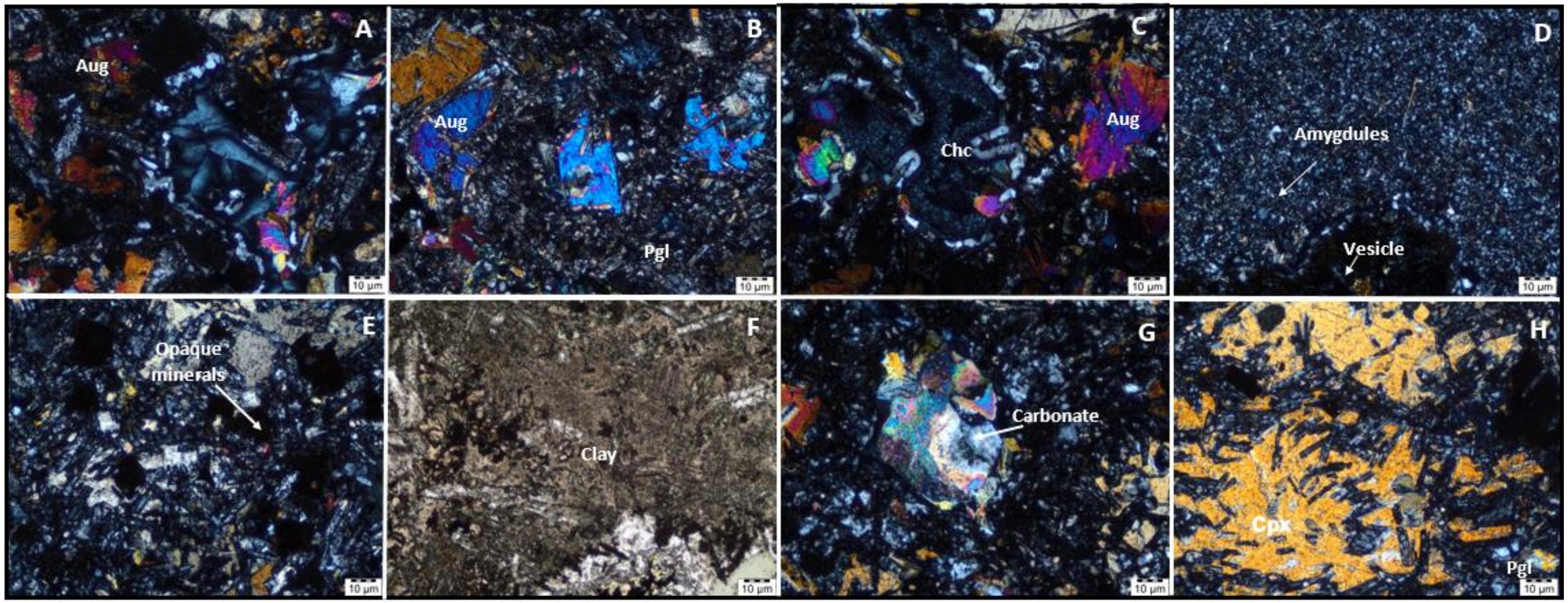

Figure 4.1: The crossed polarised view showing photomicrographs of basaltic rocks in thin sections

These rocks reveal large, colourful crystals of pyroxene which appear embedded in the fine-grained matrix of plagioclase grains revealing an intersetal texture. (A) Large euhedral crystals of clinopyroxene, commonly augite occurring in proximity with amygdule filled-in with secondary fibrous mineral, zeolite (chlorite); (B) The euhedral to anhedral clinopyroxene crystals show high interference colours depicting blue titano-augite, in a fine-grained moderately altered matrix with some clay; (C) The concentrically zoned amygdule crystal filled-in with secondary mineral, chalcedony, with pinkish augite crystal at close proximity; (D) Amygdaloidal basalt crystal; filled-in with fine grained various secondary minerals. Vesicles (dark) also present and associated with some iron oxide; (E) Heavy minerals (magnetite and ilmenite) appear black and often accompanied by brown-yellow wedged titanite crystals;(F) Weathered amphibole on the matrix of plagioclase which result in brown clay, shown in under PPL; (G) Rainbow coloured carbonate crystal present as a secondary mineral embedded in a fine-grained matrix of partially altered plagioclase laths; (H) Large yellowish clinopyroxene crystals show ophitically to sub-ophitically textures where plagioclase crystals are enclosed or partially enclosed by clinopyroxene.

Most of the thin sections show large, coloured crystals that appear embedded in the fine-grained basaltic matrix (volcanic glass) with olivine occurring in trace amounts. The plagioclase laths appear as thin elongated white crystals while clinopyroxene augite shows yellow to pink interference colours. The crystals are known as phenocrysts. The size of such phenocrysts depends on the rate at which it was cooled out of the magma. For instance, the larger the crystals the slower the cooling process and the smaller the crystals the faster the cooling process. Plagioclase feldspar often alters to a fine-grained micaceous material and the process is referred to as sericitization. Quartz grains occur as secondary mineral in the form of fine- grained chalcedony. Amygdules observed usually form after the rock has been emplaced and are often associated with low-temperature alteration. They form when the gas bubbles or vesicles are infilled with a number of different secondary minerals, depending on the groundwater chemistry and the physical conditions underground. The chemical weathering of the feldspars maybe rapid, producing clay minerals which possibly include, smectite/montmorillonite. Iron oxides and calcite/zeolite filling in the amygdules was observed. Fine grained euhedral shaped opaque minerals (magnetite, ilmenite) were recorded disseminated through the rock and accompanied by wedged yellow brown titanite with a volcanic glass of basic composition. Sulphides were encountered however the amounts were insignificant.

The petrographic examination focused on characterising their mineralogical composition including but not limited to texture, size, shape, nature of grain and mineral arrangements as well as alteration. The mineralogy of the basaltic rocks is characterised mainly by the presence of plagioclase feldspar and clinopyroxene (augite), and opaque phases commonly including magnetite/ilmenite. The primary mineral has been moderately to intensely altered into secondary minerals which include zeolite/chlorite, chalcedony, amphibole, sericite, clay, and carbonate.

Chlorite and smectite contents if present in high quantities could bring durability problems on shotcrete mixes. However, their level of harm is less if the contents are less than 10% of each. It is crucial for aggregates to resist tearing when subjected to physical, mechanical and chemical changes. Their resistance to these changes qualifies basalt aggregates to be deemed as suitable for the inclusion in shotcrete mix design. Although, basalt aggregates used in this study are weathered, but there is minimal influence on fresh and hardened properties of shotcrete. The properties of fresh and hardened of shotcrete with basalt and sand aggregates are discussed in the section below.

4.4. Properties of fresh and hardened shotcrete

Shotcrete that is structurally durable exhibit advantageous fresh and hardened properties. These properties of shotcrete include workability, effect of curing, compressive and flexural strengths. These factors contribute towards high strength and resistance to scaling off. This section details the results of workability and effect of curing on compressive and flexural strengths.

4.4.1. Workability

In this study, five mix proportions were prepared; namely, BC100, BC75, BC50, BC25 and BC0. After the preparation of fresh mix shotcrete, workability was immediately assessed. Workability was conducted in accordance with ASTM C230 (1997) to assess the workability of fresh shotcrete. The results derived from the workability test are depicted in Figure 4.2. The results indicate that the slump values range from 90 – 141 mm. Jolin and Beaupré (2000) stated that the slump required for pumping shotcrete is typically between 75 and 150 mm. The results from all mix proportions fall within the stipulated slump value by Jolin and Beaupré (2000). The workability of all mixes satisfactorily met the requirements of shotcrete used in underground mining. However, results showed a directly proportional relationship. Mixes with high basalt content (BC100) showed high workability whereas mixes with high content of sand (BC0) showed the lowest workability.

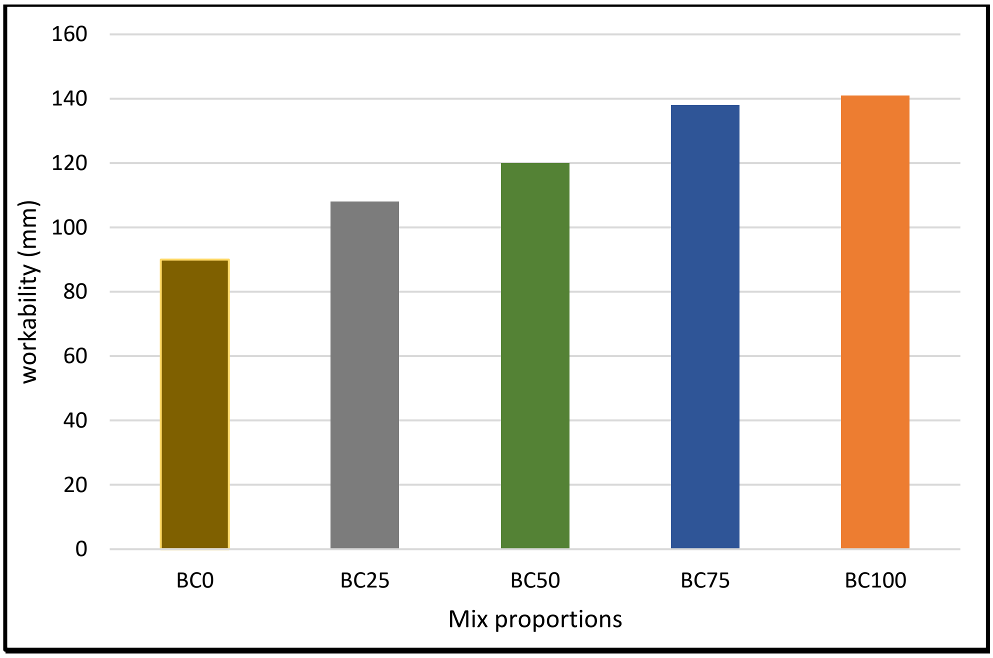

Figure 4.2: Workability of shotcrete as a function of mix type

Furthermore, hardened density generally influences strength properties of shotcrete. Section 4.4.2 details the results of hardened density of basalt and sand-based shotcrete.

4.4.2. Effect of basalt and sand aggregates on the hardened density of shotcrete

Five mix types (i.e., BC0, BC25, BC50, BC75 and BC100) were prepared. There were 24 cubes that were prepared per mix type. They were later subjected to curing after 7, 14, 21 and 28 days. Shotcrete mixes were casted and cured under water immersion until the period of mechanical strength testing was reached. About six mixes were prepared for each curing period. However, during the measurements of the masses per mix type, all six masses were noted, and the average was taken. Then, the mass and volume of the hardened cubes were calculated. The hardened density was calculated after 28 days of curing (see Appendix C). The hardened density of shotcrete cubes after 28 days was calculated using the equation expressed in Section 3.10.3. The values were recorded on a hardened density of five mix types and the obtained a graph is shown in Figure 4.2.

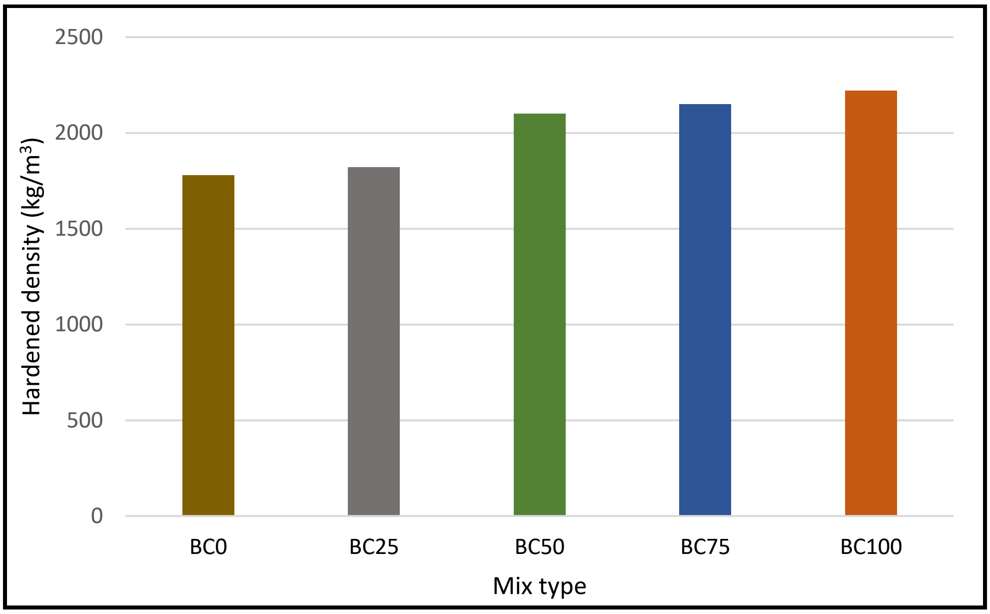

Figure 4.2: Hardened density of various mix proportions at 28 days

From the results the hardened densities ranged from 1780 kg/m^3 to 2200 kg/m^3. In accordance with ACI (2013), shotcrete is expected to have a hardened density that falls within the range of 1350 kg/m^3 to 2230 kg/m^3. The results on hardened density indicated an increase in hardened density relative to increasing basalt content in shotcrete mixes. The incorporation of basalt aggregates in shotcrete mixes yields hardened density that is within the acceptable range of shotcrete (ACI, 2013). Mixes of BC50, BC75 and BC100 produced high hardened density ranging from 1450 kg/m^3 to 1780 kg/m^3. Meanwhile, mixes BC25 and BC0 produced low hardened density ranging from 1362 kg/m^3 to 1385 kg/m^3. The control mix of sand (BC0) was reported to have the lowest hardened density of 1362 kg/m^3. Scholars such as Addis and Goodman (2009), Grieve (2009), and Yun et al. (2015) reported that shotcrete with high density is associated with high strength and durability. Therefore, shotcrete mixes with high content of basalt aggregates (BC75, BC100) are prone to produce shotcrete with high strength and durability. In contrast, shotcrete mixes with high content of sand aggregates (BC0, BC25, BC50) produce shotcrete that can have low strength and can easily crack. The hardened shotcrete cubes are subjected to flexural and compressive strength tests. The following section discusses the influence of various mix proportions and curing age on compressive and flexural strength properties of shotcrete.

4.3.3. Effects of basalt content on compressive strength

One of the aims of this study was to investigate the mechanical feasibility of using basalt aggregates in shotcrete mixes. This included looking into strength properties. Compressive strength was measured in accordance with (SANS 5863:2006) over various curing age. The results of compressive strengths are reported in Table 4.6 for each six (6) replicates of each mixture and over various curing ages. Furthermore, the standard deviation for various mix proportions was measured. This was done to express how each mix type differs from the average mean value of the shotcrete prisms over various curing ages.

Table 4.6: Mean compressive strength (MPa) of shotcrete prisms for various curing ages

Curing days	BC0	BC25	BC50	BC75	BC100	Standard deviation
7	23.9	25.1	29.6	30.5	32.1	0.561
14	28.4	29.1	32.9	33.0	34.3	0.656
21	29.6	35.4	39.5	40.19	41.3	0.731
28	31.2	36.2	39.8	41.01	43.1	0.745

From the results shown in Table 4.6, the highest mean compressive strength was derived from shotcrete mixes (BC100), i.e., 43.1 MPa at 28 days. Mean compressive strengths at 28 days of mixes BC75 and BC100 are greater than 40 MPa. According to ACI (2016) acceptable range of compressive strength is 30 – 40 MPa at 28 days of curing. This range of compressive strength justifies the use of this type of shotcrete. However, to use shotcrete for permanent lining the compressive strength is expected to be at 40 MPa at 28 days (ACI, 2016). Mixes BC75 and BC100 has shown highest mean compressive strength at 28 days. These mixes are deemed suitable to be used for permanent lining in underground mines. Mixes BC50 had a mean compressive strength of 39.8 MPa at 28 days curing age while mixes BC25 reached a mean compressive strength of 36.2 MPa at 28 days curing age. The least compressive strength was recorded from (BC0) sand aggregates with 31.2 MPa at 28 days. Mixes BC50, BC25 and BC0 can be used as temporary support while mixes BC75 and BC100 can be used as permanent lining support. Strength development over curing age of 21 days for BC75 and BC100 also falls within the expected compressive strength of permanent lining. Results of all 120 prisms that were subjected to compressive strength over various curing age are presented in Appendix D. The standard deviation of compressive strength over various curing ages has shown low variability. It can be summarised that an increase in basalt content in shotcrete mixes increases the compressive strength. The relationship between curing age, mix types and compressive strength is graphically presented in Figure 4.3.

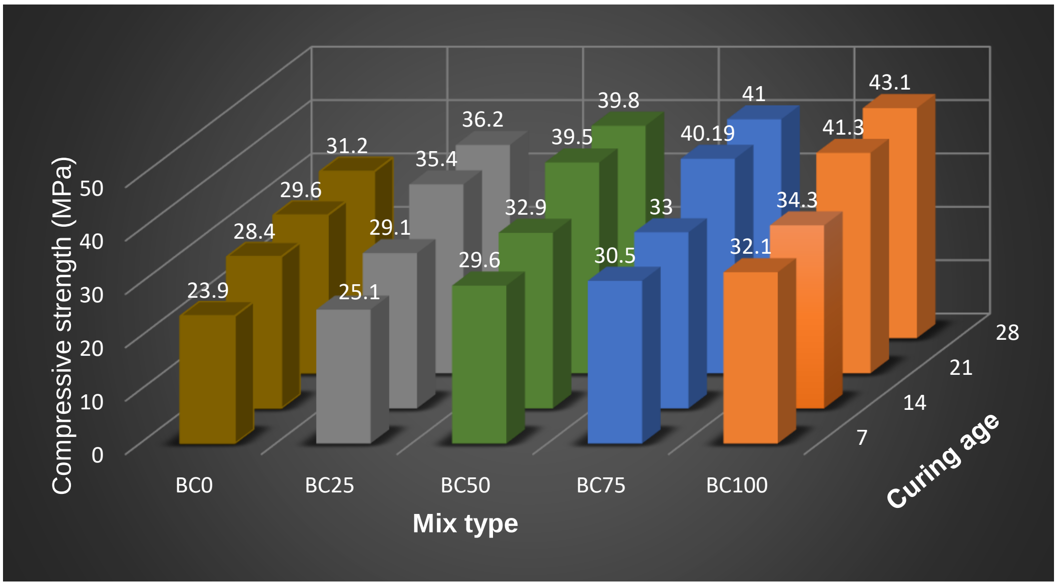

Figure 4.3: Mean compressive strength as a function of mix types and curing ages

The experimental results plotted in Figure 4.3 clearly depicted the dependence of compressive strength of shotcrete on various basalt content aggregates. The positive effect of incorporating basalt aggregates into shotcrete mix is clearly depicted in Figure 4.3. The highest mean compressive strength was observed on BC75 and BC100 mix type over all curing ages. Water immersion curing has shown to positively contribute to optimum compressive strength gain of BC75 and BC100. The least compressive strength was observed for BC0. The results of this investigation indicate a general mechanical improvement in mix properties with basalt content. Compressive strength is used as a parameter to discern the desired strength properties of shotcrete. It can be summarised that basalt aggregate is a suitable alternative aggregate source over sand aggregates. Flexural strength is also an important strength parameter that assess the quality of shotcrete. Section 4.3.4 represents the results of flexural strength of shotcrete mixes.

4.3.4. Effect of basalt content on flexural strength

Flexural strength was measured in accordance with ASTM C 78 (1997), the expected flexural strength of shotcrete at 28 days ranges from 0.6 to 8 MPa. The findings on mean flexural strength of basalt aggregates on shotcrete prisms are documented on this section. The results of flexural strengths are represented in Table 4.7 for each six (6) replicates of each mixture and over various curing ages. Furthermore, the standard deviation for flexural strength of various mix proportions was measured.

Table 4.7: Mean flexural strength (MPa) of shotcrete prisms for various curing ages

Curing days	BC0	BC25	BC50	BC75	BC100	Standard deviation
7	4.200	4.700	5.400	5.893	5.966	0.128
14	4.800	5.400	5.700	6.771	6.900	0.130

21	4.971	5.800	6.500	7.152	7.667	0.150
28	5.100	5.900	6.700	7.500	7.701	0.169

The results in Table 4.7 indicated that the highest mean flexural strength was derived from shotcrete mixes with highest basalt content BC100. The flexural strength of BC100 after 28 days was recorded to be 7.701 MPa. Meanwhile, the least mean flexural strength was recorded from shotcrete mixes BC0 with 5.100 MPa at 28 days. The elevated flexural strength of mixes BC100 and BC75 depicts high resistance to cracking. These mixes can be deemed suitable for underground support. Mixes BC50, BC25 and BC0 also fell within stipulated range of ASTM C78 (1997). However, their flexural strength did not exceed the upper limit of flexural strength. This would imply that their resistance to cracking is reduced compared the resistance of mixes BC75 and BC100. Variability was indicated from these results through standard deviation. It can be deduced from the results that an increase in basalt proportion increases flexural strength in shotcrete mixes. Figure 4.4 illustrates the relationship between mix type, curing age and flexural strength.

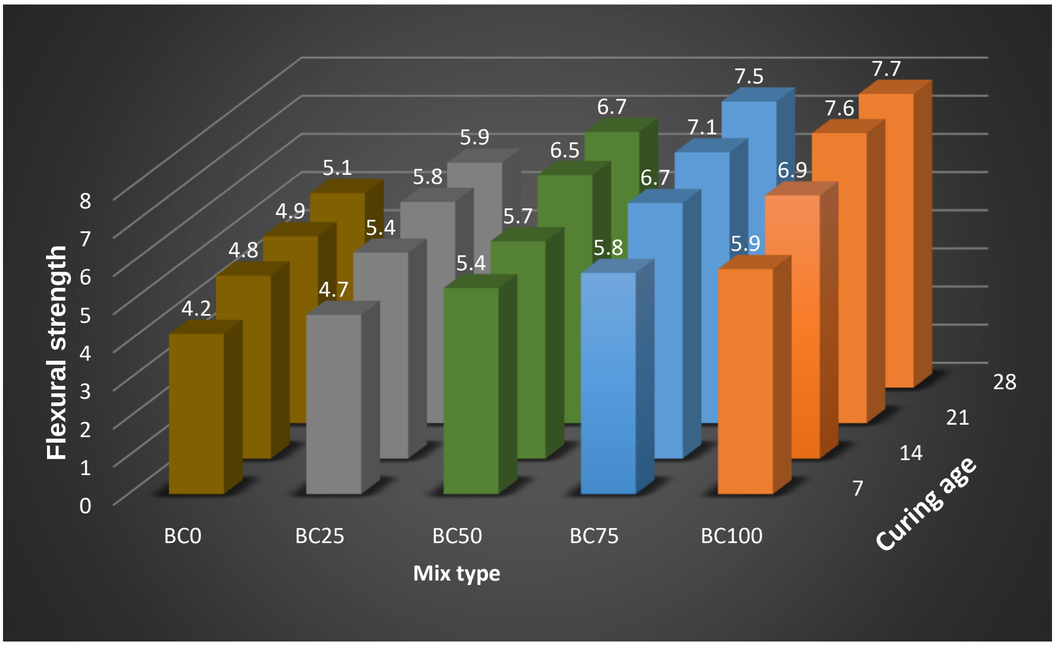

Figure 4.4: Mean flexural strength as a function of mix types and curing ages

The experimental results in Table 4.7 were plotted and represented in Figure 4.4. Furthermore, flexural strength measured for over 120 shotcrete prisms is indicated in (Appendix E). The dependency of flexural strength on various mix types was indicated. The graph shows that an increase in flexural strength is due to elevated basalt content. Throughout all curing ages, mixes BC75 and BC100 indicated a high flexural strength compared to mixes BC50, BC25 and BC0. The overall results indicate a general improvement in flexural strength when the content of basalt is increased. Meanwhile, BC0 indicated the lowest flexural strength. These results are indicative of the mechanical advantages of incorporating basalt aggregates to the shotcrete mix design. The results of this study are meant to showcase the possibility of substituting sand with basalt aggregates. The major findings from this section are summarised in Section 4.4.

4.4. Summary of major findings of the study

The work carried out in this study has demonstrated the effect of physical, mechanical and geochemical characteristics of aggregates on shotcrete. Physical characteristics tests that were conducted included fineness modulus, bulk density, specific gravity, water absorption, moisture content. Petrographic and geochemical analyses were also conducted. Results of basalt aggregates indicated a low fineness modulus, moisture content and water absorption compared to sand. Also, findings of basalt aggregates showed high specific gravity and bulk density over sand aggregates. The geochemical and petrographic analysis reported high values of minerals such as Al_2O_3 and Fe_2O_3 in basalt aggregates over sand aggregates. These minerals contribute towards desired mechanical properties of shotcrete. These findings from this study have indicated that basalt aggregates have advantageous physical characteristics over sand aggregates.

Mixes used in this study included BC0, BC25, BC50, BC75 and BC100. Shotcrete mix (BC100) depicted high workability while shotcrete mix (BC0) indicated the lowest workability. These mixes were cured and measured for hardened density. The results reported that mixes (BC100) showed elevated density, compared to mixes (BC0). Again, the mixes were subjected to compressive strength over 7, 14, 21 and 28 curing days. Mixes BC75 and BC100 showed the highest compressive strength compared to mixes BC50 and BC25. It was noted that BC0 mix reported the lowest compressive strength in all curing ages. Due to the compressive strength of BC75 and BC100 these mixes were deemed suitable to be used as a permanent lining.

Flexural strength tests were conducted for mixes BC0, BC25, BC50, BC75 and BC100. Measurements of these mixes were taken over 7,14, 21 and 28 curing days. The incorporation of basalt in BC75 and BC100 indicated the highest flexural strength compared to BC50 and BC25. The lowest flexural strength was recorded on mixes of BC0 throughout all curing ages. These results showed that mixes BC75 and BC100 have the highest resistance to cracking compared to the other mixes while mix BC0 may easily crack upon application. The incorporation of basalt aggregates has shown mechanical improvements on shotcrete mixes.

The accuracy of these results is tested through statistical methods. This includes plotting of statistical models, two-way ANOVA test and 2D performance model for shotcrete mixes. Furthermore, discussion of the results is covered in the next chapter.

Chapter 5: Mechanical properties of shotcrete for use as support in underground mining

5.1. Introduction

This study aimed to assess the physical and mechanical behaviour of basalt-based shotcrete in comparison with sand-based shotcrete. These shotcrete mixes were subjected to immersion curing method. Emphasis was placed on the physical properties of the aggregates. Other properties of interest included fresh mix properties, hardened density, flexural and compressive strength. This section discusses the observations depicted in Chapter 4. The discussion is conducted in alignment with the literature reviewed in Chapter 2. The arguments presented in Chapter 2 will assist in explaining the observations of Chapter 4. The discussion addresses the observations made on the workability. Also, the effects of basalt aggregates on hardened properties of shotcrete are discussed. The hardened properties include hardened density, compressive and flexural strength. Finally, explanations on the impact of different basalt content on mechanical properties (flexural and compressive strengths) and curing age are presented. The two-way analysis of variance (ANOVA) test was also performed on compressive and flexural strengths. This was done in order to test the effect of curing age and basalt aggregates content in shotcrete mix. Also, to determine the level of interaction between these variables. Overall, the two-way ANOVA test was performed for five (5) shotcrete types (BC0, BC25, BC50, BC75 and BC100) cured under water immersion for a period of 7, 14, 21, and 28 days. Lastly, 2D deformation analysis model was computed for basalt-based shotcrete and sand-based shotcrete.

5.2. Effect of basalt aggregates addition on fresh mixes

Workability is one factor that contributes towards strength development and self-compacting ability. In this study, five (5) mix types were prepared (i.e., BC0, BC25, BC50, BC75 and BC100). The results derived from the workability test were reported in Figure 4.2. The results indicated that the slump values range from 90 – 141 mm. The slump value expected of shotcrete that is used underground is typically between (75 – 150 mm) (Jolin and Beaupre, 2000). The findings of this study fall within the acceptable slump range. However, basalt-based mix (BC100) had the highest workability compared to sand-based mix (BC0). This is because basalt aggregates have less absorption compared to sand aggregates as indicated in Table 4.3. Fewer void spaces enable the shotcrete mixture to increase cohesion and prevent segregation. The prevention of segregation generally increases the workability of shotcrete mixes (Choi et al., 2017; Satheesh and Rajasekhar, 2018). Kuchta (2002) indicated that high workability of shotcrete ensures the development of early strength. The use of crushed basalt aggregates may be accepted by industries because there are minimal issues on pumpability (Al-Baijait, 2016; Kishore, 2016).

Similar studies conducted by Choi et al. (2017), Stepien and Kostrzewa, (2017), and Kumar (2019) are in consensus with findings of this study. Their studies showed that basalt-based shotcrete had high workability. Therefore, basalt-based shotcrete was considered more durable than sand-based shotcrete. Neville (2011) had indicated that an increase in workability reduces the compressive strength. However, the findings in this study (i.e., Figures 4.3 and 4.4) indicated basalt-based shotcrete showed the highest compressive strength than sand-based shotcrete. Lee et al. (2013) assessed the influence of moisture content of aggregates on workability. It was reported that aggregates with low moisture content generally have high workability. In this study, basalt aggregates had less moisture content compared to sand aggregates (Table 4.3). Low moisture content is an indirect measure of void spaces. Therefore, aggregates with less void spaces form a consistent shotcrete mixture. In this case, basalt-based shotcrete had the highest consistency compared to sand-based shotcrete. It can be stated that the findings of this study are in agreement with the findings of Lee et al., (2013). The fresh properties of shotcrete influence the hardened property of shotcrete. One important factor of hardened properties of shotcrete includes hardened density. The next section will detail the observations of hardened density in this study.

5.3. Effect of basalt proportions on hardened density of shotcrete

The freshly mixed shotcrete was prepared with various basalt aggregate content ranging from 0% to 100%. Shotcrete specimens were casted and cured under water immersion. The hardened density was weighed after 28 days. The results on hardened density indicated an increase in shotcrete mixes with high content of basalt aggregates (i.e., Figure 4.2). The least hardened density was reported from shotcrete mixes with high sand aggregates. According to ACI (2013), the expected density of shotcrete lies within the range 1350 kg/m^3 to 2230 kg/m^3. The important finding was that incorporating basalt aggregates yields shotcrete that is within the acceptable range of the expected density of shotcrete.

Factors such as specific gravity, bulk density, absorption capacity, shape of aggregates and geochemical analysis contribute to hardened density of shotcrete mixes. The following lines of discussions will focus on the hardened properties of shotcrete mix in relation to the above-mentioned characteristics.

Similar studies conducted by Mindess (2002), Korkanç and Tuğrul (2004) as well as Grieve (2009) reported their findings on the relationship between hardened density and specific gravity. Their findings indicated that an increase in specific gravity generally leads to an increase in hardened density of shotcrete. The results of this study reported specific gravity of basalt aggregates as (2.82 g/cm^3) while the specific gravity of sand was (2.71 g/cm^3). In this case, mixes BC50, BC75 and BC100 produced high hardened density ranging from 1450 kg/m^3 to 1780 kg/m^3. Meanwhile, mixes BC25 and BC0 had a hardened density ranging from 1362 kg/m^3 to

1385 kg/m^3. The control mix of sand (BC0) depicted the lowest hardened density of 1362 kg/m^3. The important finding was that incorporating basalt aggregates in shotcrete mixes produced dense shotcrete. Similar observations were made by Mindess (2002), Korkanç and Tuğrul (2004), and Grieve (2009). These scholars ascribed their findings of high hardened density to high specific gravity of basalt aggregates.

The findings of the bulk density can be used to possibly explain the difference in hardened density of these shotcrete mixes. Bulk density is a direct indicator of packing capacity. Therefore, an increase in bulk density of aggregates could potentially imply that the shotcrete matrix has a high packing capacity. An increase in packing capacity generally means an increase in hardened shotcrete.

From the results, it was reported that the bulk density of basalt aggregates was 2.98 kg/cm^3 while for sand aggregates it was 2.60 kg/cm^3. Similar studies were conducted by Al-Bakri et al. (2013) and Ubi et al. (2020). The authors concluded that shotcrete mixes with high basalt content is associated with higher hardened density. This is because of the increased bulk density of basalt aggregates.

Another possible explanation can be attributed to the effect of shape of aggregates. Sand aggregates are rounded while basalt aggregates are sharp and angular. Abalaka (2012) as well as Alsadey and Omran (2021) mentioned that basalt aggregates are angular, sharp and strong. This enables for adequate packing density in the shotcrete matrix. On the other hand, sand aggregates are rounded and consist of poor interlocking behaviour that form weak bond strength. However, the angular shape of basalt aggregates lead to greater bond with the cement paste. Other researchers (Wu et al., 2010; Alsadey and Omran, 2021; Yazici and Mardani-Aghabaglou, 2022) elaborated that angular shape of aggregates leads to improved compactness and cohesion thereby leading to a heavy and stronger shotcrete matrix compared to concrete mixes produced from round shape aggregates. Hence, shotcrete mixes with high basalt content have high hardened density compared to mixes with high sand content. The findings of this study are supported by Al-Bakri et al. (2013) and Ubi et al. (2020). High hardened density generally provides high strong performing shotcrete. It can be summarised that shotcrete mixes with high content of basalt aggregates (BC75, BC100) are prone to produce shotcrete with high strength and durability compared to shotcrete mix with high content of sand aggregates (BC0, BC25, BC50).

From the geochemical analysis it was reported that there is a considerable amount of heavy minerals in basalt aggregates (i.e., Table 4.4). These minerals include aluminium oxide (Al_2O_3) and iron oxide (Fe_2O_3). The mass of Al_2O_3 is 101.96 g and that of Fe_2O_3 is 159.69 g. Table 2.4 has indicated that sand aggregates predominantly consist of silica oxide (SiO_2) (Howari, 2015). The mass of SiO_2 is 60.01 g. The presence of Al_2O_3 and Fe_2O_3 have contributed to elevated density of basalt aggregates. Hence, the incorporation of basalt aggregates generally leads to increased hardened density of shotcrete. Physical characteristics of aggregates contribute towards hardened density and strength properties of shotcrete mixes. The effect of basalt content on mechanical properties of shotcrete mixes is discussed in the following section.

5.4. Effect of different basalt proportions on compressive strength of shotcrete

This research work entailed assessing if the substitution of sand by basalt aggregates would still meet the strength requirements of shotcrete. The shotcrete cubes were cured for a period of 7, 14, 21 and 28 days. Then later subjected to compressive strength test over the various curing period. The experimental results were plotted in Figure 4.3. The findings clearly indicated the relationship between shotcrete mixes, curing age and compressive strength. The overall compressive strength performance of shotcrete cubes increased with the addition of basalt content. Furthermore, the compressive strength of shotcrete cubes also increased with an increase in curing age. The relationship between compressive strength, shotcrete mixes and curing age was attributed to various physical characteristics. Shotcrete mixes with high basalt content have high compressive strength throughout all the curing ages. This is because basalt aggregates are considered dense, durable and less water absorbing (Kalra and Mehmood, 2018; Tuğrul Tunç, 2018). Similar studies (e.g., Al-Baijait, 2008; Kishore, 2015) indicated that shotcrete mixes with basalt aggregates show general improvement in compressive strength. Conversely mixes with high sand content reported the lowest compressive strength. This is because sand aggregates have high water absorption Table 4.3. The high absorbability of sand slows down the rate of the hydration reaction, which is responsible for compressive strength gain (Neville, 2011). Therefore, shotcrete mixes with high sand will not develop adequate compressive strength. The increased compressive strength in shotcrete mixes with high basalt content is also attributed to the shape of aggregates. Similar studies reported that high compressive strength of shotcrete made with basalt aggregates stems from the fact that these aggregates are angular and sharp, resulting to increased cohesion (Korkanç and Tuğrul, 2004; Abdullahi, 2012; Murray, 2019). Also, the sharp edges of basalt aggregates, forms an interlocking matrix and improve the bonding effect. High bonding effect and adequate interlocking matrix result in elevated compressive strength (Grieve, 2009) while sand aggregates are rounded; they often have small voids within their matrix. The presence of multiple void spaces reduces the compressive strength in sand-based shotcrete mix. In addition, the use of water immersion curing method affected the compressive strength of shotcrete cubes. The quality and durability of shotcrete does not depend solely on properties of ingredients. Other factors include curing and environmental conditions to which the shotcrete is exposed to over its service life. Adequate curing is indispensable in developing high strength performing shotcrete. Rahman et al. (2012) and Adejuyigbe et al. (2019) mentioned that water immersion curing is the most effective method for early and late strength development. Furthermore, water immersion curing is considered to be one of the most effective curing methods that produces the highest compressive strength. This is achieved through reducing moisture content and enhancing hydration. Also, elevated moisture content of sand aggregates contributed towards reducing the compressive strength while basalt aggregates reported a low moisture content compared to sand aggregates Table 4.3. Shotcrete mixes with high basalt content indicated high compressive strength due to the fact that basalt aggregates have low moisture content. The presence of low moisture content is associated with high compressive strength (Atoyebi et al., 2020). The moisture content value that was reported for basalt aggregates by Kishore (2015) is similar to the one reported in this study. Researchers such as Jimoh and Awe (2007), Kubiszewski (2012), and Dobiszewska (2019) reported that increased density is associated with elevated compressive strength. In this study, the bulk density of sand and basalt aggregates were reported to be 2520 kg/cm^3 and 2720 kg/cm^3 respectively (refer to Table 4.2). These results also help explain why basalt-based shotcrete mixes have high compressive strength compared to sand-based shotcrete mixes. The results of this research study also suggests that the hardness, density, and nature of basalt aggregates contribute towards compressive strength. From the basalt-based shotcrete mixes the compressive strength value of 43.1 MPa was recorded after 28 days of curing. A similar study conducted by Al-Baijait (2008) reported a compressive strength of 41.1 MPa after 28 days of curing. Basalt aggregates from this study were collected from Sibasa Formation while those used in the study of Al-Baijait (2008) were collected from Jordan in the Middle East. However, basalts derived from the Sibasa Formation reported the highest compressive strength compared to basalt aggregates derived from Jordan. These findings put emphasis on the influence on advantageous aggregate physical characteristics of basalt aggregates that contribute to shotcrete strengthening. High compressive strength of shotcrete mixes with basalt aggregates is associated with chemical and physical resistance. Compressive strength is used as a parameter to measure the quality of shotcrete. It can be deduced that basalt aggregates are a suitable alternative aggregate source over sand aggregates. As they can produce high strength performing shotcrete. Another, property that determines the quality of shotcrete is flexural strength. It is discussed in the next section.

5.5. Effect of different basalt proportions on Flexural strength of shotcrete

The ability to withstand bending forces is regarded as a crucial property for measuring the quality of shotcrete. This study assessed the effect of various mix types on flexural strength over 7, 14, 21 and 28 curing days. The experimental results plotted in Figure 4.4 clearly depicted the relationship between flexural strength, curing age and shotcrete mixes. High flexural strength was reported for shotcrete cubes with high basalt content (e.g., BC50, BC75, and BC100). These results remained highest throughout all curing ages while in all curing ages the lowest flexural strength was reported for shotcrete mixes with high sand content (BC0, BC25). The elevated flexural strength in shotcrete mixes is attributed to the strength of basalt rock. Being that basalt aggregates are derived from crushing basalt rock; they are also considered strong. Physical properties such as durability, high strength and hardness are associated with basalt aggregates. Conversely, sand is derived as a product of erosion of rocks on the land. These rocks generally can include sandstone, schist and granite. For instance, according to the Mohr scale, the hardness of basalt is within the range from 6 – 7 (Bajad and Sakhare, 2018). On the other hand, sandstone has a hardness that ranges from 5 – 6 (Illangovana et al., 2008). The hardness of the aggregates subsequently contributed to the strength properties of shotcrete mixes. Hence, basalt-based shotcrete depicted the highest flexural strength compared to sand-based shotcrete.

Another possible explanation to the increased flexural strength is attributed to the fineness modulus of aggregates. Abalaka (2012) and Al-Bakri et al. (2013) reported that aggregates with low fineness modulus form more paste which contribute towards producing stiff shotcrete. From this study, results of fineness modulus were the lowest for basalt aggregates and highest for sand aggregates. Similarly, Pilegis et al. (2016) and Luc Leroy et al. (2020) reported that basalt aggregates that were used in the shotcrete mixes had a fineness modulus of 3.04. Also, shotcrete mixes made from these aggregates indicated general improvement in flexural strength. Conversely, sand aggregates reported the highest fineness modulus, therefore the amount of paste formed will be minimal. In this case, flexural strength of shotcrete mixes with high sand content is minimised (Azunna and Okolo, 2019). Another physical characteristic that explains the elevated flexural strength in shotcrete mixes is specific gravity. Specific gravity of aggregates is considered an indication of strength. Basalt aggregates have high specific gravity compared to sand aggregates Table 4.2. Studies conducted by (Ryu and Monteiro, 2002; and Kumar, 2019) reported that shotcrete mixes with high basalt content recorded the highest flexural strength compared to sand-based shotcrete. Higher specific gravity is generally associated with high elevated strength properties. Hence, basalt-based shotcrete mixes have high flexural strength compared to sand-based shotcrete mixes. The findings of this study are similar to those reported by (Ryu and Monteiro, 2002; Kumar, 2019). Flexural strength is deemed crucial for shotcrete that is meant to support the roof, shoulders and the sidewall in underground excavations. This is because small key blocks of rocks that could potentially lead to fall of ground require support from shotcrete with high flexural strength (Bamigboye et al., 2018; Yasmin, 2018; Chotaliya et al., 2020). These findings presume that basalt aggregates may be a good alternative to sand aggregates. Furthermore, it can therefore be deduced that curing age, basalt and sand content contribute to strength properties of shotcrete. In order, to produce high strength performing shotcrete, physical parameters of aggregates have to be considered. Relationships between physical aggregate characteristics and strength properties are indicated through statistical modelling in the next section.

5.6 Statistical analysis

Statistical analysis of flexural and compressive strength on the five mix types (i.e., BCO, BC25, BC50, BC75 and BC100) is presented. Linear regression statistical models are constructed for compressive and flexural strength of various mix types over various curing ages. These statistical linear regression models are discussed in this section.

5.6.1. Statistical regression model

The statistical regression model assesses the relation between variables, these relations are approximated by functions. The parameters in this model depend on the x and y variable and the relationship between these variables is denoted by a simple linear regression model equation:

$$\mathrm{Y} = Ax + \mathrm{B} \tag{5.1}$$

where Y is the dependent variable, x is the independent variable, B is the Y-intercept, and A is the slope of the regression line.

Simple linear regression models involve only one independent variable which the response of variable Y depends upon. In this study, the scope is to establish the relationship between variable x (mix types) and Y (compressive or flexural strength). Compressive and flexural test results in Figures (4.3) and (4.4) reported elevated compressive and flexural strength for mix types with increased basalt content. From the linear statistical model there is an R^2 value. The R^2 value is a statistical measure that represents the variance for a dependent variable in a regression model. Also, R^2 is considered as a goodness of fit measure for linear regression models. A value of R^2 that is close to 0 implies that there is zero correlation between independent and dependent variables. Conversely, a value of R^2 that is close to 1 implies that there is high correlation between independent and dependent variables. This analogy is used in explaining the results found in this study, pertaining the relationship of compressive and flexural strength with various mix types over various curing ages.

5.6.2. Statistical analysis of compressive strength

Statistical simulations of the relationship between compressive strength and mix types over various curing ages. A linear regression model was used, and Equation (5.1) was used to explain the relationship between parameters. The parameters used in this model depend on the X and Y variable whereby X-variable represents mix types and Y-variable represents the compressive strength. The relationship between mix type and compressive strength over various ages is indicated in Figures 5.1 – 5.4.

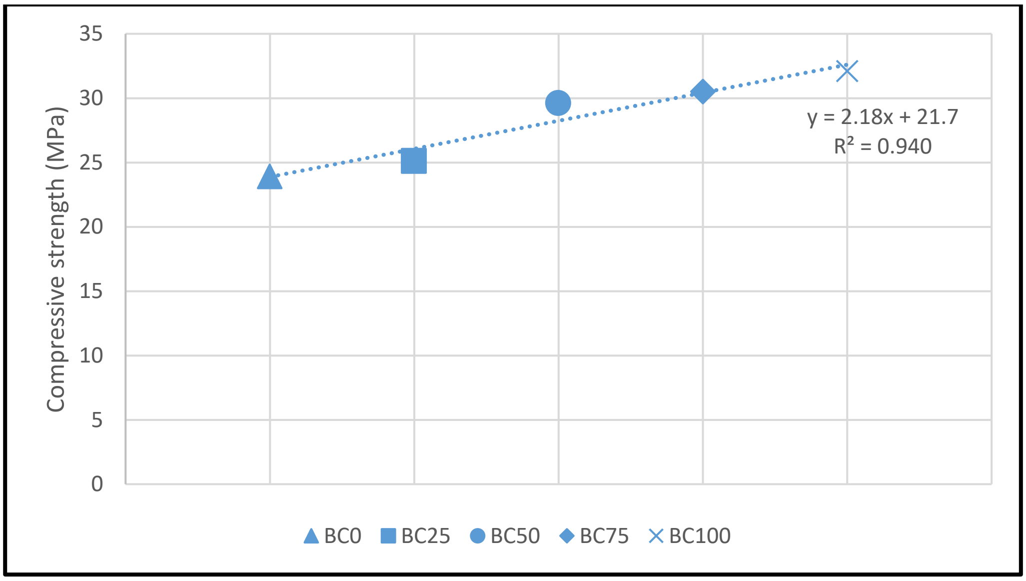

Figure 5.1: The relationship of mix types and compressive strength after 7 days of water immersion curing

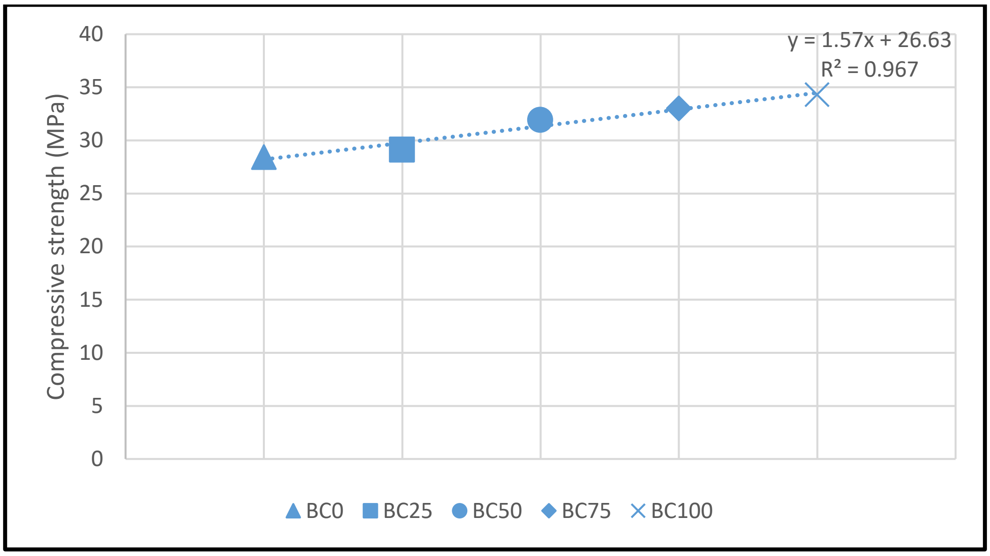

Figure 5.2: The relationship of mix types and compressive strength after 14 days of water immersion curing

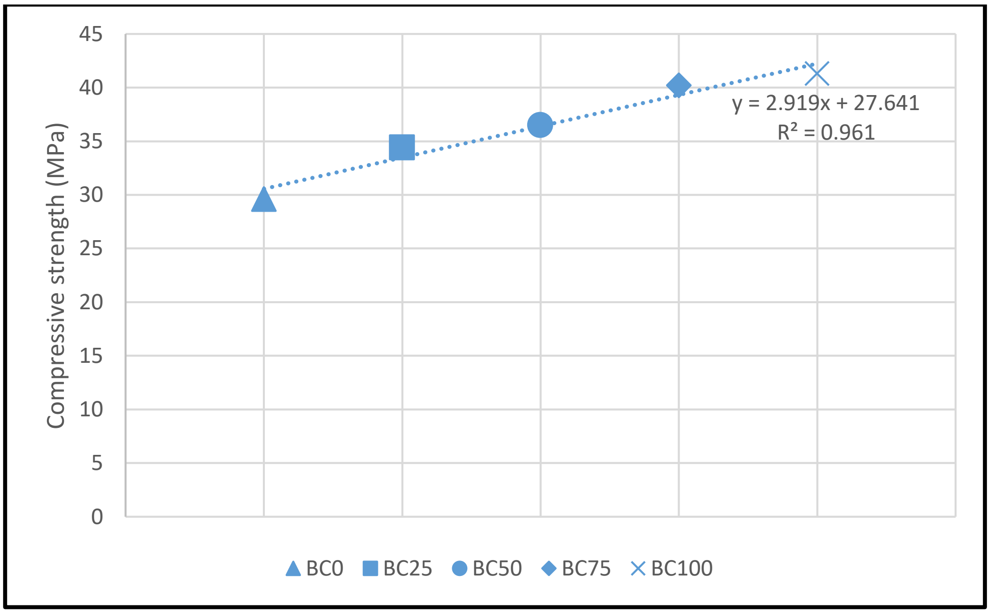

Figure 5.3: The relationship of mix types and compressive strength after 21 days of water immersion curing

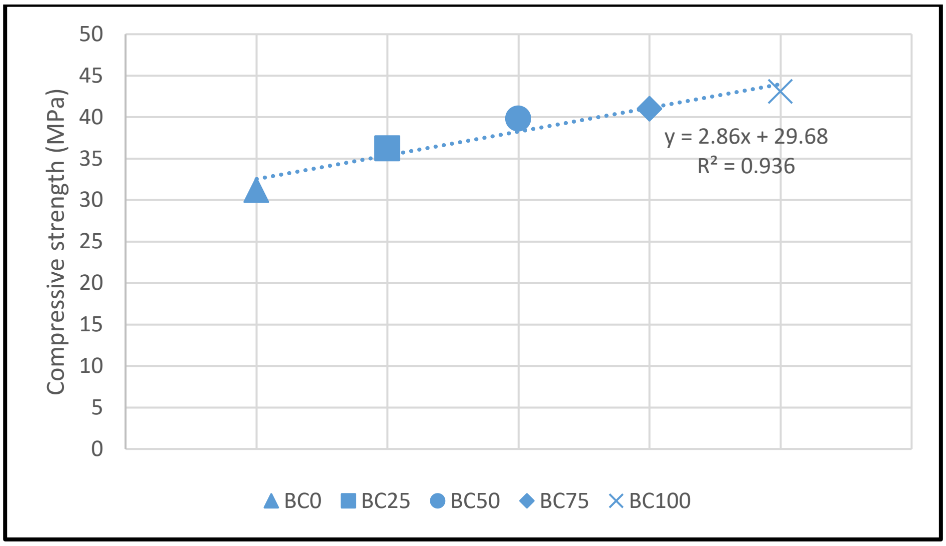

Figure 5.4: The relationship of mix types and compressive strength after 28 days of water immersion curing

Compressive strength of mixes BC100 remained the highest throughout the various curing ages. Shotcrete mixes BC75 is deemed considerably high while the lowest compressive strength was reported on mixes BC0. Lastly, BC25 and BC50 were also considered low compared to mixes BC100 and BC75. Elevated basalt content in mix type continuously reports high compressive strength. Strength development is continuously measured over 28 days. The discussion of statistical analysis of these linear statistical models is detailed next.

The discussion focuses on the R^2 value as a statistical indicator of existing correlations. In order to exhibit correlation between mix type and compressive strength over curing ages. In this study, R^2 value ranges from 0.936 to 0.967. This R^2 values indicate high correlation between mix type and compressive strength over various curing ages. Which implies that an increase in basalt content in the mix types generally leads to an increase in compressive strength. This trend was clearly depicted in all curing ages Figures 5.1 – 5.4. These statistical trends are best explained through addressing the influence of aggregate physical characteristics on compressive strength. Physical characteristics such as grain size, bulk density, specific gravity, porosity, water absorption and fineness modulus.

Furthermore, statistical relationship of these aggregate characteristics with compressive strength is presented in Appendix F. Basalt aggregates used in this study are of grain size 425 μm which is considered as fine. Also, the findings from fineness modulus also have indicated that basalt is finer than sand aggregates (Table 4.1). The presence of basalt content has led to increased bond cohesion of the shotcrete mixes. Thereby improving the compressive strength of shotcrete mixes with high basalt content. Furthermore, increased cohesion and interlocking of the shotcrete matrix have led to increased compressive strength (Howari, 2015; Choi et al., 2017; Alsadey and Omran, 2021). In addition, high density of basalt aggregates is inversely proportional to the amount of air-entrained in shotcrete mixes (Atoyebi et al., 2020). This relationship has supported the improvement of the internal shotcrete structure. Conversely, sand aggregates are more porous and have high air-entrained, later resulting to low compressive strength (Howari, 2015; Adejuyigbe, 2019). Overall, this implies that shotcrete mixes with basalt aggregates results in internal structure that is compact and impermeable. Therefore, shotcrete mixes with high basalt content are deemed suitable at producing high strength shotcrete compared to shotcrete mixes with sand aggregates. An inverse relationship was exhibited between fineness modulus and water absorption content with compressive strength on sand-based shotcrete mixes (see Appendix F). Previous studies (Bryne, 2014; Adejuyigbe, 2019; Choi et al., 2021) have documented that an addition in basalt content has improved compressive strength, durability and abrasion resistance. Again, the introduction of basalt aggregates has contributed to an increased level of active centres during hydration reaction, where it is possible to crystallize hydration products. More especially the C–S–H phase, which has an influence on the increased shotcrete compressive strength (Al-Baijat, 2008; Jankovic et al., 2011; Dobiszewska et al., 2019). One of the scientific objectives of this research was to determine the effect of basalt content on the mechanical properties of shotcrete mixes. It can be highlighted that the compressive strength of shotcrete mixes increases when there is an increase of basalt content. Compressive strength is an important parameter, however, a measure of resistance to failure during bending is equally important. Section 5.6.3 focuses on the influence of flexural strength on mix types over various curing ages.

5.6.3. Statistical analysis of flexural strength

Statistical analysis of the relationship between flexural strength and mix types over various curing ages. The relationship between various mix types and flexural strength is indicated in Figures 5.5 – 5.8.

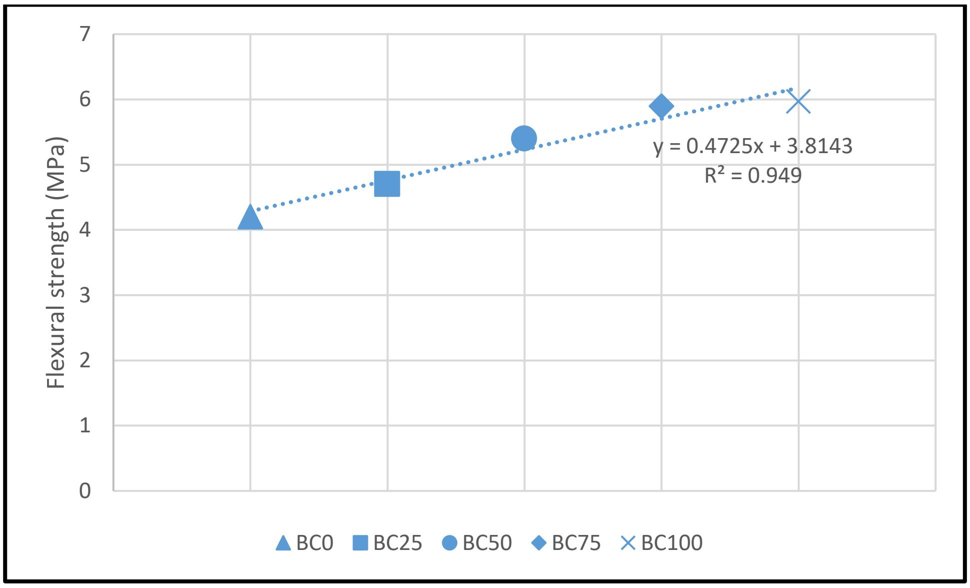

Figure 5.5: The relationship of mix types and flexural strength after 7 days of water immersion curing

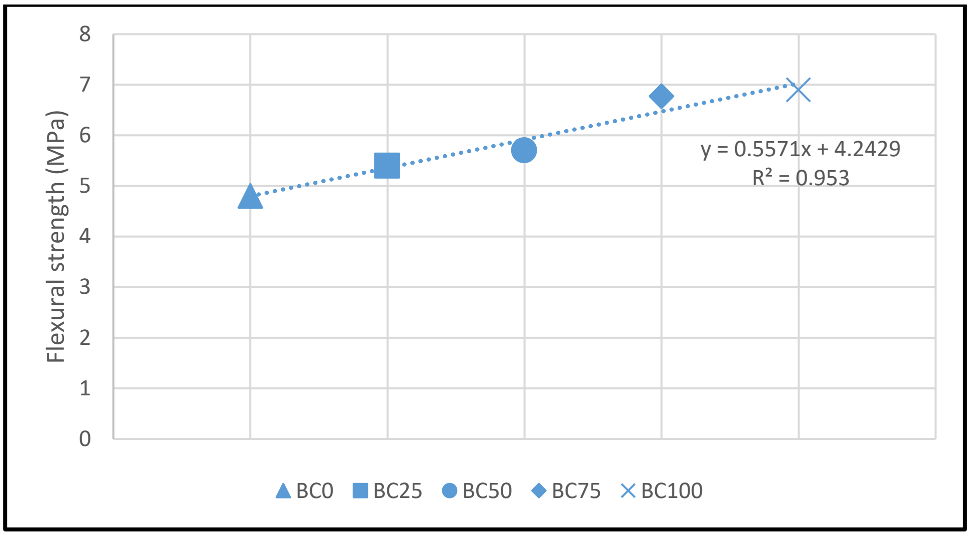

Figure 5.7: The relationship of mix types and flexural strength after 14 days of water immersion curing

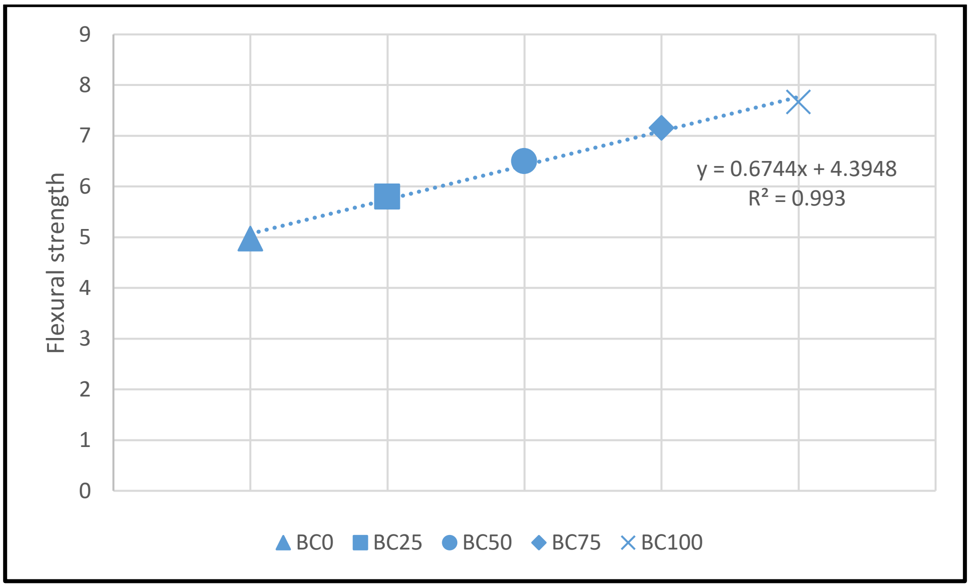

Figure 5.8: The relationship of mix types and flexural strength after 21 days of water immersion curing

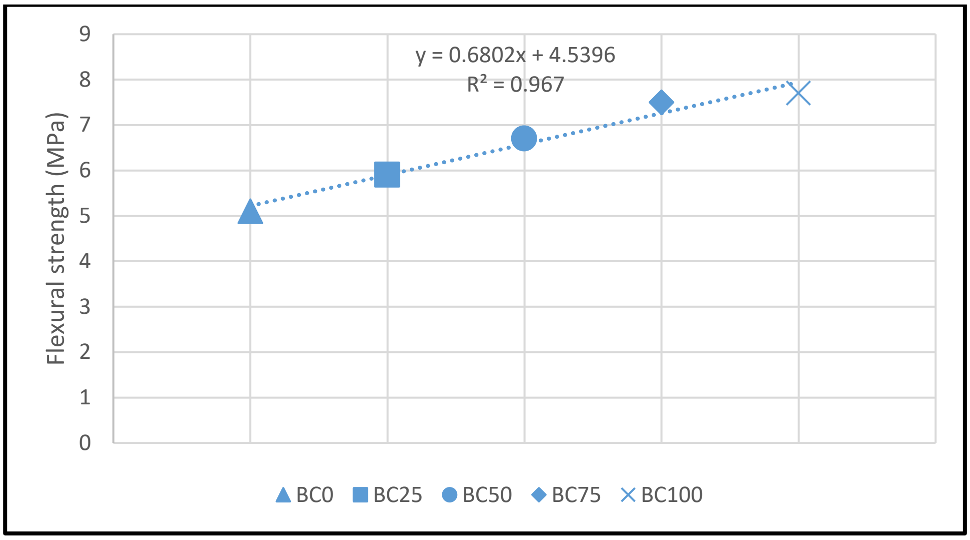

Figure 5.9: The relationship of mix types and flexural strength after 28 days of water immersion curing

Throughout all the curing ages mixes BC75 and BC100 reported the highest flexural strength compared to mixes BC0, BC25 and BC50. It can be summarised that elevated basalt content leads to an increase in flexural strength of shotcrete mixes. These statistical findings are discussed in detail with the support of the literature review below.

Flexural strength is deemed as a crucial strength parameter that contributes towards the quality of shotcrete. From the statistical correlation, the R^2 value ranges from 0.949 to 0.993. This R^2 value is close to 1, this implies that there is high correlation between mix types and flexural strength. Furthermore, an increase in basalt content of shotcrete mixes subsequently leads to an increase in flexural strength properties. This relationship is presented in Figures 5.5 – 5.8 throughout all curing ages. Also, flexural strength is affected by physical aggregates. The general trends exhibited between flexural strength and physical aggregate characteristics are represented in Appendix G.

As mentioned earlier in Section 5.3.1, the interlocking matrix of shotcrete mixes with basalt aggregates, subsequently leads to an increase in flexural strength. A directly proportional relationship is exhibited between mix type and flexural strength. As indicated in Figures 5.5 – 5.8, an increase in basalt content leads to an increase in flexural strength. The hardness and abrasion resistance of basalt aggregates contributed to high resistance of shotcrete mixes with high basalt content (Bajad and Sakhare, 2018). These results are consistent with previous work (Abalaka, 2012; Al-Bakri et al., 2013; Luc Leroy, 2020) in that shotcrete mixes with high basalt content yield high flexural strength. A matrix-aggregate bond that is stronger, result in high flexural strength. Cracks usually develop at the matrix- aggregate point that is inconsistent (Kishore, 2015). In this case, shotcrete mixes with high basalt content indicated the highest workability and consistency. Also, the basalt aggregates are deemed strong and durable (Al-Baijat, 2008). Therefore, their resistance to crack development serves as an advantage of using basalt as an alternative to sand. All in all, 120 prisms were casted, however, 24 prisms were designated to each mix type. The repeats of each mix type were six (6) per curing age. These repeats did not produce the same results. The next section focuses on ANOVA two-way test to assess the validity and reliability of the results.

5.7. ANOVA two-way test

5.7.1. ANOVA two-way test for compressive strength

The analysis involved two set of factors. Factor A stands for mix types which describes the basalt content and factor B for curing age. In the ANOVA two-way test, variable a = 5 labels of factor A represent the mix types (i.e., BC0, BC25, BC50, BC75, and BC100). On the other hand, b = 4 labels represent curing age (4 curing ages, i.e., 7, 14, 21 and 28 days). The experiment has n = 6 replicates for each mix types. Each replicate contained all a.b = 5 x 4 = 20 prisms. The total number of observations was a.b.n = 5 x 4 x 6 = 120 for all mixes over all curing ages.

The compressive strength value, as the observation is described by the linear statistical model:

$$y_{ijk} = \mu + \tau_i + \beta_j + (\tau\beta)_{ij} + \varepsilon_{ijk} \qquad \text{with,} \quad \begin{array}{l} 1 \le i \le a \\ 1 \le j \le b \\ 1 \le k \le c \end{array} \qquad (5.2)$$

Where μ is the overall mean effect

τ_i represents the effect of the ith level of factor A

β_i represents the effect of the jth level of factor B

τ_β represents the effect of the interaction between factors A and B

ε_{ijk} is the random error component having normal distribution with mean 0 and variance σ^2.

The hypothesis made for this test was as follows:

H_0: $\tau_1 = \tau_2 = \cdots = \tau a = 0$ (No main effect of curing age)
H_1: at least one $\tau i \neq 0$

H_0: $\beta_1 = \beta_2 = \cdots = \beta a = 0$ (No main effect of mix type)
H_1: at least one $\beta i \neq 0$

H_0: $(\tau\beta)_{11} = (\tau\beta)_{12} = \cdots = (\tau\beta)ab = 0$ (No interaction)
H_1: at least one $(\tau\beta)ij \neq 0$

In this case, H_0 is the null hypothesis and H_1 represent the alternative hypothesis. The ANOVA two-way variance test was performed at 5 % confidence level using an electronic spreadsheet set in Microsoft® Excel® (2013). From the ANOVA test, there are indicators such as *SS* which stands for sum of square, *dF* stands for degree of freedom, *MS* implies square value and, F_0 and F_{crit} respectively mean F-distribution of observed values and of critical values. The results of the test are summarised in Table 5.1.

Table 5.1: Two-way ANOVA test on compressive strength values obtained over various curing ages

Source of Variation	*SS*	*df*	*MS*	F_0	F_{crit}
Basalt content	1177.86	4	294.465	92.02031	2.485885
Curing age	1756.75	3	585.583	182.9948	2.718785
Interaction	103.5	12	8.625	2.695312	1.875262

Error	256	80	3.2		
Total	3294.11	99			

Based on the above, it can be concluded that all the hypothesis of the averages being equal (H_0) are rejected since all hypothesis F_{crit} are less than F_0:

For basalt content: F_0 = 92.02031 > F_{crit} = 2.4855885

For curing age: F_0 = 182.9948 > F_{crit} = 2.718785

For the interaction: F_0 = 2.695312 > F_{crit} = 1.875262

5.7.2. ANOVA two-way test for flexural strength

ANOVA two-way variance test was conducted between flexural strength of mix types over various curing ages. Factor A stands for mix types which describes the basalt content and factor B for curing age. In the ANOVA two-way test, variable a = 5 labels of factor A represents the mix types (i.e., BC0, BC25, BC50, BC75 and BC100). On the other hand, b = 4 labels represent curing age (4 curing ages, i.e., 7, 14, 21, and 28 days). The experiment has n = 6 replicates for each mix types. Each replicate contained all a.b = 5x4 = 20 prisms. The total number of observations was a.b.n = 5 x 4 x 6 = 120 for all mixes over all curing ages. Also, the flexural strength values were defined by the linear statistical model indicated by Equation (5.2).

The hypotheses were as follows:

H_0: $\tau_1 = \tau_2 = \cdots = \tau_a = 0$ (No main effect of curing age)
H_1: at least one $\tau_i \neq 0$

H_0: $\beta_1 = \beta_2 = \cdots = \beta_a = 0$ (No main effect of mix type)
H_1: at least one $\beta_i \neq 0$

H_0: $(\tau\beta)_{11} = (\tau\beta)_{12} = \cdots = (\tau\beta)_{ab} = 0$ (No interaction)
H_1:at least one $(\tau\beta)_{ij} \neq 0$

Table 5.2: Two-way ANOVA test on flexural strength values obtained over various curing ages

Source of Variation	*SS*	*df*	*MS*	F_0	F_{crit}
Basalt content	71.4454	4	17.86135	155.1811	2.485885
Curing age	31.036	3	10.34533	89.88126	2.718785
Interaction	2.685	12	0.22375	1.943962	1.875262
Error	9.208	80	0.1151		
Total	114.3744	99			

For basalt content: F_0=155.1811>F_{crit}=2.4855885

For curing age: F_0=89.88126>F_{crit}=2.718785

For the interaction: F_0=1.943962>F_{crit}=1.875262

5.8. Discussions of the ANOVA results

The statistical analysis of the ANOVA two-way test was performed on repeated measurements of compressive and flexural strengths respectively, in order to test for the following:

- The effect of curing age and of basalt content on compressive and flexural strengths respectively,
- And, to determine the level of interaction between them.

During the conduction of this test, the level of significance was set at 0.05. All the three (3) null hypothesis (H_0) sets in the ANOVA two-way tests for both compressive and flexural strengths were rejected since all F_{crit} values are less than F_0. The effect of curing age and basalt content on compressive and flexural strengths were found to be statistically significant. Furthermore, the ANOVA two-way test indicated significant interaction between basalt content and curing age on compressive and flexural strength respectively.

The response of compressive strength was found to be effectively impacted by curing age (7, 14, 21 and 28 days) and basalt content. Such that, compressive strength of shotcrete mixes increases with curing age and elevated basalt content. In the case of ANOVA two-way test conducted for compressive strength, F_0 value for basalt content was higher compared to that of curing age. This implies that basalt content exerted the greatest influence on shotcrete mixes compared to effect of curing age. As previously indicated in (Figure 4.3), elevated basalt content caused an increase in compressive strength, throughout all curing ages. Furthermore, mix type BC75 and BC100 showed the highest compressive strength. While mix type BC50, BC25 and BC0 indicated the least compressive strength. Mix type with high basalt content reported the highest compressive strength compared to mix type with high sand content. Also, interactive influence was noted between curing age, basalt type and compressive strength. It was deduced that mix type with high basalt content, cured over various ages indicate elevated compressive strength (Neville, 2011; Alsadey and Omran, 2021).

Also, the response of flexural strength was found to be effectively impacted by curing age (7, 14, 21 and 28 days) and basalt content. Also, flexural strength of shotcrete mixes increases with curing age and elevated basalt content. In the case of ANOVA two-way test conducted for flexural strength, F_0 value for basalt content was higher compared to that of curing age. This implies that basalt content exerted the greatest influence on shotcrete mixes compared to effect of curing age. As previously indicated in Figure (4.4), elevated basalt content caused an increase in flexural strength, throughout all curing ages. Furthermore, mix type BC75 and BC10 showed the highest flexural strength while mix type BC50, BC25 and BC0 showed the least flexural strength. Also, interactive influence was noted between curing age, basalt type and flexural strength. It was deduced that mix type with high basalt content, cured over various ages indicate elevated flexural strength (Al-Bakri et al., 2013; Luc Leroy, 2020). It was proven statistically that both flexural and compressive strengths gains occur over curing ages. The longer the shotcrete mixes are subjected to water immersion curing, the higher the flexural and compressive strength. Also, basalt aggregates have demonstrated advantageous physical characteristics over sand aggregates (see Chapter 4). These characteristics favour flexural and compressive strengths gains over sand aggregates. Hence elevated basalt content is marked with elevated compressive and flexural strengths compared to sand content. The influence of basalt content over sand content on shotcrete mixes is further subjected to deformation performance analysis. The next section analyses the performance of sand-based shotcrete (BC0) and basalt-based shotcrete (BC100) in underground excavations using a 2D deformation analyses model.

5.9. 2D Modelling of shotcrete performance

The Optum G2 geotechnical software is a finite element program for geotechnical stability and deformation analyses. It allows for the full load-displacement response to be traced. This software package was used in this study to generate a 2D deformation analyses model of shotcrete. Two types of shotcretes were analysed which are sand-based shotcrete (traditional shotcrete) and basalt-based shotcrete (hybrid shotcrete). The methodology of this software includes five (5) stages which are definition of geometry, materials, loads, analysis and results. Upon opening the program, a screen similar to the one presented in Figure 5.10 pops up.

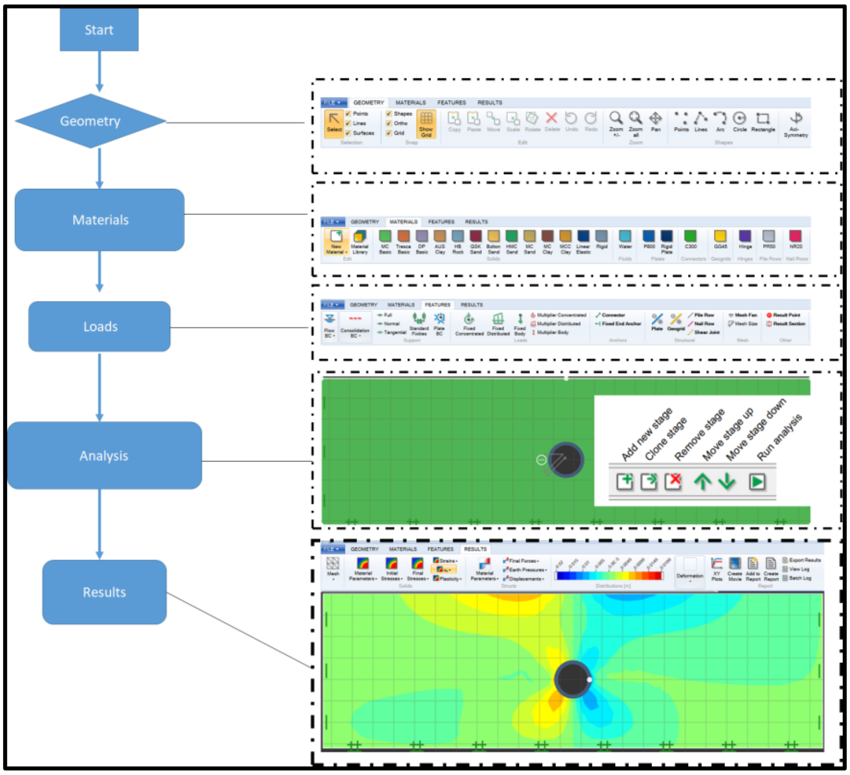

Figure 5.10: The step-to-step process of developing the deformational analysis of traditional and hybrid shotcrete (Optum Computational Engineering 2020).

The pop-up contains the option to start a new project. There is a taskbar containing the four functional tabs; geometry, materials, features and results, as depicted in Figure 5.10. The first step is to model the geometry of underground excavation. The geometry tab contains a number of options such as point, line, arc, circle and rectangle. However, in this case a circle was selected to create the 2D model. All points are selected in creating a circle and they are assigned their own co-ordinates, which are manually inputted. Once the model geometry has been established, the material properties can be chosen. In the development of this model, properties selected are indicated in Table 5.3. These materials properties are selected from the material tab. Then, feature tab was selected, it allows for the setting of fixed loads and multiplier loads. It is necessary to set boundary conditions to prevent the model from moving in the (x) or (y) direction. In this study, the x-axis was (20 m) and y-axis was (30 m). A fixed load is applied to represent constant loads on permanent tunnel support. After this stage, the analysis is set up and a multi-staged project can be created.

Table 5.3: Properties of material used in the deformation analysis (Optum Computational Engineering 2016)

Colour	
Material Type	Mohr-Coulomb
E (MPa)	42
v (-)	0.25
c (kPa)	40
ϕ (º)	30
$\psi 0$ (º)	0
kt (kPa)	0
ϕt (º)	90
γdry (kN/m^3)	21
γsat (kN/m^3)	21
K0 (-)	0.58
$\sigma 0$ (kPa)	0
Kx (m/day)	1
Ky (m/day)	1
h* (m)	0.5

The first goal of the analysis is to determine the ultimate magnitude of deformation. For this purpose, Limit Analysis is used. The result of this analysis is the load multiplier. The factor of the multiplier load (is shown in red) it is assumed that it has to be magnified in order to induce a state of collapse as indicated in Figure 5.11. The results of the deformation analysis are discussed below.

To this end, a modelled solution on stress and displacement in deep underground circular tunnels is analysed. The tunnels were subjected to the application of traditional and hybrid shotcrete, which was later subjected to a force of 40 MPa. The required compressive strength for underground tunnels is expected to fall within the range of 30 – 40 MPa. Hence the development of model took into account the stress level of 40 MPa. The results indicated that circular tunnel which had the application of hybrid shotcrete experienced a displacement of 0.05302 m along the x- axis. Also, a displacement of 0.005443 m along the y-axis. While circular tunnel which had the application of traditional shotcrete experienced a displacement of 0.05293 m along the x-axis. A displacement of 0.005681 m was presented along the y-axis. It is visible that high displacement was experienced in traditional shotcrete compared to hybrid shotcrete. This implies that hybrid and traditional shotcrete are both pivotal to the support of underground tunnels. However, hybrid shotcrete offers high strength properties over traditional shotcrete. Although, the performance of traditional and hybrid shotcrete experience minimal variability. However, this model provides evidence of the advantageous opportunity that is presented in using basalt aggregates over sand aggregates. The difference between the performance of the traditional and hybrid shotcrete can be attributed to the overall compressive and flexural strengths. Statistical analysis has shown that high compressive and flexural strength were noted on shotcrete mixes with elevated basalt content. Conversely, the compressive and flexural strengths of traditional shotcrete mixes were lower compared to hybrid shotcrete. It can therefore be concluded that hybrid shotcrete has high yielding support compared to traditional shotcrete. Therefore, it is imperative to consider the use of basalt aggregates as an alternative replacement of sand aggregates in the shotcrete mix design.

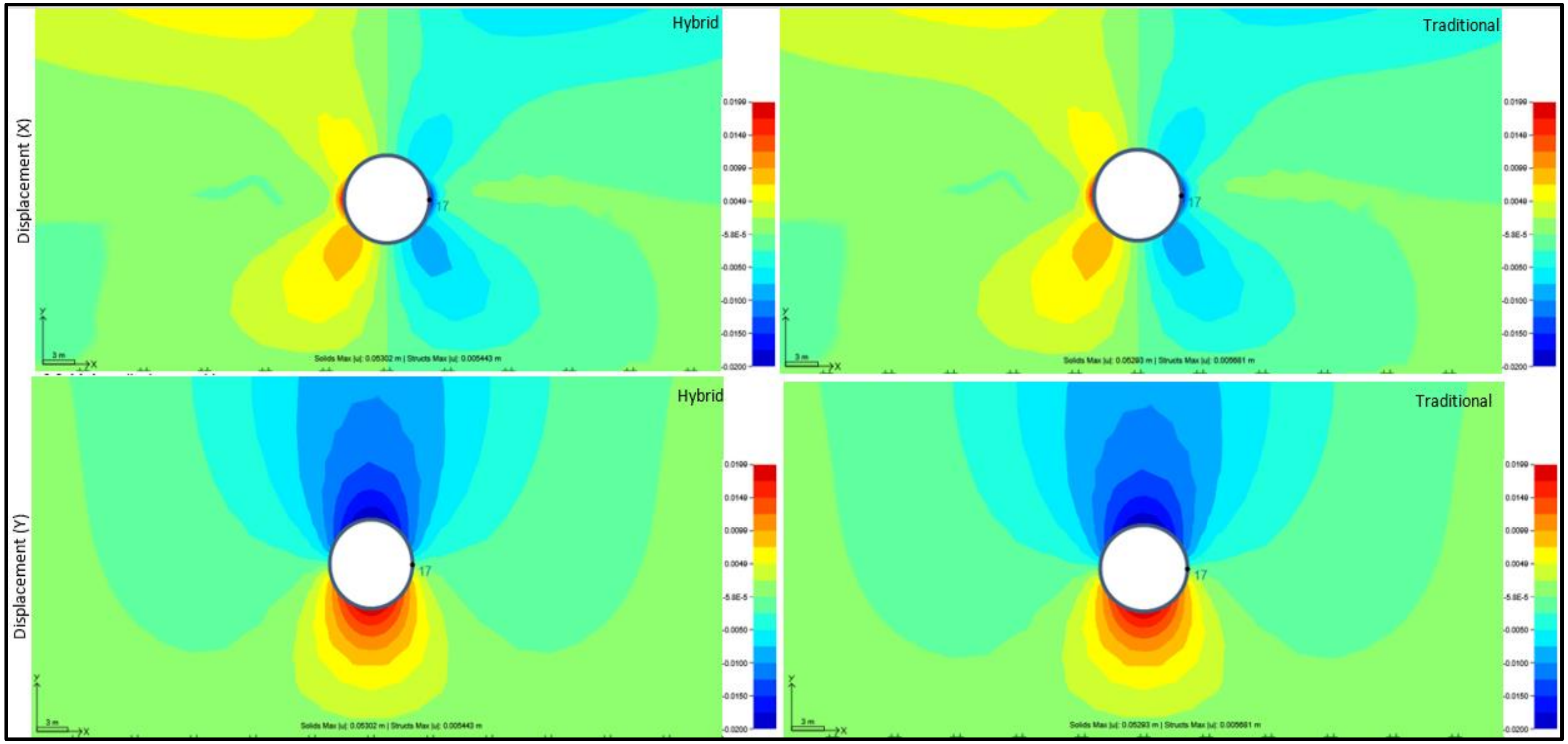

Figure 5.11: Horizontal (x) and vertical (y) stresses experienced in underground circular tunnels, after the application of hybrid and traditional shotcrete

5.10. Summary

This chapter presented various discussions related to the outcomes of Chapter 4, obtained from the experimental work conducted in Chapter 3. The findings observed in the workability of different mixes were attributed to various physical properties. Furthermore, mixes BC100 and BC75 had the highest consistency compared to mixes BC0, BC25 and BC50. The shotcrete mixes were later subjected to water immersion curing. Outcomes relating to the hardened densities of shotcrete mixes indicated that the addition of basalt content has been found to produce denser shotcrete compared to that produced from sand content. Mechanical properties were tested specifically flexural and compressive strength. The compressive strength was found to be the highest for mixes BC75 and BC100. However, the lowest compressive strength was represented on BC0, BC25 and BC50. Also, flexural strength was found to be the highest for mixes BC75 and BC100. The lowest flexural strength was recorded for mixes BC0, BC25 and BC50. The increase in flexural and compressive strength of BC75 and BC100, was attributed to the sharp angular basalt aggregates. These aggregates contribute towards improved interlocking effect and bonding with cement paste, allowing for elevated strength properties. The low flexural and compressive strengths of mixes BC0, BC25 and BC50 were attributed to the presence of void spaces and circular shape in sand aggregates. These aggregates lead to a low packing density, which slows down the strength development of shotcrete mixes. As a result of this, the bond to the formation cement paste was reduced. Also, the flexural and compressive strengths of BC75 and BC100 remain the highest over curing ages (i.e., 7, 14, 21 and 28 days) while the flexural and compressive strength of BC50, BC25 and BC0 remained the lowest over curing ages (i.e., 7, 14, 21 and 28 days). The effect of curing age indicated a directly proportional relationship with compressive and flexural strength. A statistical test indicated that basalt content has a strong interaction with compressive and flexural strengths over various curing ages. Also, the basalt content leads to an increase in flexural and compressive strengths over various curing ages.

Lastly, a 2D deformation analysis was conducted for the two shotcrete mixes. These mixes included (BC100) named hybrid shotcrete and (BC0) named traditional shotcrete. It was reported that traditional shotcrete experienced the highest deformation along the x and y axis compared to hybrid shotcrete. These findings can be attributed to the hardness and durability of basalt aggregates compared to sand aggregates. The results have provided an engineering and scientific basis of using basalt aggregates as an alternative to sand aggregates. The major findings presented under the conclusion and further recommendations are listed in Chapter 6.

Chapter 6: Conclusions and recommendations

6.1. Introduction

The main objective of this study was to assess the performance of shotcrete containing basalt aggregates in comparison to shotcrete with sand aggregates. Basalt aggregates were incorporated as sand replacement in shotcrete at the following mass fractions: 0%, 25%, 50%, 75% and 100%. Physical characteristics of aggregates were tested for sand and basalt prior to their inclusion in the mix design. Physical characteristics that were tested for included fineness modulus, moisture content, density, water absorption, geochemical and petrographic analyses in both basalt and sand aggregates. Shotcrete mixes that were designed included BC0, BC25, BC50, BC75 and BC100. The desired compressive strength of shotcrete mixes ranges from 30 – 40 MPa to ensure adequate support in underground excavations. On the other hand, the desired flexural strength was within the range 0.6 – 8 MPa. However, high flexural strength was favoured. Shotcrete cubes that amounted to 120 were casted and strength measurements were recorded over 7, 14, 21 and 28 days. Statistical analysis was used to assess the interaction and influence of basalt content and curing age on flexural and compressive strength. The performance of traditional shotcrete (BC0) and hybrid shotcrete (BC100) were analysed through the deformation analysis 2D model on the Optum modelling software. The main findings of the physical characteristics of aggregates and mechanical properties of shotcrete are summarised.

6.2. Basalt aggregates as shotcrete-making aggregate

Basalt aggregates derived from Sibasa formation were found to possess properties that enhance strength properties of shotcrete. Results derived from the physical characteristics test of aggregate are detailed in this section and summarised.

The findings indicated that basalt aggregates had a fineness modulus of 3.07 and sand had 3.99. Both aggregates were characterised as coarse according to their fineness modulus. However, sand aggregates are coarser compared to basalt aggregates. Low fineness modulus is favoured, as it contributes towards enhancing the consistency and workability of shotcrete. Furthermore, fine aggregates easily bond with the cement paste, thus contributing towards strength development. It can therefore be concluded that fineness modulus of basalt is favourable in the production of shotcrete. Shotcrete produced with the incorporation of basalt aggregates is less susceptible to cracking compared to shotcrete with sand aggregates.

Basalt and sand aggregates reported a specific gravity of 2.82 g/cm^3 and 2.71 g/cm^3 respectively. In the production of shotcrete high specific gravity of aggregates is favoured. This is because specific gravity increases the hardened density of shotcrete mix. Through reducing the void spaces and promoting elevated hardened density. The relationship exhibited by specific gravity and flexural and compressive strengths respectively is depicted in Appendices F and G. The findings from this study are indicative of the importance of high specific gravity of aggregates. In this case, basalt aggregates proved to be favourable over sand aggregates, due to their elevated specific gravity.

Results of the measured water absorption test were reported to be 0.66 wt% for basalt and 1.30 wt% for sand. The water absorption coefficient describes the permeability of aggregates. Aggregates with less water absorption are deemed suitable and favourable for incorporation in the mix design of shotcrete. This is because they tend to be resistant to the initiation of deleterious reaction. That can affect the quality and durability of shotcrete.

Results of moisture content were acquired in accordance with ASTM Standard C566-13 and were reported for basalt (0.3wt%) and sand (0.81wt%). From the findings of this study, it was indicated that basalt aggregates have less moisture content compared to sand. The incorporation of basalt aggregates does not promote spalling of shotcrete during application. High moisture content of aggregates reduces the quality of aggregates as well as the shotcrete mixes. Elevated moisture content affects the rate of hydration reaction. Disturbance to this reaction affects the strength development of shotcrete mixes.

Geochemical analysis was conducted through XRF. Silica content was recorded to be very high in sand aggregates and moderate for basalt aggregates. Silica content contributes towards enhancement of tensile strength. Furthermore, silica content improves the bonding between the aggregates and cement matrix. Basalt aggregates contained the highest iron oxide compared to sand aggregates. The presence of elevated iron oxide is responsible for compressive strength. Also, elevated iron oxide content contributes towards corrosion resistance of basalt aggregates. This affirms the reason behind high compressive strength that was recorded for mixes with elevated content of basalt. It was recorded that basalt aggregates have mineral content such as iron oxide, aluminium oxide and magnesium oxide that contribute towards strength development. Conversely, sand aggregates recorded minimal values for iron oxide, aluminium oxide and magnesium oxide. Hence, basalt aggregates are favourable over sand aggregates.

Petrographic analysis recorded the presence of plagioclase, quartz and pyroxene that enhance strength development in aggregates. Furthermore, the presence of this minerals has influenced resistance to thermodynamic change, to chemical change and corrosion. It is crucial for aggregates to resist tearing when subjected to physical, mechanical, and chemical changes. These properties affirm the suitability of basalt aggregates in shotcrete mix design that is used in underground excavation.

Workability test was conducted, and the slump value ranged from 90 – 141 mm for mixes BC0, BC25, BC50, BC75 and BC100. The results indicated a directly proportional relationship. Mixes with high basalt content (BC100) showed high workability, whereas mixes with high sand proportions of sand (BC0) showed the lowest workability. Mixes with high workability are indicative of shotcrete that easy to place during application. In this case, mixes with elevated basalt content were associated with easy placement during application.

The findings of hardened density reported 1780 kg/m^3 for BC0 and 2220 kg/m^3 for BC100. Elevated hardened density for BC100 mix was attributed to specific gravity, hardness of the rock and the presence of heavy oxides. Another possible explanation can be attributed to the effect of shape of aggregates. Sand aggregates are rounded while basalt aggregates are sharp and angular. As a result, angular aggregates enable for adequate packing density in the shotcrete matrix making it stiff. It has also been noted that the angular shape of basalt aggregates formed a greater bond with the cement paste. Hence, there was elevated compressive and flexural strength compared to sand mixes. In this case, shotcrete mixes with basalt aggregates led to higher interlocking compared to shotcrete mixes with sand aggregates. Findings derived from compressive and flexural strength, indicated that optimum performance was yielded when there was 100% replacement of sand by basalt aggregates. Finally, compressive and flexural results were statistically modelled. The statistical models indicated a strong correlation between mix types and strength properties. It was reported that mix types that had high content of basalt aggregates had a strong relationship with compressive and flexural strength. The explanation of this findings is ascribed to the advantageous characteristics of basalt aggregates. These characteristics include the shape of the aggregates; high interlocking packing density; high density and low water absorption. Furthermore, a statistical two-way ANOVA test was performed over all curing ages (i.e., 7, 14, 21 and 28 days). This was done to assess the interaction and influence of basalt content on compressive and flexural strength. It was deduced that basalt content influenced compressive and flexural strength over all curing ages. Also, that there was an interaction between basalt content, compressive and flexural strength over all curing ages.

A numerical model was developed to assess the performance of shotcrete with sand and basalt aggregates in underground excavations. Major findings depicted that high displacement was experienced in the application of shotcrete with 100% sand aggregates. While the least displacement was experienced in underground excavation that had the application of shotcrete with 100% basalt aggregates. This was because basalt aggregates have high durability and resistance to chemical and physical weathering. Finally, this current study has provided basis for the use of basalt aggregates as an alternative aggregate source to sand aggregates. This is indicated through the elevated compressive and flexural strength values derived from shotcrete mixes with elevated content of basalt aggregates. Furthermore, basalt aggregates derived from Sibasa Formation have shown potential of producing high quality shotcrete that could be used as support in underground excavations. It can therefore be concluded that basalt aggregates are a suitable replacement for sand aggregates.

6.3. Recommendations for future work

The current study has addressed the potential use of basalt aggregates derived from Sibasa Formation as a sand replacement alternative source of aggregates. In light of this study, further areas of research work have surfaced, and would provide pivotal information to the engineering body of knowledge. Below are some recommendations for future work:

- Basalt aggregates fall under the igneous rock group, it would be beneficial to furthermore look into the mechanical properties of other igneous rocks. This will be done to discern which aggregate type would be highly suitable in terms of mechanical properties in comparison with basalt aggregates.
- Also, it would be beneficial to look into recycled aggregates that fall under igneous rocks that can be crushed and incorporated into shotcrete that will be used for support.

- Further experimental investigations are needed to account for basalt aggregates that have a diameter greater than 425 μm. This is meant to address if there will be any change on mechanical properties of concrete mixes with basalt aggregates that are greater than 425 μm.

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Appendices

Appendix A

Table A.1: Compressive and flexural strengths of trial mixes. These measurements were taken at 28 days. These trial mixes were conducted under various water to cement ratio. Highest compressive and flexural strength was recorded for trial mixes with water to cement ratio of 0.6.

Mix ID	No. of Samples	Sand (g)	Basalt (g)	Cement (g)	Water (g)	Water-to-cement ration w:c (-)	Compressive strength (MPa)	Flexural strength (MPa)
BC0	1	1350	0	450	180	0.4	24.3	3.1
	1	1350	0	450	225	0.5	27.6	4.2
	1	1350	0	450	270	0.6	31.2	5.0
BC25	1	1012.5	337.5	450	180	0.4	24.7	4.5
	1	1012.5	337.5	450	225	0.5	32.7	4.9
	1	1012.5	337.5	450	270	0.6	36.2	5.9
BC50	1	675	675	450	180	0.4	34.1	5.0
	1	675	675	450	225	0.5	37.2	5.5
	1	675	675	450	270	0.6	39.8	6.7
BC75	1	337.5	1012.5	450	180	0.4	36.1	5.7
	1	337.5	1012.5	450	225	0.5	38.4	6.0
	1	337.5	1012.5	450	270	0.6	41.0	7.5
BC100	1	0	1350	450	180	0.4	38.2	6.1
	1	0	1350	450	225	0.5	40.5	6.3
	1	0	1350	450	270	0.6	43.1	7.7

Appendix B: Thin sections

Eight (8) thin sections were prepared from basalt rock collected from Sibasa Formation. The thin sections are indicative of the finely grained texture of basalt aggregates. The grain distribution from the grain measurement ruler indicates optimum densely packed grains. This is seen in basalt aggregates photomicrograph.

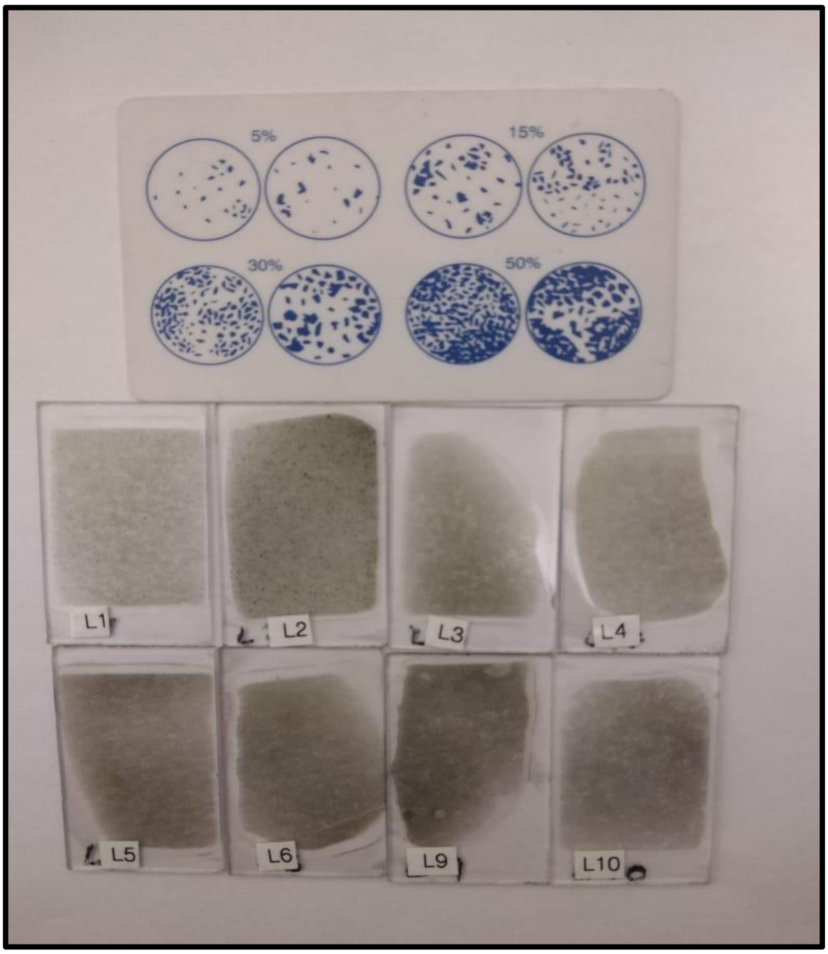

Figure B.1: Thin sections of basalt aggregates collected in various locations along the Sibasa Formation.

Appendix C: Hardened density

Six (6) hardened densities per shotcrete mixes were taken at 28 days after water immersion curing. The average mean hardened density of these mixes ranged from 1780 kg/cm^3 and 2220 kg/cm^3. These mean hardened density lies within the acceptable hardened density of 1350 kg/cm^3 to 2230 kg/cm3. These results indicated less variability amongst the repeats. High hardened density was associated with elevated basalt content in shotcrete mixes.

Table C.1: Six (6) Hardened density per shotcrete mix type taken at 28 days of curing.

Hardened density (kg/cm^3) 28 days of water immersion curing	No of cubes	BC0	BC25	BC50	BC75	BC100
	1	1880	1900	2150	2096	2321
	2	1870	1905	1960	2200	2166
	3	1765	1800	1910	2080	2112
	4	1750	1801	2210	2184	2190
	5	1700	1810	2001	2170	2260
	6	1715	1706	2380	2173	2270
Average mean		1780	1820	2100	2150	2220
Average standard deviation		2.341	1.987	2.018	1.234	1.019

Appendix D: Compressive strength

Compressive strength was taken on 24 cubes per mix type (i.e., BC0, BC25, BC50, BC75 and BC100). Six (6) cubes per mix type were subjected to compressive strength test over a period of 7, 14, 21 and 28 days. Highest compressive strength values were recorded for mixes BC100 and BC75. While the lowest compressive strength values were reported for mixes BC0, BC25 and BC50. Also, the variability of the 6 repeats was minimal which is indicative of the level of accuracy in conducting this strength test.

Table D.1: Compressive strength of shotcrete mixes taken over 7 days.

Compressive strength After 7 days of water immersion curing	No of cubes	BC0	BC25	BC50	BC75	BC100
	1	23.81	26.51	28.81	31.32	32.39
	2	23.81	26.10	30.82	29.04	30.28
	3	22.71	25.21	30.50	28.85	31.83
	4	23.82	26.80	29.31	29.86	31.63
	5	24.91	25.01	29.31	32.85	32.68
	6	24.10	26.12	28.70	31.18	33.62
Average mean		23.86	25.96	29.58	30.52	32.16
Average standard deviation		0.175	0.231	0.296	0.582	0.337

Table D.2: Compressive strength of mixes taken over 14 days.

Compressive strength After 14 days of water immersion curing	No of cubes	BC0	BC25	BC50	BC75	BC100
	1	28.21	27.80	32.01	32.40	33.64
	2	25.81	28.11	31.91	31.37	32.86
	3	28.23	28.31	33.10	34.63	33.22
	4	31.25	30.61	34.12	35.94	36.99
	5	30.01	29.71	32.10	31.46	35.39
	6	26.81	30.21	33.60	32.51	33.90
Average mean		28.39	29.13	32.81	33.05	34.33
Average standard deviation		0.443	0.429	0.327	0.608	0.505

Table D.3: Compressive strength of mixes taken over 21 days.

Compressive strength After 21 days of water immersion curing	No of cubes	BC0	BC25	BC50	BC75	BC100
	1	29.81	34.60	41.90	39.07	40.65
	2	29.32	33.01	40.51	40.81	41.22
	3	28.61	34.91	36.51	41.10	40.82
	4	30.91	36.71	40.32	39.38	40.59
	5	29.41	37.21	38.90	39.15	43.65
	6	29.41	36.21	38.81	41.02	40.91
Average mean		29.58	35.44	39.49	40.09	41.31
Average standard deviation		0.213	0.518	0.585	0.322	0.320

Table D.4: Compressive strength of mixes taken over 28 days.

Compressive strength After 28 days of water immersion curing	No of cubes	BC0	BC25	BC50	BC75	BC100
	1	28.51	36.31	41.80	41.30	46.61
	2	30.61	33.60	40.51	41.61	45.01
	3	31.90	35.10	36.51	40.01	39.61
	4	33.40	35.10	39.80	43.02	41.01
	5	31.50	38.90	40.50	42.41	42.10
	6	31.32	38.31	39.90	39.81	44.41
Average mean		31.21	36.22	39.84	41.36	43.13
Average standard deviation		0.448	0.661	0.457	0.420	0.906

Appendix E: Flexural strength

Flexural strength was taken on 24 cubes per mix type (i.e., BC0, BC25, BC50, BC75 and BC100). Six (6) cubes per mix type were subjected to flexural strength test over a period of 7, 14, 21 and 28 days. Highest flexural strength values were recorded for mixes BC100 and BC75. While the lowest flexural strength values were reported for mixes BC0, BC25 and BC50. Also, the standard deviation values of the six (6) repeats were minimal; this is indicative of the level of accuracy in conducting this strength test.

Table E.1: Flexural strength of shotcrete mixes taken over 7 days.

Flexural strength After 7 days of water immersion curing	No of cubes	BC0	BC25	BC50	BC75	BC100
	1	3.81	4.79	5.57	6.37	5.50
	2	4.31	4.35	5.28	5.51	6.44
	3	4.43	4.96	5.06	5.62	5.85
	4	4.08	4.80	5.10	5.96	5.93
	5	4.29	4.34	4.67	5.62	5.84
	6	4.57	4.90	6.74	6.28	6.23
Average mean		4.25	4.69	5.40	5.89	5.97
Average standard deviation		0.082	0.095	0.204	0.127	0.101

Table E.2: Flexural strength of shotcrete mixes taken over 14 days.

Flexural strength After 14 days of water immersion curing	No of cubes	BC0	BC25	BC50	BC75	BC100
	1	4.92	5.25	5.87	6.21	6.94
	2	4.84	5.28	5.58	6.83	6.60
	3	4.55	5.06	5.55	6.52	7.06
	4	4.88	5.10	5.68	7.09	6.96
	5	5.19	4.67	5.71	6.82	7.13
	6	4.45	6.74	6.00	7.16	6.90
Average mean		4.81	5.35	5.73	6.77	6.93
Average standard deviation		0.008	0.189	0.055	0.111	0.050

Table E.3: Flexural strength of shotcrete mixes taken over 21 days.

Flexural strength After 21 days of water immersion curing	No of cubes	BC0	BC25	BC50	BC75	BC100
	1	4.94	5.64	6.54	7.39	7.59
	2	5.22	5.81	6.52	6.71	8.05
	3	5.11	5.70	6.43	7.96	7.47
	4	4.99	5.77	6.47	6.32	7.49
	5	4.67	6.38	6.68	7.80	7.54
	6	4.90	5.77	6.35	7.46	7.86
Average mean		4.97	5.85	6.50	7.27	7.67
Average standard deviation		0.055	0.075	0.033	0.207	0.079

Table E.4: Flexural strength of shotcrete mixes taken over 28 days.

Flexural strength After 28 days of water immersion curing	No of cubes	BC0	BC25	BC50	BC75	BC100
	1	4.80	5.49	6.81	6.92	6.78
	2	5.54	6.05	6.71	7.50	6.74
	3	4.71	5.94	6.87	8.00	8.13
	4	5.16	5.58	6.48	7.61	7.98
	5	5.07	6.15	6.61	7.76	8.29
	6	5.29	6.39	6.52	7.48	8.03
Average mean		5.10	5.93	6.67	7.55	7.66
Average standard deviation		0.096	0.109	0.053	0.130	0.244

Appendix F: Correlation of compressive strength with physical aggregate characteristics

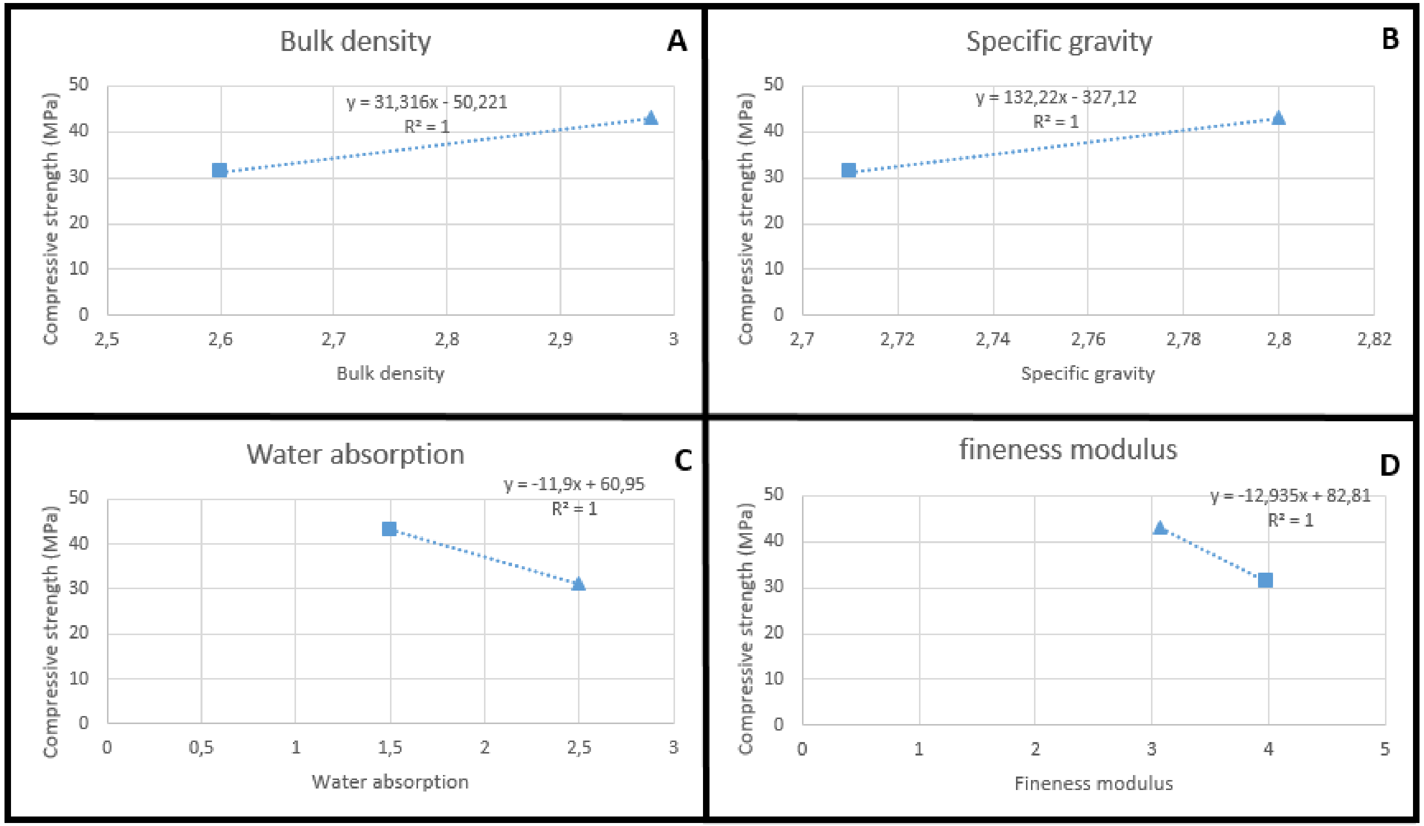

Figure E.1: (A) Linear regression model of the relationship between compressive strength and bulk density; (B) Specific gravity; (C) Water absorption; (D) Fineness modulus.

Appendix G: Correlation of flexural strength with physical aggregate characteristics

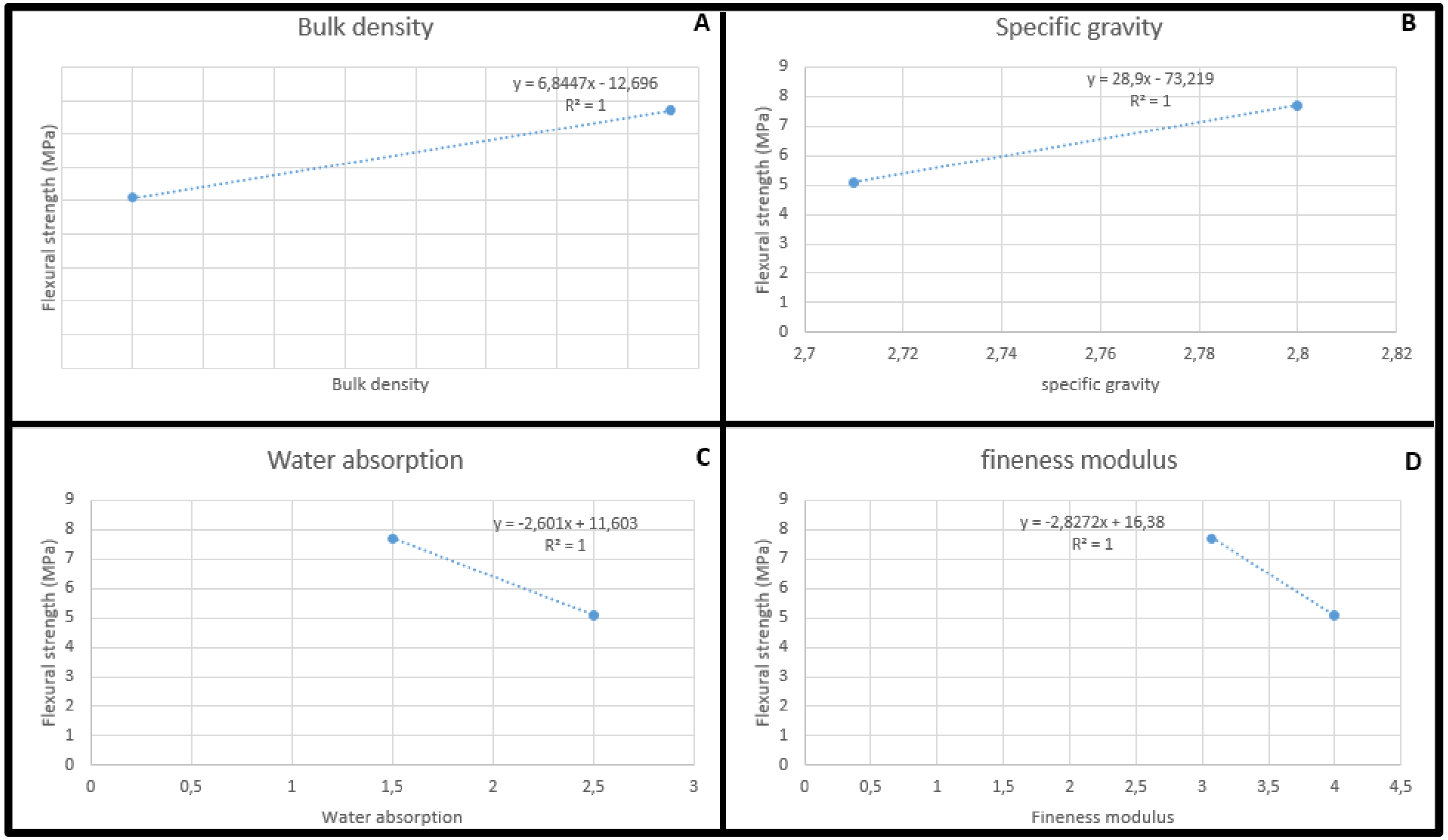

Figure F.1: (A) Linear regression model of the relationship between flexural strength and bulk density; (B) Specific gravity; (C) Water absorption; (D) Fineness module