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Hintsa, Afikile Goodman

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PERFORMANCE-BASED DESIGN CONSIDERATIONS FOR ABRASION-RESISTANT CONCRETE FOR STRUCTURES IN MINERAL PROCESSING PLANTS

Prepared by: Afikile Goodman Hintsa
Student Number: 1716238

A research report submitted to the Faculty of Engineering and the Built Environment, University of the Witwatersrand, Johannesburg, in partial fulfillment of the requirements for the degree of Master of Science in Engineering.

Johannesburg, 2025

DECLARATION

I, Afikile Goodman Hintsa (Student Number:1716238), declare that this research report is my unaided work. It is being submitted to the Degree of Masters in Engineering at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination to any other University.

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A.Hintsa

Date: 12 June 2025

Afikile Goodman Hintsa

ABSTRACT

Impact and abrasion-wear on reinforced concrete (RC) silos used for ore material storage in mineral processing has over the years resulted in costly deterioration, mining operation downtime, and structural failure in some severe cases. Despite the current advancements in the study of abrasion resistance, and the limited knowledge of tribosimulative abrasion resistance testing, further advancements are needed to allow for the development of performance-based design considerations for concrete structures in abrasive exposure environments.

In this research, a structural assessment is conducted on a platinum processing plant RC silo using the Anglo-American guideline to qualify and evaluate the aggressiveness of the exposure environment, and its influence on the silo's internal wall concrete deterioration. The information obtained from the assessment report, with respect to the design specifications and concrete performance, is then used to advise the research methodology followed in the experimental work. In addition to the results from the laboratory analysis, the information is then contrasted against the findings in literature and used to propose abrasion resistance performance-based criteria for silos in mineral processing.

The SANS 1058 abrasion test was identified as the most tribosimulative test for assessing the impact and abrasion wear of silo concrete during loading and unloading operations in mineral processing. This test was then employed to explore the abrasion resistance properties of various concrete mix designs. A total of 324 cubes, with 18 distinct mixes were cast and cured for 3, 7, 28 and 7,14 and 28-days for the concrete compressive strength and abrasion resistance tests respectively.

The 18 distinct mixes consisted of a permutation of dolerite, granite, and andesite aggregates with the following aggregate sizes; 13,2 and 19 mm, binder types; 100% PC, 85/15 PC/FA, 92.5/7.5 PC/CSF, and a w/c ratio of 0.4. These mixes were compared against each other to establish the influence of the variation in aggregate type, size, and binder types on the compressive strength and abrasion resistance of concrete. Additionally, an analysis of the workability and setting times of the above-mentioned mixes was conducted to evaluate the salient constructability requirements for the construction of bulk storage silos using the slip-form method, as outlined by the American Concrete Institute (ACI).

The results show a considerable influence of concrete compressive strength on the development of abrasion resistance, where the increase in compressive strength resulted in an increase in abrasion resistance. However, minimal improvement in the abrasion resistance was observed when the concrete strength was increased further than 70 MPa, where the average abrasion mass loss observed was less than 1 g for all the mixes, except for the mixes with the granite aggregates, which will be discussed below.

At 28 days, the aggregates were observed to have a more pronounced influence on the abrasion resistance performance when compared to the influence of binder type. It was found that the aggregates with lower LA (Los Angeles) Abrasion %, ACV %, and higher aggregate densities resulted in higher abrasion resistance. Dolerite and andesite aggregates had the lowest LA abrasion, ACV%, and higher densities when compared to the granite aggregate mixes. These andesite and dolerite mixes (both 13,2 and 19 mm) were observed to exert a substantial influence on the reduction of abrasion mass loss at a constant w/c ratio, with a 96 and 111 % difference in abrasion mass loss observed between the andesite and granite, and the dolerite and granite mixes respectively. Furthermore, the mixes with the granite aggregates were observed to show the greatest abrasion mass loss observed throughout the 28-day test period, due to the significantly high LA abrasion%, ACV%, and lower aggregate densities when compared to the other aggregate types mentioned above.

Lastly, the findings from this study advocate for the application of material storage and flow principles along with advanced concrete technology to mitigate the deterioration of concrete silos due to impact and abrasion wear. Additionally, the results obtained from the study were then used to propose performance-based design acceptance criteria and considerations for impact and abrasion-resistant concrete with respect to the relevant exposure conditions. These are based on allowable mass loss values at 28 days, the constituents of concrete, and the effects of the exposure environment on the above-mentioned performance criteria.

ACKNOWLEDGEMENTS

I would like to express my heartfelt gratitude to my supervisor, Prof. Mike Otieno, for the invaluable guidance, technical support, and encouragement provided during my research period at the University of the Witwatersrand, Johannesburg.

I extend my gratitude to Concrete Proficiency for their assistance with my lab work. I would like to give special thanks to the concrete laboratory and workshop personnel who provided their invaluable assistance during the experimental work.

Furthermore, I would like to thank AfriSam South Africa for their support in sourcing relevant literature and supplying materials.

Finally, I would like to express my gratitude to my family for their unwavering support, encouragement, and prayers throughout my research period.

I dedicate this research report to my late sister

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Nomenclature

Cases

ACV: Aggregate Crushing Value ..... passim
ADT: Articulated Dump Trucks 3
AFm: Monosulfate 40
AFt: Ettringite 40
C_2S: Dicalcium Silicate 40
C_3A: Tricalcium Aluminate 40
C_3S: Tricalcium Silicate 40
C_4AF: Tetracalcium Alumino-ferrite 40
CBD: Compacted Bulk Density ..... passim
CEM I: Portland Cement 49, 61
CSA: Canadian Standards Association 51
CSF: Condensed Silica Fume 61, 63, 70
FA: Fly Ash ..... passim
$f_{cu:}$ *Concrete Compressive Strength* ..... passim
FM: Fineness Modulus 82, 97
ITZ: Interfacial Transition Zone 63
kN: Kilo Newton ..... passim
LA: Los Angeles ..... passim
$m_{L:}$ Mass Loss (g) 87, 88
NBRICSIR: National Building Research Institute of the Council for Scientific and Industrial Research 50
OEMs: Original Equipment Manufacturers 3, 5
PC: Portland Cement ..... passim
RC: Reinforced Concrete ..... ii, 1
RD: Relative Density 90
RoM: Run of Mine 2, 3, 10
SCM: Supplementary Cementitious Materials 7
SF: Silica Fume ..... passim
t: Time 15, 23, 87
ZAR: Zuid-Afrikaanse Rand 8

CHAPTER 1

1. INTRODUCTION

Reinforced concrete (RC) silo and bin storage structures play a crucial role in the minerals processing system by ensuring a consistent flow of ore material from the mine to the crushing plant, and subsequently to the mineral processing facility. They serve as essential components for material handling, enabling the efficient storage and controlled discharge of bulk materials to maintain optimal throughput and processing efficiency (Nateghi and Yakhcgalian, 2011).

Over the past fifty years, many advancements in material technology and structural mechanics have contributed to an enhanced understanding of the behaviour and response of the construction materials used to build these ore storage structures (Ferreira, 2021). However, the combined effects of impact and abrasion wear, along with their synergistic interactions, have resulted in the deterioration of the structures mentioned above, leading to costly disruptions in production and high rehabilitation-related expenses (Maraveas, 2020). It is therefore essential to ensure that these material handling and storage structures are designed, constructed, operated, and adequately maintained to ensure their efficiency and reliability in performing their economic functions within strategic operational safety margins (Carson, 2012).

Mining and mineral processing structures require the integration of impact and abrasion wear-resistant components due to the severity of the energies and masses of interacting bodies (Teeri, et al., 2006). Wear is a phenomenon caused by moving surfaces and their interaction, which causes material loss on the surface (Stachowiak, 2006) and is a function of the particles' erosion parameters (abrasive energy, impact angle, hardness and size) (Kulu, et al., 2008).

These combined wear mechanisms mentioned above subject the silo internal wall concrete to continuous deterioration resulting in cross-sectional material loss. This deterioration exposes the steel reinforcement and ultimately results in the reduction in the structural integrity (Ferreira, 2021). The application of advanced concrete technology, selection of suitable construction materials, and construction methodology can ensure that structures meet their intended design life by increasing their durability within their respective design environments (Carson, 2012).

This research aims to investigate the effects of dry bulk ore materials flow on silo concrete deterioration due to impact and abrasion-wear, and to utilise a tribosimulative test to provide a comprehensive understanding of the influence of the constituents of concrete on improving abrasion wear-resistance. This approach intends to deliver a comprehensive understanding of performance-based design considerations for abrasion-resistant concrete, tailored for silos used for material storage within the mineral processing industry.

1.1 Background: Materials Flow and Materials Handling

The challenges related to these structures are multidisciplinary and involve other fields of engineering, i.e., mechanical engineering (materials handling), chemical and process engineering (process of storage) and civil engineering (structural design) (Ferreira, 2021). Thus, a comprehensive review of the materials handling process is required to fully understand the structures' environmental exposure and upstream processes that influence the impact and abrasion-wear exposure of the storage structures reviewed in this research.

1.1.1 Materials flow in comminution, liberation and particle size reduction

The flow of material in mining and mineral processing generally starts with mining of the ore-bearing rock, which is done using one of two methods: surface or underground mining (Kapadia, 2018). The mining method depends on the deposit, geology, resource availability and environmental impact (Hayes, 2022). The selected method then dictates the type of materials handling and processing operations, which can be either wet or dry process operations. These processes have unique required material flow, storage, comminutions, and beneficiation operations (Bitarafan and Ataei, 2004). These process operations must be considered when designing concrete structures, as they expose structures to different environmental loads and thus different deterioration mechanisms affecting the structure's durability.

As shown in Figure 1.1, ore material is transported from the mine and unloaded (Figure 1.1(a)) into a the Run of Mine (RoM) feed conveyor, which then feeds into RC silos or bins (Figure 1.1(b)). This material feed conveyor is often referred to as RoM feed (Yamashita, et al., 2021). The RoM then feeds into a size reduction process, namely the crushing and comminutions process. This feed varies depending on the ore characteristics and blast pattern in the mining contractors' budget (Hayes, 2022).

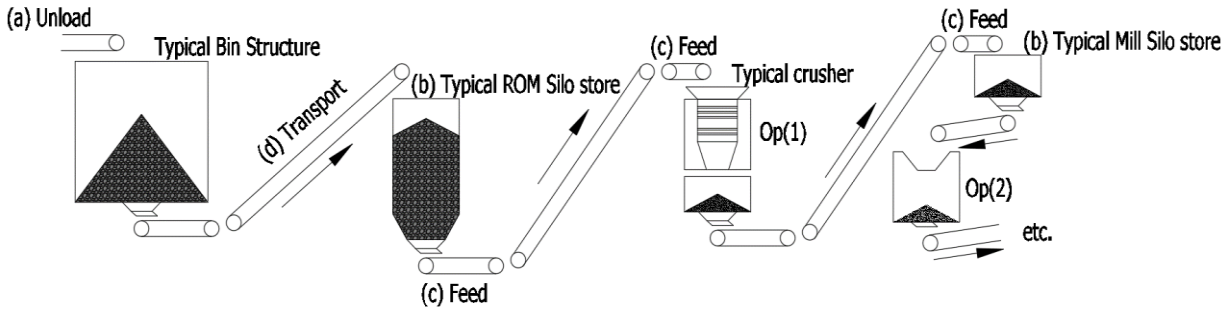


Figure 1.1: Diagram showing a process flow for dry materials handling: (a) Unloading and unloading, (b) Storage, (c) Feed, (d) Transport (Metso, 2011).

The size reduction process consists of a system of crushing equipment that reduces the material size to facilitate ore transportation, liberation of the valuable minerals from the rock matrix, and increased surface area for high reactivity (Fuerstenau and Han, 2003). After the ore size reduction, the crushed material is again stored in bins and silos to

ensure a constant feed of material for further processing and beneficiation (Haldar, 2018).

Mineral beneficiation refers to the process of extracting the maximum value from a given raw material (Kapadia, 2018). This beneficiation process falls outside the scope of this research, as this involves machinery and structures supplied by different Original Equipment Manufacturers (OEMs), which provide their own liner protection systems for their equipment. The material storage structures marked (b) in Figure 1.1 are the main areas of interest in this research, as they are usually made of RC structures and experience high deterioration over the design life of processing plants.

The 'Op' indicated in Figure 1.1 depicts different operations required in the process, such as size reduction, size control, enrichment and upgrading of the rock or mineral. '$Op_{(1)}$' indicates primary crushing, which involves the reduction of the ore particle with a typical top size of ±1 500 mm to around 400 mm. The operation referred to as '$Op_{(2)}$' indicates secondary and tertiary crushing, which involves a further reduction of the feed size from ±400 mm to around 20 mm, depending on the mineral processing requirements (Haldar, 2018). Storage structures (Figure 1.1(b)) are then constructed between the different operations to ensure a continuous material flow between the various operations. Both these material storage structures are subjected to impact and abrasion-wear, with the ore size identified as the primary differentiating variable (Teeri, et al., 2006). The processes and operations referred to above are detailed below.

a. Loading and unloading

The loading and unloading process is where the RoM material is fed through to the crushing plant using Articulated Dump Trucks (ADTs), conveyor belts or a combination of the two. The material is dumped from the transport facility into a bin structure usually equipped with a primary crusher to reduce the particle size as shown in Figure 1.2 on page 4. The dumped material impacts the RC bin surface below, causing impact wear on the bin structure. Free-falling material over an extended period will cause the liner material to fail, thus significantly affecting the durability of the structure (Hayes, 2022).

b. Storage buffers

Figure 1.3 on page 4 shows a typical silo used as a storage buffer, which is introduced before and after each operation to achieve maximum efficiency and reliability of the processing system (Phillis and Gumede, 2011). These buffers reduce feed material variability due to the availability of physical resources such as material, human resources, and equipment throughout the mineral processing operations (Bitarafan and Ataei, 2004).

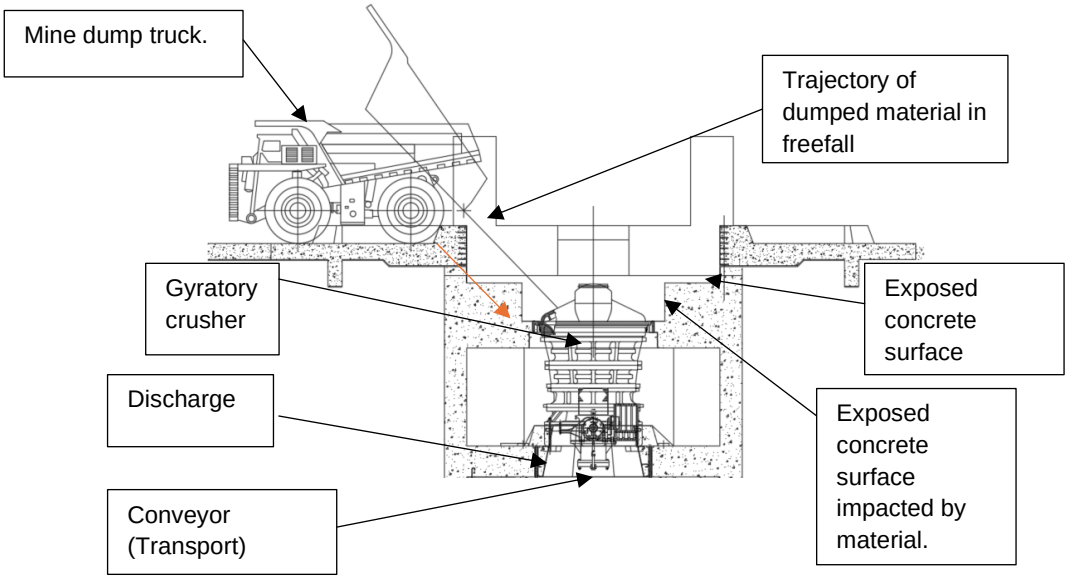


Figure 1.2: Typical bin elevation drawing showing RoM tip bin structure (Hayes, 2022).

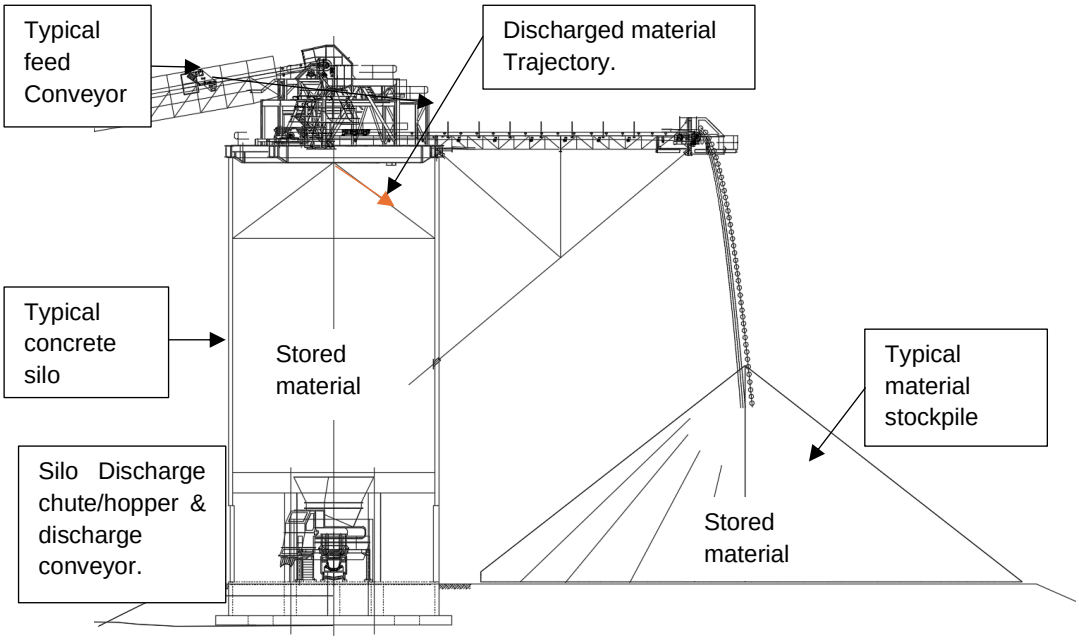


Figure 1.3: Diagram depicting typical ore material stores in minerals processing plants (Hayes, 2022).

The cyclical nature of mining production (depending on the blasting and hauling), shiftwork, and mineral value variations can significantly impact production in mineral processing without storage buffers in the system (Phillis and Gumede, 2011). Thus, buffer store systems are a simple and practical way to ensure maximum reliability, and regulate the distribution flow of material at the face, where it most matters. Storage buffers are usually in the form of material stockpiles and silos as shown in Figure 1.3 (Ferreira, 2021). This research focuses on the concrete design and construction considerations for silos; thus, stockpiles will not be considered.

c. Feeding

Feeders regulate the flow of material and ensure a uniform flow from one operation to another (Yamashita, et al., 2021). Feeders are used to distribute material to conveyors, which are then used to transport material from one process to another. These structures fall outside the scope of this research.

d. Transportation

Ore transportation comprises of ADTs, conveyors, lifts or trains that transport material from one operation to another. These transport structures also fall outside the scope of this research, as these include equipment and structures supplied by OEMs. Even though these structures are subjected to similar wear as the concrete structures used for storage and loading/unloading, OEMs supply protective liners for their equipment. It is, however, important to mention these processes to give a holistic understanding of the entire dry materials process flow.

1.2 Comparison of Abrasion in Conventional RC Applications and RC Silos in Mineral Processing Applications

Over the years, extensive research has been conducted on the abrasion of concrete, particularly in commercial and industrial applications, where surfaces are exposed to mild to moderate abrasion caused by rubber tyres, hard plastic, steel wheel traffic, and high tyre traffic loads. This type of abrasion is commonly observed in light to medium industrial floors and pavements (Warudkar and Elavenil, 2020). In severe cases, the concrete surfaces are exposed to impacts from steel or the dragging of metallic objects due to intensive use, which can lead to unintentional abrasion-wear. This however rarely occurs as the pavements are not designed to withstand such abrasive loads (Warudkar and Elavenil, 2020).

Even though RC silos in mineral processing are designed and constructed to contain ore material in direct abrasive contact with the internal concrete wall for the entire service life of the structure, there is a notable lack of comprehensive literature on the abrasive properties of bulk ore solids on RC concrete (Maraveas, 2020). Thus, the development of comprehensive abrasion resistance specification would prove challenging as the aggressiveness of the exposure environment is sparsely understood.

Furthermore, though abrasion test methods and procedures have been established for the above-mentioned commercial and industrial applications, they are seldomly applied to silos and bins in mining and mineral processing applications (Heerden, et al., 2005). The literature examined in this study further corroborates the previous statement, revealing a lack of substantial information on the use of South African National Standards (SANS) or the American Society for Testing and Materials International (ASTM) abrasion tests, when specifically used to evaluate abrasion resistance of RC structures used in mineral processing. The application and limitations of the various abrasion test methods used for other concrete applications will be discussed in Section 2.10 on page 50.

1.3 Research Significance

Engineering is a continuously developing practice. New construction materials and methodologies are constantly being explored and applied in the industry. With the current shift from a prescriptive to a performance-based approach to concrete design. Advanced design methodologies and concrete practices must be developed and adopted to ensure that concrete structures are durable and fit for purpose over the prescribed design life.

Based on historical evidence and knowledge of the minerals processing industry, crushing ore plants experience friction and impact abrasion-related problems on their concrete ore pass, feed, and storage systems (Heerden, et al., 2005). This concrete deterioration is sometimes adequately counteracted by using mesh reinforcement and a 50 to 100 mm thick concrete cover to line the face experiencing abrasion (Carson, 2012). Normal-strength concrete (i.e. concrete with compressive strengths below approximately 60MPa (Beushausen, et al., 2021a, p. 406)) is commonly used for this application. This alone is oftentimes inadequate as relining is required later during the structure's design life, thus increasing rehabilitation-related costs.

Retrofit protective liners and sacrificial plate applications have been adopted in the past for other applications but are seldomly used in silos. The specification of these liners depends on the determination of the material properties and characteristics of the stored bulk solid during the design phase (Maraveas, 2020). However, it is important to note that these characteristics and properties could vary over the life of mine, as the inherent variation in the ores' geological properties and characteristics will affect the liners performance (Asbjornsson, et al., 2022). At any given instant, particles with different characteristics are fed to the process, subjecting it to the variability of toughness, hardness and abrasiveness (Faramarzi, et al., 2018). As mentioned above, this research focuses on silos without liners at the ore-concrete interface. Thus, the application of liners will be referenced but will not form part of this study.

1.3.1 Safety

Safe structures translate to the overall safety of a processing plant. Structural failures have the potential to cause injuries and often fatalities, with the risk of a structural failure being associated with the condition of a structure (Carson, 2012). Visual inspection of some structures is often challenging, and a complete structural inspection is impossible. Silos are an exemplary case, as these structures are closed on all sides and sometimes on the top. The reduction in concrete volume on the inner wall of bins and silos due to abrasion might not be closely monitored, which could lead to a total collapse of the structure if the cross-sectional area of the concrete reduces to less than the concrete area required to resist the load (Bilcik, et al., 2021). In some cases, the silo liner falls off the silo wall penetrating through the discharge chutes, which could be fatal to mine personnel working in the area (Dutta, 2013). These safety concerns indicate a need to research ways to reduce the aggressivity of the environment the concrete is exposed to or find solutions to make the concrete better withstand the exposure environment.

Providing additional design considerations to ensure structures remain fit for purpose throughout their design life can mitigate the risk of structural failures and/or collapse, which could cause potential risks during operation.

1.3.2 Sustainability

Sustainability refers to the art of balancing limited resources to meet today's needs without compromising the available resources in the future (Taylor, 2013). This is achieved by taking the economic, environmental, and social aspects into account when carrying out engineering activities (Taylor, 2013). This analysis should consider the entire life cycle of a project, i.e., the life of mine in this case. Sustainability can be achieved by progressively adopting design and construction approaches that produce durable structures while limiting the use of non-renewable resources, energy, and materials without compromising quality (Collis, 2021).

Portland Cement (PC) has a very high energy requirement and carbon footprint. Reducing the amount of PC in a concrete mix design and using non-PC-based Supplementary Cementitious Materials (SCMs) can reduce the amount of clinker required in the cement, thus improving the overall mix design (Beushausen and Dehn, 2021). This reduction in cement content is one of the aspects this research seeks to explore when considering the use of SCMs. The use of SCMs has also been identified to improve the microstructure of the paste, thus improving compressive strength. This improvement in compressive strength has also been found to have a direct correlation to abrasion resistance (Poyo, 2018). Adopting the use of SCMs in the design of abrasion-resistant concrete not only enhances the concrete's durability but also provides additional sustainability benefits. This aspect of improved abrasion-wear resistance due to the use of SCMs is discussed in more detail in Section 2.4 on page 21.

1.3.3 Design codes.

A comprehensive review of the globally accepted design codes for silo design, namely the British Standard BS EN 1991-4:2006, Australian Standard AS 3774-1996, American Society of Agricultural Engineers ANSI/ASAE EP433 DEC1988 (R2011) and the American Concrete Institute ACI 313-97 shows that insignificant considerations are made on the influence of impact and abrasion wear on the internal silo concrete due to the stored bulk ores, as emphasis for design is placed majorly on structural loading (Maraveas, 2020). This gap in standards, therefore, poses a significant risk in the design and construction of these structures for the mineral processing industry.

Thus, addressing these issues requires extensive interdisciplinary research and collaboration among industry experts. Further development of mineral processing industry specific design standards is required to provide more simulative testing for concrete experiencing more severe impact and abrasion when compared to commercial applications.

1.3.4 Cost

Bulk material handling problems in minerals processing plants are the major cause of costly downtime for many plants, especially during start-up (Hayes, 2022). These bulk materials handling problems can be eliminated during the design stage with better analysis and research. The costs associated with rehabilitating these structures are usually much more significant when compared to the initial construction costs. This observation was also corroborated by a comparative study conducted on the initial costs of lining an ore pass when compared with the costs of relining after twelve years, shown in Table 1.1.

Table 1.1: Initial cost of constructing an ore pass compared to the relining of a failed ore pass after 12 years (Heerden, et al., 2005).

Initial cost of installing an ore pass lining in an ore pass with a diameter of 2,70m and length of 100m			**Cost to reline a failed ore pass after 12 years in operation (based on current costs)**	
Item	Cost (Rand)		Item	Cost (Rand)
Raise boring	R2 500 000		Relining and supporting	R3 000 000
Installation of support lining	R1 800 000		16,0 mm shepard's crook	R6 652
16,0 mm sheperd's crooks	R6 652		Cement Capsule	R4 384
Cement capsules	R4 384		Grout cable anchors	R11 500
Grout cable anchors	R11 500		Welded mesh	R6 786
Welded mesh	R6 786		OPC based lining 300 mm thickness	R318 000
CAC lining 300 mm thickness	R954 000			
OPC based lining 300 mm thickness	R318 000			
Total	**R5 601 322**		**Total**	**R3 347 322**
			Original + Rehabilitation cost (Excl CAC lining 300 mm)	**R7 994 644**

The data presented in Table 1.1 demonstrate that the overall expenditure incurred for relining an ore pass in the year 2000 amounted to ZAR 3,347,322. This indisputably signals a 72% escalation in costs over the course of twelve years of operation. It is important to note that this escalation could have been avoided if the structure had been designed with abrasion-wear resistance performance considerations for its intended application.

1.4 Aim and Objectives

1.4.1 Research aim.

This research aims to investigate RC silo internal wall deterioration due to the impact and abrasive-wear properties of the stored dry bulk ore materials in mineral processing and to utilise a tribosimulative test to provide a comprehensive understanding of the influence of the constituents of concrete on improving its impact and abrasion wear-resistance.

1.4.2 Research objectives.

i. Study minerals crushing and comminutions plant circuit flows to investigate the impact different stored ore material characteristics have on the concrete counterface.

ii. Investigate the tribology of impact and abrasion in minerals processing structures to establish methods to reduce the aggressiveness of the concrete's exposure environment.

iii. Perform structural forensic engineering investigations into the causes of concrete deterioration in silos and bins used in mineral processing.

iv. Provide a comprehensive review of the influence concrete constituents have on the abrasion-wear resistance of concrete.

v. Recommend suitable performance-based considerations for abrasion-resistant concrete applications that meet silo slip-form construction requirements.

1.4.3 Research questions.

- How do the stored ore material abrasive properties influence the severity of the exposure environment?
- How do the principles of material flow in silos and bins influence the severity of the exposure environment?
- How do the concrete constituents influence the impact and abrasion-wear resistant properties of concrete?
- How do the mixes proposed in this study compare to an industry-standard mix design used for the construction of a RoM and mill silo for platinum processing.
- What are the best-suited performance-based design considerations for concrete used in mineral processing silo construction?

1.5 Scope and Limitations.

This research primarily focuses on RC silos and bins used in the processing of dry bulk ore materials, with a specific emphasis on facilities involved in the processing of Platinum Group Metals (PGM). This focus is motivated by the abrasive characteristics of PGM ores due to their hardness (Junge, et al., 2023), which present unique challenges in handling and storage. Furthermore, the silo inspection that forms a critical component of this study was conducted at a platinum processing plant. Silos constructed with other materials, and used in different fields, such as agriculture manufacturing and cement production, are briefly referenced but fall outside the scope of this study.

The focus of this study is centered on silo concrete mix design and salient construction considerations. Minimal attention is placed on other factors such as the structural design and analysis, construction deficiencies, noncompliance with operational regulations, lack of maintenance and other environmental conditions affecting the durability of the RC structure. However, these factors are in no way less significant to the performance of the structure. Thus, they are briefly referenced but do not form part of the main aim of this study.

Lastly, sacrificial liner applications on silos are not considered in this study. However, literature on this application has been sparsely referenced.

1.5.1 Scope limits to silo Inspection

The effect of flow types, material types and size were investigated, and similarities and differences were drawn from RoM and Mill silos. The influence of feed and discharge geometries were also examined and contrasted against information provided in literature. The following limits are based on safety, and the limits defined by the silo concrete visibility, i.e.:

i. The wall concrete and below the base.
ii. Silo base concrete.
iii. Silo walls covered by material or rendered unsafe to explore.

1.6 Research Report Outline

The research report is divided into six chapters as follows:

Chapter 1 gives a general introduction and background of the study.

Chapter 2 is a literature review. It provides an overview of concrete durability, and an in-depth analysis of the influence of silo exposure environments on the deterioration of the internal concrete walls of silos. It also looks at the influence of concrete constituents and construction practices on improving the impact and abrasion resistance of concrete. Lastly, the suitability of various concrete abrasion resistance tests and acceptance criteria is outlined in the study.

Chapter 3 gives details of the methodology adopted in the study, including the experimental work carried out in the laboratory.

Chapter 4 outlines and discusses the results obtained in the study.

Chapter 5 discusses the performance-based design considerations obtained from the results and discussion.

Chapter 6 presents conclusions based on the findings of this study and provides recommendations for future research.

CHAPTER 2

2 LITERATURE REVIEW

The term “silo” in this research is used to refer to deep and shallow bins, which are also commonly known as bunkers. Silos are unusual structures, and sometimes present unique design challenges that engineers may be unfamiliar with, including the computation of design loads and detailing requirements (ACI 313R-97, 1997). This unfamiliarity results in the frequency of structural failures in bins and silos being much higher than most industrial equipment used in bulk materials storage and handling (Carson, 2012).

This literature review primarily focuses on silos constructed using reinforced concrete with their surfaces in contact with the bulk stored material. It is important to note that these silos are often designed without additional lining material (excluding shotcrete liners) on the internal face and have the stored material body in direct contact with the concrete surface. Ores are the primary stored bulk material referred to above, but references are drawn from other stored bulk solids as mentioned above.

2.1 Causes of Failures in Circular Concrete Silo Walls Under Environmental Influences

The four major contributing factors to silos failures are the design, construction, usage, and lack of maintenance of these structures (Dutta, 2013). Each of the four factors can contribute individually or as a synergy. One of the leading causes of durability related failures observed in RC silos is caused by the wear of the concrete cover to the steel reinforcement, due to bulk solid impact and abrasion-wear from the stored material (Maraveas, 2020), which will be discussed in detail in Section 2.5.

The design of silos necessitates a comprehensive understanding of the material’s flow properties (Jenkins, 1964), geometric flow channel aspects, flow, and both static and dynamic stress development within the silo structure (Taher, 2023). Applying materials handling knowledge, as mentioned above, during analysis and design of silos will prevent undesired flow interruptions such as ratholing and arching while ensuring a reliable discharge at the required rate (Dutta, 2013). Furthermore, the characterization of the aggressiveness of the exposure environment based on the abrasive properties of the ore particles should also be considered during the design phase. This will be looked at in more detail in Section 2.4 on page 21.

In the context of the structural design of RC silos, the knowledge of materials flow is not translated and is often not applied to the design and construction of these structures (Taher, 2023). This creates a gap between the materials flow and the structural concrete design philosophy, with a potential impact on the durability of the structure. Most engineers refer to design codes for information on designs with the expectation of full, detailed guidance on the design procedure. The oversimplification of the design parameters and procedures offered in the design codes mentioned in

1.3.3 may potentially result in an underestimation of their significance. Therefore, it is important to re-establish the importance of these parameters and their influence on the intended silo durability performance.

Properly designed and constructed concrete should withstand the design environment without serviceability issues over the design life, given that these structures are appropriately used and maintained (Concrete Institute, 2013). This does not always occur, as problems can arise due to changes in flow properties and stored materials' properties during operation (Maraveas, 2020). Changes in the feed and discharge into and out of a silo can affect the material flow properties and flow patterns, resulting in excessive wear on the concrete face, thus radically affecting the structure's durability (Carson, 2012). This would therefore unambiguously contribute to silo concrete durability concerns, as the flow type changes result in the development of shear and normal pressures on the internal face over time (Dutta, 2013). As mentioned above, the change in flow parameters and properties are often not accounted for in the design and detailing of the concrete, as different flow parameters and material properties could've been assumed during the design.

Poor construction methodology and practices have been observed to pose the most significant risk of silo failure compared to other construction projects in the 20th century (Maraveas, 2020). Silo failures due to construction can manifest in two ways, poor workmanship, and the use of incorrect construction material, which ultimately results in poor concrete quality (Dutta, 2013). The use of incorrect construction processes includes adopting an unsuitable or inadequate mix design, concrete mixing, steel reinforcement (Carson, 2012), transportation, placing, compaction and curing (ACI 313R-97, 1997). Failures can be caused by unauthorised and poorly decided design changes during construction, either to expedite the work or reduce costs (Carson, 2012).

2.2 Introduction to Concrete Durability

In structural concrete, the ASTM E632 (1988) refers to durability as "the ability of a structure or component to withstand the design environment over the design life, without undue loss of serviceability or need of major repair.". Furthermore, concrete durability is a function of its intrinsic and extrinsic properties, but most importantly, its performance (Beushausen, et al., 2021a). For concrete to be considered durable, it must withstand its design environment with minimal rehabilitation required, while also considering the 'triple line benefits'. These triple-line benefits are; economic, social, and environmental considerations for sustainable practice (Beushausen, et al., 2021a). Durable concrete structures reduce life cycle costs linked to their maintenance and rehabilitation, which is an essential consideration for sustainability (Khan, 2018).

To predict the durability of concrete structures, the relationship $S \leq R$ can be used (Maraveas, 2020). In this case, *R* represents the ability of the concrete to resist the aggressive environment, while *S* denotes the loading, specifically the deterioration

mechanism influenced by the exposure environment. In the case of impact and abrasion-wear on silos, *S* considers nonmaterial factors such as the severity of the abrasive properties of the stored bulk solids and the type of flow. In contrast, *R* considers material-related factors such as the abrasion-resistant properties of concrete, which are discussed in the following subsections.

If the condition $S \leq R$ is maintained, there is a marginal risk on structural durability. However, suppose the loading *(S)* is much greater than the resistance *(R)*; then there is an increased probability that the structure may not be able to meet its expected design life without undue loss of serviceability and the need for significant repair (Maraveas, 2020). Which, in more extreme cases, may result in failure. This means that the two parameters, *S* and *R*, must be evaluated and modified where reasonably applicable to ensure that the structure can resist deterioration and meet its intended service life. The influence of the two parameters on concrete durability is scrutinised in the following subsections.

2.2.1 Modern performance-based approach to durability design and specification philosophy

There is a growing trend of modern concrete design and specification moving away from a prescriptive approach to a performance-based approach (Beushausen, et al., 2021a). The modern durability design approach considers not only the material content of the concrete but also the following aspects (Concrete Institute, 2013):

i. A proper understanding of the environmental conditions the structure is exposed to.

ii. Structural interactions, including serviceability and service stresses. Understanding the deterioration mechanisms.

iii. Quality of construction and assessing the as-built structure to give assurance that it has been built to specification.

iv. Required level of durability and to design for optimal durability throughout the expected life of the structure. This involves developing practical service models that can accurately predict the likely durability performance.

The aspects mentioned above also form part of the performance-based durability design, specification, and construction approach. As discussed above, current silo design codes oversimplify the effect environmental conditions, structural interaction, and service stresses have on the silos. This reinforces the need for a rigorous deductive durability design process to help maintain conservatism and safe margins of error.

2.2.2 Durability design considerations for concrete in bulk solid storage structures.

The concrete material content and the environment in which the concrete is placed form an interactive system that determines how durable the structure will be. This, therefore, means that we need to evaluate both the aggressiveness of the exposure environment and the concrete system when assessing durability (AfriSam, 2021). The concrete system is differentiated into intrinsic and extrinsic factors. The intrinsic factors listed below are independent of other external factors influencing the concrete's durability performance. However, extrinsic factors depend on factors other than the concrete's constituents, such as the production, construction processes and methodology (Khan, 2018).

The key intrinsic factors most likely to affect concrete durability are the binder type and the w/c ratio (Ballim, et al., 2009). For extrinsic factors, the curing and early age temperature history have the most influence (Ballim, et al., 2009). When considering the aggressiveness of the exposure environment, the most critical factor is the aggressiveness of the agents attacking the concrete, with the effects of cracking accelerating the ingress of harmful substances into the concrete (Rankine, 2021). These can be classified as physical or chemical attacking agents. A diagrammatic representation of the concrete and environmental factors influencing durability is shown in Figure 2.1 below.

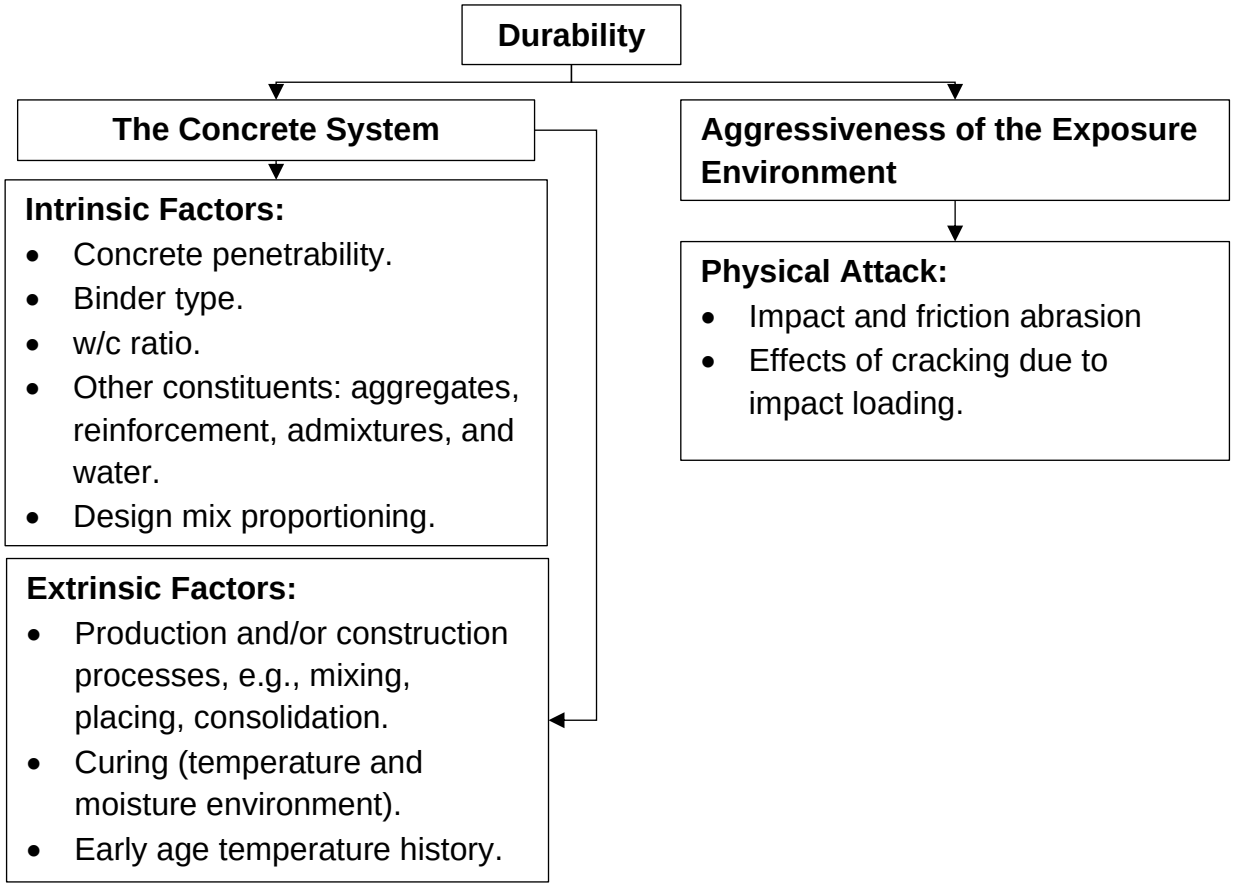


Figure 2.1: An adaptation of the concrete intrinsic, extrinsic, and environmental factors influencing the durability by (Beushausen, et al., 2021a).

As shown above, the concrete system's durability performance is dependent on both intrinsic and extrinsic factors. Admixtures such as retarders, for example, are commonly used during the construction of silo walls to control the initial set of concrete and, therefore, the rate at which slipforms may be raised (ACI 313R-97, 1997). This therefore shows how the intrinsic (admixture) and the extrinsic factors (slipform) can affect the concrete system. These admixtures are adjusted to suit the ambient site conditions and to maintain a constant rate of rise for the slipforms (Collis, 2021). Slipforms are largely fabricated, and mechanically handled sections of temporary moulds used to support concrete while it gains strength to be self-supporting, which is continuously raised as the concrete is placed (Collis, 2021). The use of slipforms for silo construction is discussed in Section 2.8.4 on page 48.

Other factors such as concrete placing and finishing, are considered extrinsic factors that could affect the concrete system. An example would result from unforeseen slipform interruptions during construction, which lead to an insufficient bond forming between the newly placed concrete and concrete from the precedent pour. This lack of bond formation results in cold joints forming, subsequently impacting the quality of the concrete (ACI 313R-97, 1997), and making it more susceptible to durability related to issues. To adequately design for durability, appropriate structural design, materials selection, deterioration modelling, and construction practices must be adhered to (Alexander, et al., 2009), which should also be related to the environment in which the concrete is placed (Khan, 2018).

2.3 The Influence of the Exposure Environment on the Concrete Durability of Silos in Mineral Processing.

Concrete properties affecting durability can be differentiated into three: transport, chemical, mechanical and physical properties (Ballim, et al., 2009). These three properties are influenced by the concrete mix design, construction, and the exposure environment in which the structure will be constructed (Khan, 2018). Some of the literature referenced in this section has been adopted from research conducted outside the mineral processing industry. Similar references are drawn as the mechanisms of deterioration due to impact and abrasion can be considered to be fairly similar. However, it is important to note that there is a significant difference in the respective exposure environments, thus a simple comparison does not always suffice.

The transport properties of concrete are a function of how easily a fluid or ion moves through the concrete microstructure (Ballim, et al., 2009). Deterioration mechanisms such as chloride ingress, chemical attack, carbonation and leaching rely on transport properties such as permeation, absorption diffusion and migration (Concrete Institute, 2013). Chemical concrete properties relate to "the thermodynamic stability of its hydrates and other phases in the presence of aggressive or transported agents, and to the nature of the interaction of these phases with other agents." (Ballim, et al., 2009:155-183). Concrete transport and chemical properties aren't key considerations in this research. However, the impact and abrasion-wear of concrete has a significant

influence on these mechanisms of deterioration. More information on these synergistic interactions can be obtained from *Fulton's Concrete Technology* (Beushausen, et al., 2021a).

The most familiar mechanical and physical properties of concrete to design engineers are the strength, stiffness, creep, shrinkage, thermal expansion coefficient and density (Ballim, et al., 2009). Unfortunately, this has resulted in the use of concrete compressive strength and stiffness as indicators of the overall durability of concrete (Concrete Institute, 2013). Although a strong correlation between concrete compressive strength and abrasion resistance has been identified by many researchers. This oversimplification should not be the norm, as there are various factors that contribute to both physical and chemical durability of concrete. The specification of appropriate concrete properties should be more explicit and rational, thus resulting in more economical and durable concrete (Khan, 2018).

2.3.1 Mechanism of deterioration of concrete in mineral processing

The occurrence and rate of deterioration is a function of the interaction between the concrete and the environment (Khan, 2018). The severity of concrete damage due to this interaction depends on the physical and chemical resistance of the concrete. Furthermore, the severity of deterioration also depends on the nature and degree of the aggressiveness of the environment (Alexander, et al., 2009). For silos used in mineral processing, it is these physical and mechanical processes that mostly contribute to the deterioration of the silo's internal concrete surface (Heerden, et al., 2005).

The concrete cover should be designed to withstand the physical wear resulting from the following tribological contact types: contact stresses at normal load, sliding, abrasion and impact as shown in Figure 2.2. "Tribology is the study of science and engineering of interacting surfaces in relative motion." (Takadoum, 2008:49).

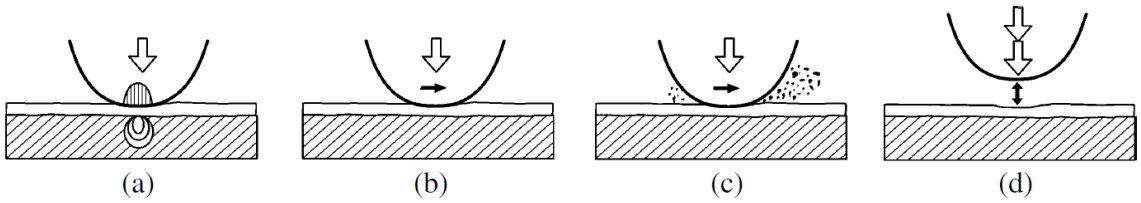


Figure 2.2: Various contact conditions in tribological applications (a) contact stresses at normal load; (b) sliding; (c) abrasion; (d) impact (Holmberg and Matthews, 2006).

From the basic tribological contact conditions shown in Figure 2.2 above, *abrasion (c)* and *impact (d)* have a dominating influence on the wear of silos when compared to the other contact types (Heerden, et al., 2005). The less influential contact types to silo concrete deterioration shown above are *contact stresses at normal load (*Figure 2.2*(a))* and *sliding (Figure 2.2(b)).* Contact stresses are a function of the force and the contact area, while sliding is generally associated with flat-on-flat surface shearing with insignificant wear occurring (Stachowiak, 2006). Thus, the focus is to be placed on

impact and abrasion, as more wear and the deterioration of the internal concrete surfaces of silos results from them.

*Abrasion (*Figure 2.2*(c))* occurs when a hard, sharp counterface ploughs in one surface, which is one of the most significant mechanical deteriorations in terms of material loss (Holmberg & Matthews, 2006). This occurs when a hard counter body moves against and ploughs through a softer material body, causing the surface to exhibit large plastic deformations such as grooves (Holmberg & Matthews, 2006). Ploughing is a phenomenon that occurs in two bodies with different hardness (Takadoum, 2008). In the specific case of abrasion in mineral processing, abrasion caused by materials with Mohs values significantly higher than that of concrete will result in greater deterioration when compared to a softer material abrading the concrete counterface (Heerden, et al., 2005).

The abrasion resistance of concrete depends on the composition of its constituents. In a study on concrete surface treatment methods, cement pastes with an untreated surface and a compressive strength of 56.2MPa at 28 days were shown to have a Mohs value of 2.5 (Yu, et al., 2022). Furthermore, the primary minerals that make up aggregates have been found to have relative hardness values ranging from 6 to 7 on the Mohs scale. Thus, it can be presumed that the hardness of concrete is predominantly dependent on the aggregates, which are also influenced by their mineralogical properties. These properties are elaborated on in Section 2.7.1 on page 36.

The mineralogical characteristics of Platinum Group Metals (PGMs) yield a hardness value ranging from 6 to 7 on the Mohs scale (Junge, et al., 2023), depending on the location and mineral group composition. This notable difference in Mohs hardness values alludes to the fact that the paste of the concrete is more susceptible to deterioration due to abrasion. The abrasion of the concrete paste leads to the exposure of the aggregates, which are then dislodged from the concrete matrix as the paste around them is abraded, leading to further material loss (Liu, et al., 2024). This also shows that for bulk ore storage silos in mineral processing, the extent of deterioration due to abrasion is significantly influenced by the stored ore material characteristics.

Abrasion on a surface is influenced by particle erosion parameters such as abrasive velocity, impact angle, and hardness, in addition to other factors like the size of the abrasive particle, shape, and density (Kulu, et al., 2008). The increase in particle size and specific gravity amplifies the impact energy, thus, increasing deterioration as the softer material exhibits difficulty in effectively absorbing the energy without fracturing (Poyo, 2018). Additional factors considered to have a significant influence on the aggressiveness of the environment are the bulk material flow types in silos (Hayes, 2022), which are discussed further in Section 2.5 on page 25.

Lastly, the ability of a material to abrade a surface depends on the relationship between the surface material hardness H_m to the abrasive hardness of the ore material H_a. If the material hardness is higher than the abrasive particle hardness, micro-cutting or scratching of the surface will occur, and the mechanics of abrasion follow a fatigue nature rather than a rapid abrasion process. However, if the ore particles' abrasive hardness is higher than the abrasive-resistance of the surface, clear removal of the surface will take place and follows a process similar to the one shown in Figure 2.4 on page 19 (Kulu, et al., 2008).

Impact wear *(Figure 2.2(d))* is an erosive type of wear that occurs when a surface is continuously exposed to momentary and acute high speed contact with other materials or surfaces, resulting in the degradation of the surface over time (Roberts, 1992). The deterioration by impact occurs when the moving solid hits a surface locally, applying the impact energy to a single point rather than a large surface (Ranade, et al., 2017). These high stresses can result in the initiation and propagation of cracks on the impacted surface. Cracking due to impact depends on the intrinsic properties of the concrete and the stress level at the tip of the crack (Rankine, 2021).

The continuous and cyclical impact of ore material on the concrete surfaces also results in fatigue failure of the concrete. Material fatigue due to impact is caused by the cyclical impact of ore bodies on the material surface (Roberts, 1992). This type of wear is caused by several impacts and rebounds taking place, resulting in plastic deformation and cutting wear. The repetition in impact loading results in the cracks growing and joining together, causing concrete pieces to dislodge from the main concrete mass (Rankine, 2021). In the impact contact condition, the concrete surface must have high toughness to absorb the impacts that result in instantaneous stress fields (Ranade, et al., 2017).

2.3.2 Influence of particle size on impact and abrasion

As shown in Figure 2.3 on page 19, the tribological contact type depends on the particle size, where some structures can be exposed to a synergy of different contact types resulting in deterioration. This, therefore, means that different feed and changes in feed gradation need to be considered when designing for impact and abrasion-wear resistance in concrete.

It is important to note that the graph in Figure 2.3 is specific to all dry mineral processing equipment such as crushers, feeders and chutes used plants. In the case of this research, Figure 2.3 is used to provide an understanding of the influence different rock and ore sizes would have on the deterioration of concrete. Furthermore, it provides an appreciation of the tribological contact types and synergic actions that result from the variation in rock particle size. As a result of the particle size differences in RoM and Mill Silos discussed in Section 1.1, RoM silos would experience more severe heavy impact and a less severe synergy of impact and sliding. Mill silos store

ore materials with smaller particle sizes and would therefore experience more sliding than impact wear.

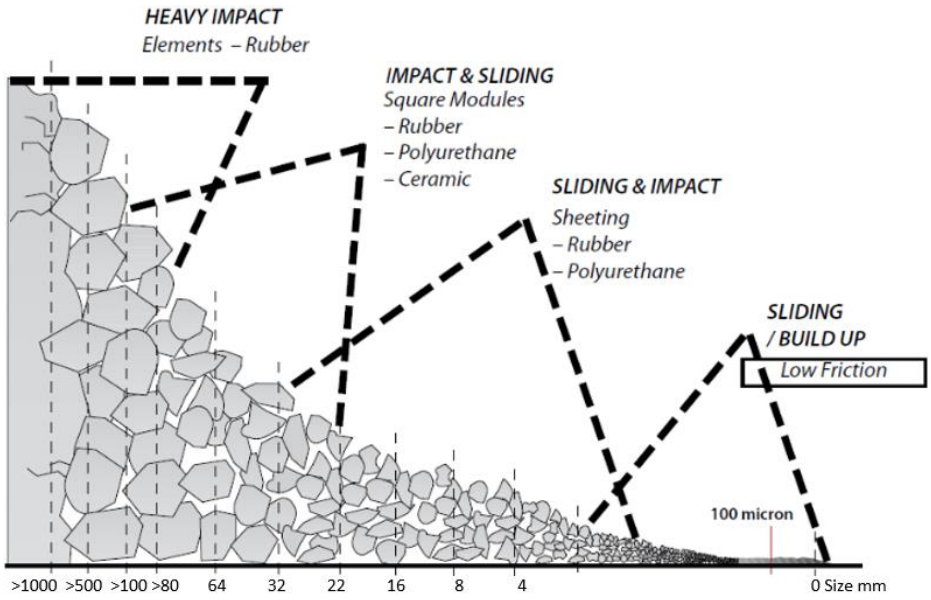


Figure 2.3: Diagram showing tribological contact types experienced by equipment liners for different material gradation (Metso, 2011).

2.3.3 The mechanics of concrete abrasion in silos in mineral processing.

Wear on concrete due to abrasion follows a chronological order shown in Figure 2.4. A concrete substrate undergoes initial exposure to pre-abrasion peeling, leading to the formation of a wedge effect within the material. Pre-abrasion peeling refers to the initial formation of microcracks from deformations around contact points, which over the loading time cause the intersection of the cracks and detachment of a fragment from the surface (Liu, et al., 2024). This phenomenon promotes the incremental exposure of the underlying substrate as a result of progressive material degradation and delamination mechanisms (Liu, et al., 2024). The extent of this impact is correlated to the material velocity and the normal pressure exerted by the stored material particles on the wall.

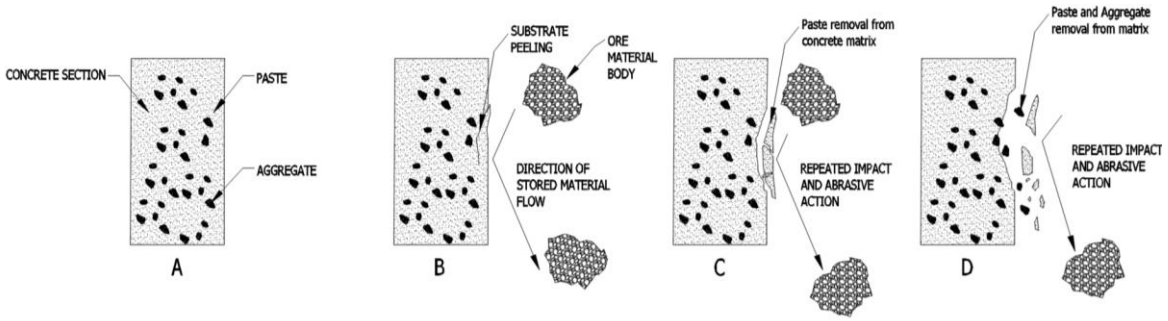


Figure 2.4: Adaptation of the sequence of abrading concrete surfaces. *A*: initial stage, *B*: concrete surface under abrasive action, *C*: loss of coarse aggregate and mortar from the concrete surface, and *D*: further loss of coarse aggregate and mortar from the concrete surface (Scott and Safiuddin, 2015).

Repeated impact cycles on the surface result in interface cracking between the concrete paste and the aggregates, as shown in Figure 2.4(b); this is influenced significantly by the size of the impacting particle, in this case, the top size of the ore. Lastly, removal of the concrete from the surface then finally occurs; the severity is a function of the particle hardness and velocity. Low energy polishes and mills the system, while the increase in energy, size, and number of impact cycles, the rate of deterioration becomes more severe (Scott and Safiuddin, 2015). With respect to the concretes' response to impact and abrasion, the severity of material loss from the surface is influenced by the aggregate-paste bond and aggregate hardness (Liu, et al., 2024). These abrasion-resistance properties of concrete will be discussed in Section 2.7.1 on page 36.

2.3.4 Reinforced concrete responses to impact load.

When concrete is subjected to impact load, the surface may respond in several ways depending on the nature and magnitude of the impact (Sangi, 2011). These are local, global, and combined responses. Global response is described as a bending or deformation of the entire member, while local response is defined as local damage where majority of the impact energy is dissipated around the impact zone (Sangi, 2011). A combined response is a result of a synergy of the two. Majority of the responses experienced in silos are local responses where the energy from stored material is low enough to dissipate around the impact zone.

For silos in mineral processing, the most common responses to impact load are predominantly cone cracking, spalling, cracks on the proximal face, and in more severe cases, perforation. (Li, et al., 2009) conducted an extensive review of the local impact responses of concrete, which is explained in more detail below:

i. Cone cracking: This refers to the formation of a cone crack on the proximal concrete face under the projectile.

ii. Spalling: This refers to the ejection of material from the proximal face of the concrete.

iii. Penetration: The development of a crater in the target zone of impact.

iv. Perforation: Complete passage of the projectile through the target.

It is essential to understand and differentiate these contact conditions and impact responses influencing deterioration mechanisms. In mineral processing, these local impact responses can result from material rolling off the angle of repose of the stored material and impacting on the silo wall, as shown in Figure 2.6 on page 27. In more severe cases, they can result from a discharge of material into the silo contacting the silo wall initially before coming to rest on the material bed below. These cases will be discussed in more detail in Section 2.5 on page 25.

2.4 Characterisation and Classification of Abrasive Particles and Surfaces in Mineral Processing

2.4.1 Characterisation of abrasive particles and surfaces

Abrasive particles are an inherent feature of the tribological systems mentioned above when discussing the mechanisms of concrete deterioration. The three most important factors controlling the abrasivity of a particle are its size, hardness, and sharpness (Kamil, 2023). Furthermore, in the context of impact wear, the kinetic energy of the particle body impacting the concrete face has a key influence on the severity of the deterioration, alongside the previously discussed factors.

Particles with higher sharpness will intuitively generate higher abrasion wear rates when compared to those with a more rounded surface. (Stachowiak, 2006:340) describes sharpness as “The shape of the particle or surface protrusions in terms of its potential to abrade or erode.”. It has also been observed that the particle size also influences particle abrasivity. Its influence is discussed regarding its correlation with the particle shape and hardness during abrasion. Generally, it is accepted that the wear rate increases with the particle size due to the energy that is transferred from the particle to the abraded surface (Podsiadlo, et al., 2005).

The above-mentioned particle properties are a major differentiating factor when comparing concrete exposed to relatively common types of abrasion like foot traffic, tyre loads and abrasive erosion due to waterborne particles on hydraulic structures (Swanson and Vetter, 1984). These inherently different material features need to be characterised to contextualise concrete abrasion in mineral processing compared to other applications, as they differ significantly from common types of abrasion on concrete mentioned above.

2.4.2 Characterisation and classification of abrasive ores in bulk material stores in mineral processing

Mineral deposits, rocks and ores all have different hardness, which depends on their chemical and geological composition and environment (Kapadia, 2018). Mohs numbers were developed in 1813 to classify different minerals according to their hardness. The qualitative test relies on one mineral being able to scratch those that precede it (Wilfred, 1949). Mohs numbers are a simple way to classify and rank minerals from the order of hardest to least hard, with the hardest mineral having a Mohs number of 10.

Minerals processing plants have different operations due to the mineral hardness and size range (Kapadia, 2018). Additionally, these parameters also affect the design of structures used in mineral handling operations. For instance, structures constructed with highly abrasion-resistant materials are preferred for environments where hard ore material will be stored when compared to materials with a lower hardness, as the

abrasion resistance parameters have a significant influence on the rate and extent of abrasion wear (Kulu, et al., 2008). Figure 2.5 shows the difference in the hardness of construction materials and metallic minerals. Most minerals generally have a hardness less than that of construction, but metallic minerals, on the other hand, have a hardness equal to and sometimes harder than construction materials.

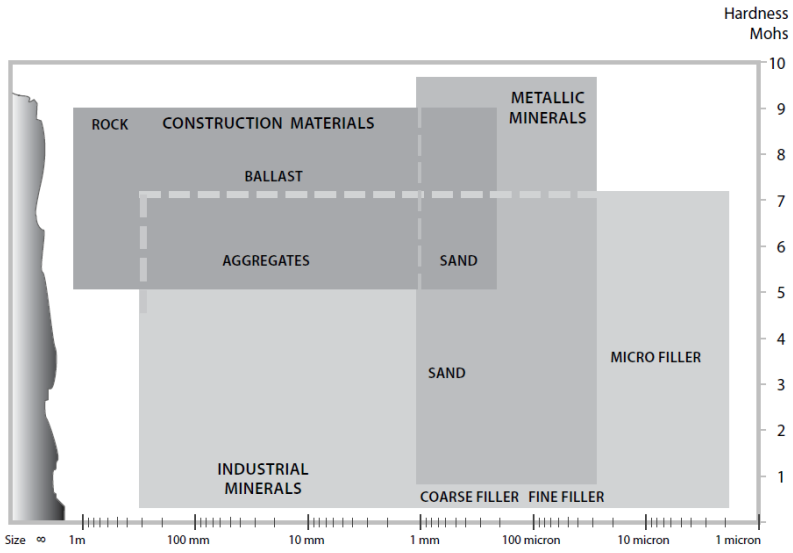


Figure 2.5: Diagram showing the relationship between size and hardness of different materials (Metso, 2011).

Where:

i. Construction materials are regarded as useful materials, including granite, building sand, limestone coals and clays (Grewal, 2006). These materials are not regarded as minerals.
ii. Industrial minerals are usually regarded as useful minerals. These usually include fluorite, apatite vermiculite and chromitite (Grewal, 2006). These are used for industrial applications and have very minimal mineral processing costs attached to them.
iii. Metallic minerals are a class of RoM similar to industrial minerals but have minerals referred to as metalliferous (Grewal, 2006). These minerals usually require more elaborate mineral processing to extract value from the material. This research paper focuses mainly on these types of minerals as they have a hardness higher than the other materials, especially construction materials used for the construction of material storage structures used in minerals processing plants.

Figure 2.5 shows that most metallic minerals generally have a higher Mohs number than that of the construction materials, which therefore means that they are able to leave indentations on the surface of the construction materials. This therefore suggests that a concrete surface would be scratched by most metallic surfaces, ultimately leading to its deterioration over time.

In a study examining the Mohs hardness of various concrete samples with respect strength, concrete samples were prepared and tested with a Windsor probe test at 28 days. The study was conducted with different aggregate types and w/c ratios, which resulted in concrete samples with compressive strengths ranging from 15 to 45 MPa. Correspondingly, the Mohs hardness of the concrete specimens exhibited a range between 3.15 and 7 (Pucinotti, 2009). These Mohs values obtained from the study above are similar to those for construction materials expressed in Figure 2.5 above and are lower than some metallic materials in some cases. Hence further expressing the likelihood of the concrete surface being abraded by metallic materials of higher Mohs hardness.

The hardness alone doesn't give a full indication of the material properties, as the energy, size and sharpness, as mentioned above also have a significant influence on increasing the rate and severity of abrasion. Thus, the energy requirement, and abrasion indices of the material are also used as the design and operating parameters of a minerals processing plant. The work index influences the energy required to cause deterioration due to impact, while the abrasion index influences the abrasion wear rate of equipment used in the minerals processing plant (Kapadia, 2018). These will be discussed in more detail below.

A strong correlation between abrasive particle size and abrasion has been obtained, where the increase in particle size has been seen to result in an increase in abrasion severity (Chotěborský, et al., 2009). Larger abrasive particles result in an increase in the abraded surface area, thus causing an increase in the severity of deterioration. This brings context to the severity of abrasion in mining applications when compared to other applications. Furthermore, within mining applications, RoM silos will experience higher abrasion when compared to Mill silos, as RoM silos have a higher particle size when compared to Mill silos.

Table 2.1 on page 24 shows the typical ore top sizes for mineral processing operations. It furthermore shows that the particle size had a significant influence on the tribological contact type. As the particle size becomes smaller, contact type changes from impact to abrasion, as the impact energy reduces with size. This change in contact type significantly influences the liner design requirements, thus resulting in different liner requirements for different applications (Asbjornsson, et al., 2022). It is important to note that the application of these liners have their own limitations and fall outside the scope of this research, as the concrete silos referred to in this study do not have liners.

Work indices (Wi) refer to a measure of an ore particle's resistance to crushing. This refers to the energy required to crush an ore body (Metso, 2011). The higher the resistance of the ore particle to crushing, the higher the stress the ore body can exact on the structure without being crushed.

During material impact loading on concrete, the above-mentioned ore material resistance to crushing results in a higher transfer of the impact energy onto the impacted surface (Metso, 2011), concrete surface in this case. This is undesirable as concrete is known to have low fracture toughness, thus relatively lower energy would be required to cause the formation of cracks. Therefore, ore materials with high work indices, could potentially result in the increase in deterioration under impact loading, while ore materials with lower work indices could potentially fracture on impact, reducing the transfer of energy to the concrete face.

2.4.3 Effects of mineral processing operations on Stored bulk solid ore characteristics

The aggressiveness of the exposure environment that certain concrete structures in minerals processing are exposed to can result from the operations upstream of the processing plant (Carson, 2012). Depending on where the material store is located in the mineral process chain shown in Figure 1.1, the material characteristics such as size and sharpness will vary, which results in varying tribological contact conditions experienced by the counter surface (concrete surface).

Table 2.1 shows the different operations mentioned in Section 1.1.1 above, with different Tribological contact conditions experienced in each operation. The different operations in Table 2.1 refer to the diagrams shown in Figure 1.1.

Table 2.1: Wear conditions based on upstream operation (Metso, 2011)

Operation	**Description of upstream process**	**Typical material top size (in mm)**	**Contact and wear type**	**Factors influencing the rate of wear**
a) unloading	Material tipped from a tipper truck into a feed bin, generally with a pecker to reduce material top size.	< 1000 > 80	Heavy impact	Size, weight, impact angle (90° to 50°) and drop height (high velocity > 7m/s)
B_1) Material Store (Run of Mine Store)	RoM Material store- typically from the mine and/or material truck tip.	< 500 > 22	Impact and sliding	Size, weight, drop height, impact angle (90° to 50°) and capacity

B_2) Material Store (Mill Feed Silo)	Mill feed material- is typically from the crushing circuit ($Op_{(a)}$), where the particle top size is reduced significantly.	< 22 > 0	Sliding and impact With sliding being dominant	High abrasion and high friction (low velocity<7m/s)

Table 2.1 above further illustrates how the different upstream mineral processing operations influence the material characteristics, subsequently affecting the deterioration mechanism. Different material stores, based on where they are in the process, will be subjected to different loading conditions. How material flows into and out of these material storage structures also plays a significant part in the type and rate of wear. It is therefore important to form an understanding of material storage and materials flow philosophy to fully understand the deterioration mechanism (Heerden, et al., 2005).

2.5 The Influence of Material Flow in Bins and Silos on Concrete Deterioration

The storage and handling of materials refers to the transportation and intermediate storage of materials between different operations in the processing plant. Bulk solid storage structures have developed over the past three decades to aid the material flow design and discharge equipment. This has improved the understanding of the behaviour and performance criteria of plant equipment. The design of handling plant storage bins, reclaim stockpiles, silos, and chutes follows the following process (Maynard, 2013):

i. The determination of strength and flow properties of bulk solids.

ii. The desired geometry of the silo, bin, or stockpile to provide the desired flow and discharge properties.

iii. Analysis of bin and hopper wall, chute, and feeder loads under operation.

iv. Design and detailing of the plant, including the structure and equipment.

The design theory of gravity flow of bulk solids is based on the principles outlined in the *Storage and Flow of Solids* (Jenkins, 1964). This research will provide a contextual summary of the flow properties of materials. Silo walls carry two types of loads which are the vertical loads due to equipment and the resultant loads from the stored material during the sliding and emptying of the silo. There are two main flow modes that influence flow properties in storage bins, silos and stockpiles, namely mass flow and funnel flow discussed in Sections 2.5.1 and 2.5.2. Expanded or mixed flow discussed in Section 2.5.3 is a mix of the two main flow modes discussed above, where both flows occur simultaneously (Roberts, 2009).

With respect to all the material flow types discussed below, impact wear can be caused by the discharge of material from a conveyor. The discharge velocities can be very low in these cases, but larger lump sizes may be present, causing significant damage (Arnold, 2008). The particle's relative hardness and the surface have the most important influence on impact wear (Kamil, 2023). In both hard and soft surfaces, the severity of the damage occurs when the material strikes the surface at approximately 90 degrees. In comparison, ductile surfaces have the most erosion and abrasion when the angle of attack ranges between 15 and 30 degrees (Roberts and Wiche, 1993).

2.5.1 Mass flow

Mass flow occurs in silos or bins when the hopper is steep enough, allowing the material to flow along its surface (Maynard, 2013). This means that the entire material mass will be in motion during the discharge, even though the velocities of the material moving through the silo will not be the same. The characteristics of mass flow are discussed in detail below (Schulze, 2021):

i. Due to material moving in mass, the first material in will be the first material out.
ii. There are no dead or inactive regions, material that is stored will be discharged at the bottom.
iii. Finer powers de-aerate as they are forced to settle.
iv. Due to the mass movement and re-mixing of material in the hopper during discharge, segregation is minimised.
v. Materials feed is uniform and at a constant density.
vi. There is minimal risk of contamination of the ore material, which could affect the efficiency of the downstream processes.

Mass flow is the preferred material flow mode in mineral processing as it maximizes the amount of material reclaimed from the buffer storage. It also provides a uniform and steady feed for further operations down the processing line. However, mass flow exposes storage structures to wear by material scouring the surface of the wall interface when emptying and by impact when filling, as shown in Figure 2.6 below.

Silos with conical bases are more likely to experience concentrated wear around the intersection between the cone and the vertical wall, as the flow is highly concentrated at the interface (Arnold, 2008). Wear at the bottom of the cone is also very difficult to monitor due to access and can lead to sudden detrimental structural failure. Wear inside the silo wall is also very common in mass flow silos, as the material causes an abrasive force on the concrete wall.

The feed geometry has a very significant impact on the wear of silos, as shown in Figure 2.6. The feed should be designed such that material falls onto the pile in the silo and not against the wall. Feed flow that impacts an area of the silo wall will lead to much higher wear than feed that falls elsewhere on the stored material. More rounded boulders can also roll off the existing material and impact onto the side of the

silo wall, causing significant wear if it occurs repeatedly. This is more likely to happen on the side opposite the feed chute, as shown in Figure 2.6.

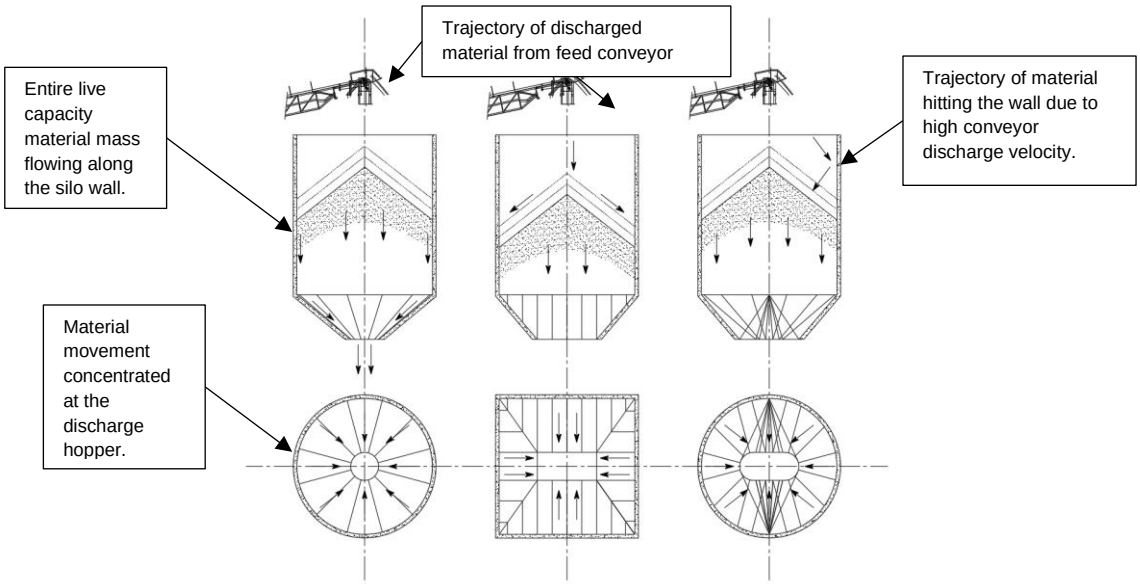


Figure 2.6: Diagram showing silo mass flow with different discharge and hopper arrangements, recreated based on (Roberts, 2009).

It is common practice for silos to have more than one discharge chute to allow for maintenance where one chute can be closed while another is in operation (Schulze, 2021). This is done to allow for the maintenance of the chute liners while ensuring production is not affected. One chute will be in use while the other is not in operation. The side that is most used will experience more concentrated wear due to material scouring the surface, which could result in a reduction in durability over time. Due to the abrupt constriction in the chute, the pressure the abrasive particle exacts on the chute wall increases. This results in the requirement for chutes to be lined with metals.

Chute liners, which are typically made of hardened steel supplied by various OEMs. Nevertheless, reinforced concrete silos are rarely constructed with different material liners at the interface between the silo's internal wall and the stored ore material. In more severe cases, shotcrete with a higher concrete compressive strength is usually installed at the interface. Abrasion on chutes falls outside of the scope of this research as this research mainly focuses on the impact abrasion experienced on the internal concrete walls of silos.

One notable disadvantage associated with mass flow is the phenomenon known as silo quaking (Carson, 2012). This phenomenon is characterized by a sudden acceleration and rapid deceleration of a sufficiently large mass of bulk solids as it is discharged through the silo, also known as the “slip-stick effect” (Schulze, 2021). The sudden acceleration is caused by the bulk solid “slipping” as it is discharged through the silo. The deceleration is mainly caused by the development of friction between the bulk solids and the silo wall, as the force is required to counteract the downward acceleration of the solid. In silos utilising mass flow for the storage of abrasive

materials, the presence of friction forces can significantly accelerate the wear of the internal silo walls, as the ore material abrades through the concrete wall. The excessive wear and sometimes failure of structures is simply due to the lack of understanding of flow and behaviour characteristics of materials under handling, storage and reclaim as mentioned above. Mass flow is, however, the most sought-after in mineral processing (Maraveas, 2020).

Under mass flow, the maximum friction wear occurs at the transition between the wall and hopper and slowly decreases towards the outlet (Roberts, 2009). The velocity profile of the bulk solid exhibits a non-linear increase as it progresses from the transition zone to the hopper and subsequently to the outlet. This, therefore, shows a correlation between the material velocity and abrasion wear. The material velocity is intrinsically related to the discharge rate at the hopper, which is further influenced by the normal pressure exerted on the stored material. An increase in normal pressure enhances the contact pressure between the material and the silo wall, which subsequently amplifies the relative wear experienced by the silo.

2.5.2 Funnel or pipe flow.

Funnel flow shown in Figure 2.7 occurs in bins and silos when material flows towards the center in a funnel-like manner, instead of flowing along the walls, as the name suggests (Deijs, 2001). This occurs when the angle of the walls is not sufficient to promote material flow along the surface.

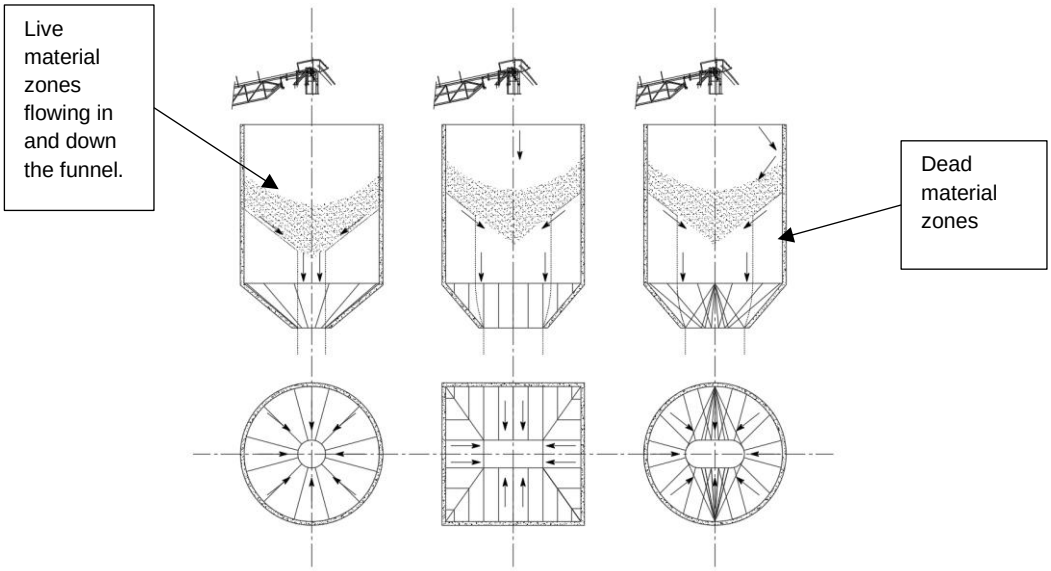


Figure 2.7:Diagram showing silo funnel flow with different discharge and hopper arrangements, recreated based on (Lobato, et al., 2016).

This flow condition minimizes abrasion and friction on the walls as there is minimal to no material movement at the material and concrete wall interface. Larger-diameter silos will tend to have funnel flow, while smaller-diameter silos will tend to have mass flow. This is because the discharge opening at the bottom of the silo is not large

enough to allow the entire surface area filled with material to move as a mass, creating a funnel to form down the centre of the discharge opening.

As shown in Figure 2.7 funnel flow reduces the risk of abrasion from the emptying silo as it directs material away from the walls through the funnel, to the discharge chute. This flow type is beneficial as it results in a reduction in abrasion at the silo wall-abrasive material interface, due to material scouring the internal silo concrete wall as its discharged through the silo. The typical material flow characteristics associated with funnel flow are as follows (Schulze, 2021):

i. The first material into the silo will be the last material to be discharged through the bottom.
ii. Material near the center of the opening will be in motion while the rest of the material around will remain stagnant.
iii. Lower headroom due to shallow hopper.
iv. The material tends to segregate, causing processing issues upstream.
v. Flow may be erratic due to the size opening not being large enough, causing an unsteady flow of material discharged by the silo.
vi. There is a potential for rathole formation due to the size opening not being large enough.
vii. The collapse of stagnant zones can cause erratic and uncontrolled flow, which can cause complications upstream.

However, in cases where ore bodies are discharged into the silo at higher velocities, like in other flow types, the silo wall still experiences the full impact of the ore body on the silo wall concrete. Therefore, the deterioration caused by this impact remains an important factor to consider for the overall durability of the structure. Furthermore, the first in-last-out characteristic of funnel flow causes material consolidation at the bottom of the silo, which can become extremely difficult to remove. This can cause excessive stoppages, which limit production, thus making it unfavourable. The type of material stored is also limited by this type of flow as the consolidation and increased pressure on flammable material can be extremely hazardous as it might combust due to the pressure (Hayes, 2022).

The segregation of material affects the overall performance of other plant equipment like mills and kilns, thus also making funnel flow undesirable (Deijs, 2001). Ratholes tend to form a stable arch and clog up during operation and can become extremely dangerous and difficult to clear, making it a nuisance to deal with. This makes Funnel flow highly undesirable for most processing plants, and mass flow being the most ideal, even though there are issues with impact and friction wear, as mentioned above.

2.5.3 Expanded flow.

Expanded flow is a combination of both funnel and mass flow occurring simultaneously. This is when the material is moving towards the centre of the

discharge chute. However, there is still a significant amount of material moving vertically along the wall of the silo, as shown in Figure 2.8. This material flow design tends to be exposed to both pros and cons explained in the above sections, respectively but is generally not used for smaller-sized silos and bins but is used mainly in stockpiles. Figure 2.8 depicts expanded flow in a stockpile.

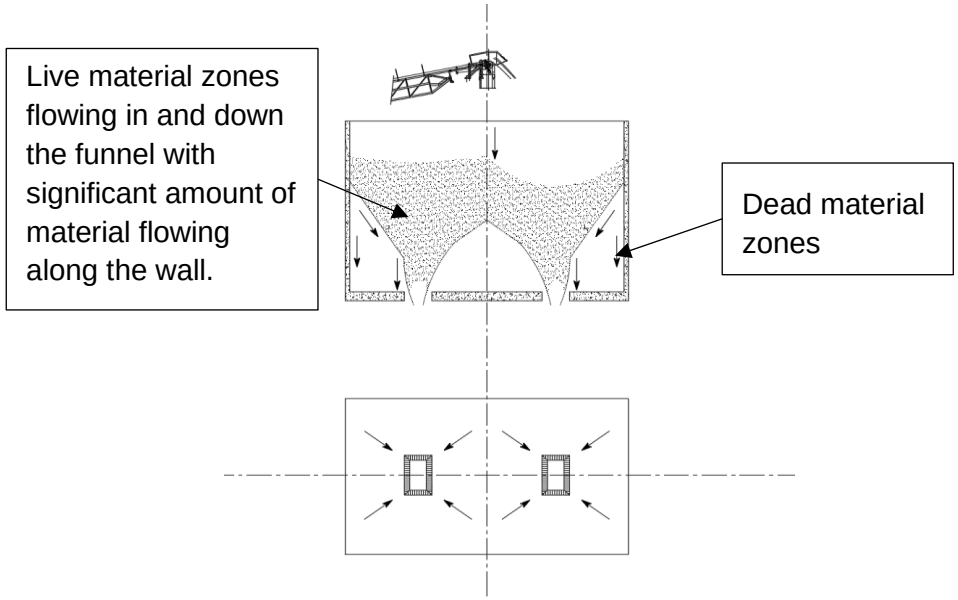


Figure 2.8: Diagram showing bin expanded flow, recreated based on (Schulze, 2021).

2.5.4 Mass-flow and funnel-flow for symmetrical bins and silos

The mass-flow and funnel-flow limits depend on the following parameters: hopper half angle α, the effective angle of the internal friction δ and the wall friction angle Φ (Kinematic friction angle between a solid and a wall). The internal friction angle and the wall friction angle are determined through laboratory tests, and from there, the hopper half-angle can be determined through the function in the form of (Roberts, 2009):

$$\alpha = (\Phi, \delta) \qquad \text{Equation 1}$$

Figure 2.9 below is used to design for a particular flow mode and shows the relationship between the above-mentioned parameters. This graph is plotted for three values of the internal friction for different wall friction angles and the hopper half angle. Larger flow hoppers promote funnel flow due to a significant change in direction at the hopper, while shallower angles promote mass flow, as shown in Figure 2.9.

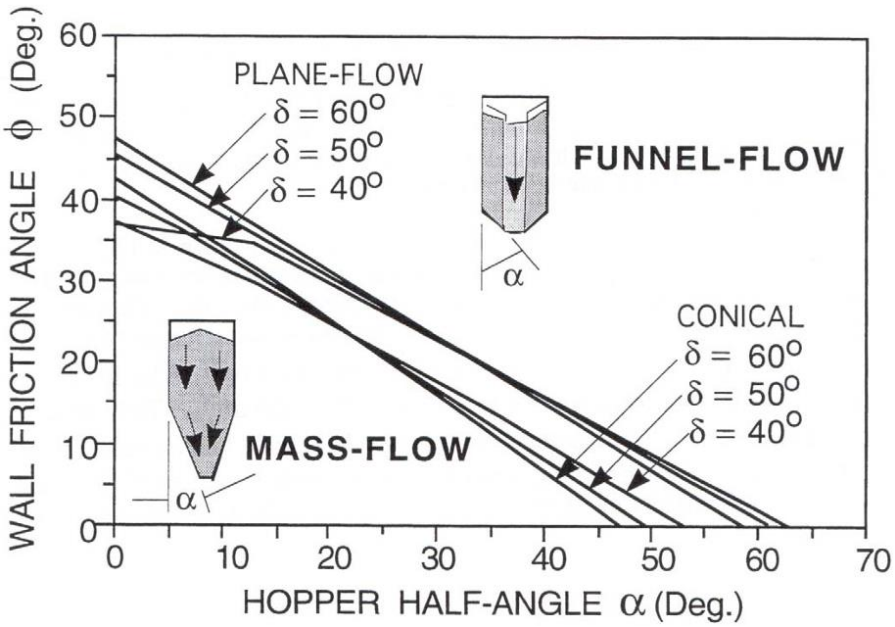


Figure 2.9: Limits for Mass-flow for Conical and Plane-Flow Channels (Roberts, 2009).

2.5.5 Material flow problems experienced in processing plants.

For many years, these critical aspects of processing have resulted in varying degrees of problems in processing plants and as mentioned above, have led to production losses, time and money being wasted (Deijs, 2001). Typical materials handling problems experienced in plant design are (Schulze, 2021):

i. Restricted or Limited flow rates.
ii. Erratic flow.
iii. Material segregation.
iv. Packing, pegging, blinding.
v. Blockage and material hangups.
vi. Excessive liner and chute wear.
vii. Mud rushes, flushing and flooding.
viii. Spillage.

Any one of the above-mentioned can be problematic, and a combination of these can bring the entire processing plant to a standstill. These problems are all dependent on the materials storage structures and the three aspects that should always be considered during design: type of flow, feed geometry and discharge. To facilitate the more precise design of these storage structures, it is important to evaluate and understand the integrated effect of these various aspects.

2.5.6 The quantification of abrasive wear on different materials

Abrasion wear can be quantified using an abrasive wear parameter W_a expressed in units of thickness loss per unit time (µm/s). W_a is a function of the normal pressure, the sliding velocity at the boundary, and the friction coefficient (Roberts and Wiche,

1993). The function for the wear parameter is expressed as follows (Roberts and Wiche, 1993):

$$W_a = \frac{\sigma_w v_s}{\sigma_{wp}} \left(\frac{\mu m}{s}\right) \qquad \text{Equation 2}$$

Where:

σ_w = normal pressure at the boundary (kPa), V_s = velocity of bulk solid adjacent to the boundary (m/s), Φ = wall friction angle and σ_{wp} = Lining wear factor (10^6 kN/m^2).

It is also stated that "The lining wear factor σ_{wp} depends on the interactive properties of the wall lining material and the bulk solid, which can be obtained by conducting wear tests on a sample of the lining material" (Roberts and Wiche, 1993:348). The total wear over the total time of operation can be obtained by integrating Equation 2 over the total operation time.

Furthermore, Figure 2.10 shows typical mass flow pressure and velocity profiles. The velocity of the material at any cross-section perpendicular to the wall is approximately uniform and increases exponentially at the hopper/wall interface. This is influenced by the converging flows in the hopper (Roberts and Wiche, 1993).

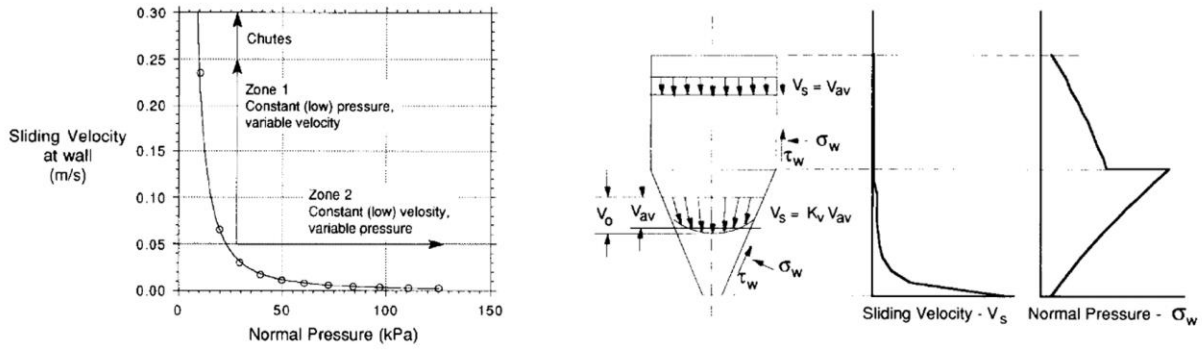


Figure 2.10 : Velocity versus pressure characteristics (left), and bin wear parameters and profiles (right) (Roberts and Wiche, 1993).

The average flow velocity V_s is a function of the throughput Q_m and the normal pressure during flow. This relationship is represented by the following equations (Roberts and Wiche, 1993):

For the cylinder (silo wall): $V_s = V_a = \frac{Q_m}{\rho A_c}$ Equation 3

For the hopper: $V_s = K_v\, V_{av} = \frac{K_v\, Q_m}{\rho A_h}$ Equation 4

Where:

A_c = cross-sectional area of cylinder (constant) (m), A_h = cross-sectional area of hopper (variable) (m), V_{ah} = average velocity at cross-section (m/s), ρ = bulk density (kg/m^3) and Q_m = discharge flow rate (t/h)

The parameter $K_v = {}^{V_s}/_{V_{av}}$ relates the velocity at the wall to the average velocity indicated in Figure 2.10, where K_v is such that $0 < K_v < 1$ (Roberts and Wiche, 1993). The normal pressure under flow conditions can be estimated using procedures established in the Australian Standard Design Code (AS3774, 1990).

Wear in silos, chutes and bins is highly influenced by the geometry of the equipment and flow patterns. The Relative Wear Number N_{WR} is a design aid used to identify zones where high wear is likely to occur due to a change in geometry. The N_{WR} also creates wear profiles for typical axi-symmetric and plan flow. The N_{WR} is represented as follows (Roberts and Wiche, 1993):

$$N_{WR} = \frac{(\sigma_w)(v_s)}{(\gamma B)v_0} tan\theta \qquad \text{Equation 5}$$

Where:

σ_w = normal pressure at the boundary (kPa), V_s = velocity of bulk solid adjacent to the boundary (m/s), V_o = velocity of bulk solid at the reference location (m/s), γ = Bulk-specific weight and B = characteristic dimension

The N_{WR} is derived from experimental wear tests and is used to provide a comparison of the wear behaviour of different materials relative to one another.

2.6 Comparison of Stockpile, Bins and Silos.

General stockpile, bins and silos designs are based on the following three factors; they require a live capacity, the angle of repose and cohesive properties of the stored material, and the feed rate from the stockpile or bin. The feed rate determines the size of the feeder size, and the angle of repose and cohesivity determines the ability of the material to flow through the discharge opening without causing arching and ratholing (Zamorano, 2006). A live capacity is required to ensure that the material is continuously being discharged.

The use of bins and silos to store material requires advanced materials handling understanding and requires a significant amount of engineering input. This then raises the question of why not use stockpiles instead? The idea is to create a material stockpile that does not require a storage structure to contain the material, which does not have concrete walls and chutes that wear over time. This, however, does not fully encompass the requirements of material storage buffers, even though stockpiles might

seem a lot more economical when compared to bins and silos, they do have their drawbacks.

Gravity reclaim stockpiles are often used as a buffer between the mine and the processing plant to store bulk solids in large quantities. Silos are used as intermediate stores between the different operations in the processing plant (Zamorano, 2006). Even though reclaim stockpiles are inexpensive, they require large plant real estate to construct, which is not always feasible (Ferreria, et al., 2022). They also result in high surcharge loads on the hopper below, often to the order of mega-Pascals, which is extremely high compared to silos and bins, which are in the order of 10 kilopascals (Ferreria, et al., 2022). This results in high design complexity when designing the discharge chutes and reclaim tunnels underneath the stockpile.

Stockpiles are suitable for storing coarse free flowing material and not cohesive materials because they depend on an angle of repose for material to flow. Such materials can lead to insufficient live capacity and stable ratholes forming and arching of material over the discharge openings (Dolman, 2012). The biggest disadvantage of gravity reclaim stockpiles is the recovery of stored material (Dolman, 2012). In a research paper on coarse ore stockpiles (Zamorano, 2006), it is noted that a live capacity of 20% to 25% of the total volume is often very difficult to achieve. This then requires additional resources to ensure that throughput frequency is maintained (Deijs, 2001). The footprint and real estate necessary for a stockpile are significantly larger than that of a silo or bin, as it depends on the angle of repose to store the material, as mentioned above. When real estate is limited, as it would be in underground operations, silos and bins are usually preferred (Dolman, 2012). Bins and silos are, however, exposed to wear like other structures used in mineral processing, requiring that we adequately account for this in design.

2.7 Influence of the Concrete System on the Abrasion Resistance of Concrete

Abrasion resistance is a material property that quantifies a surface's ability to withstand physical wear induced by mechanical interactions, such as friction and rubbing (Scott and Safiuddin, 2015). The performance of concrete with respect to its abrasion resistance depends on the microstructural characteristics, which are significantly influenced by its mix composition and constituents. Therefore, the abrasion resistance of concrete depends primarily on the aggregate, admixtures and the cement (Perrie, 2021), i.e. the hardness of the aggregate and the quality and compressive strength of the cement paste. These intrinsic factors give a basis to which this research will be conducted. Figure 2.11 below shows the interdependency of the intrinsic factors affecting concrete durability considered in this research.

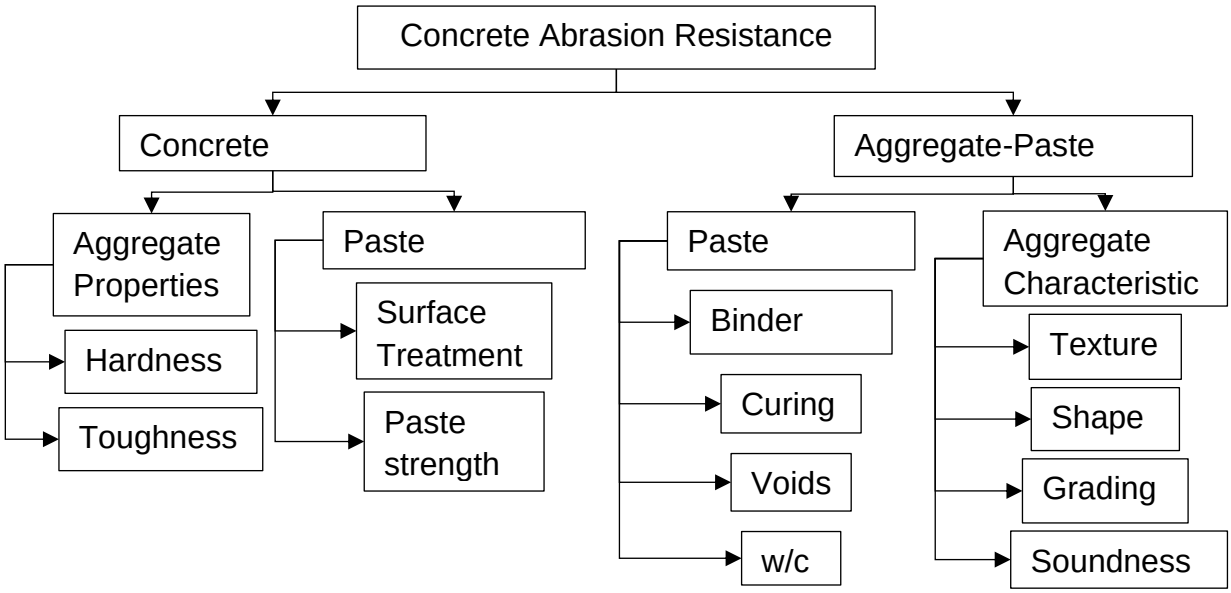


Figure 2.11: Factors affecting abrasion resistance of concrete (Papenfus, 2003).

When the concrete system is concerned, aggregates have a more significant contribution to abrasion resistance when compared to the hardened cement paste (Alexander, et al., 2009). Hence, the abrasion resistance of concrete is primarily determined by the quality, compressive strength, hardness, toughness, and abrasion resistance of the aggregate rather than the cement paste. Amin (2013:2) defined hardness as “the ability of a material to resist penetration or indentation”, while toughness as “the ability of a material resistance to fracture under impact loading”. It is often expressed in terms of the amount of energy a material can absorb before fracture.”.

Concerning the cement paste, the w/c is the most influential intrinsic factor when determining the concrete’s abrasion resistance. Its abrasion resistance increases linearly with decreasing w/c ratio. It is suggested that the secondary improvement in abrasion resistance of the concrete is a result of the improvement in the bond strength between the aggregate and the cement paste at the interfacial transition zone (Alexander, et al., 2009).

Appropriate concrete durability design and material choice will vary according to the conditions at a given location, i.e. the environmental loading (Beushausen, et al., 2021b).Thus, when maximising the abrasion resistance of concrete, the intrinsic factors with the most significant influence are: a) the aggregate, b) binder content (Heerden, et al., 2005), c) the water/cement ratio (Scott and Safiuddin, 2015), and d) mix proportioning (Bakke, 2006). These factors will be looked at in more detail below.

Lastly, the rate and extent of deterioration is significantly reduced by providing dense, well-compacted and good quality concrete, especially in the cover-crete of the concrete element. This is due to the protective barrier created by the high-quality dense concrete, which effectively shields the internal structure from the mechanical

and physical environmental actions that can lead to deterioration (Beushausen, et al., 2021b).

2.7.1 Influence of aggregate properties on abrasion resistance.

75 to 80% of the concrete volume is made up aggregates (Bonser and Alexander, 2021b), which clearly shows their importance in concrete. The aggregate hardness, therefore, has a significant influence on the hardness of the concrete, where concrete made with harder aggregates will result in harder concrete (Poyo, 2018). The relationship between hardness in abrasion resistance has been established in Section 2.3, where harder surfaces were established to be less susceptible to abrasion wear.

Gencel, et al. (2012) conducted a research study to examine how metallic aggregates influence the abrasion resistance of concrete. In this investigation, hematite was used as a substitute for limestone-based aggregates in plain Portland cement concrete. Hematite has a Mohs hardness of 5.5 to 6.5, which is significantly higher than that of limestone, which ranges from 3 to 4. The testing methodology employed in this study was guided by the standards set forth in Turkish Standard 699. The findings from the study concluded that replacing limestone-based aggregates with hematite enhanced the compressive strength of the concrete. This increase in compressive strength then led to a corresponding improvement in the abrasion resistance of the concrete (Gencel, et al., 2012).

With respect to the influence of aggregate size, Liu, et al. (2005) investigated the influence of 5, 13, and 25 mm aggregate sizes used to make concrete mixes with low to high compressive strengths (25 to 90MPa, respectively), using a waterjet with water-borne sand test method. For lower strength concrete, the increase in aggregate size led to a decrease in abrasion loss. Thus, it can be concluded that an increase in abrasion resistance was observed with an increase in aggregate size. This decrease in abrasive loss is due to the larger surface area of the aggregate being exposed to abrasion, thus reducing the surface area of the weaker exposed cement paste (Liu, et al., 2005). It is also attributed to the decreased surface area for the weaker cement paste to cover. Concerning impact abrasion, larger aggregates also require more energy to dislodge them from the concrete matrix when subjected to this deterioration mechanism (Liu, et al., 2005). Lastly, the investigation obtained no apparent correlation between the aggregate size and concrete compressive strength (Liu, et al., 2005).

Additionally, Dhir, et al. (1991) conducted a study on the effects of aggregate sizes on the near-surface characteristics of abrasion-resistant concrete, four maximum aggregate sizes were tested: 5,10,20, and 40 mm, while keeping the compression strength constant. It was documented that the 40 mm aggregate sample exhibited severe dynamic loading, leading to higher abrasive loss compared to the 10 mm and 20 mm aggregates (Dhir, et al., 1991). However, it was also concluded that the

increase in aggregate size reduced abrasion depth, thus reducing abrasive loss, which further corroborates, and strengthens the conclusions made in the paragraph above.

With respect to aggregate type, concrete made with aggregates such as quartzite, granite, and hematite are known to exhibit greater abrasion resistance compared to concrete made with limestone (Liu, 1981). Laplante et al. (1991) affirmed the aforementioned statement, as a similar conclusion was reached when conducting a similar study. Additionally, Kılıc et al. (2008) investigated the effects of the aggregates' abrasive loss on the overall concrete. This experiment evaluated five types of crushed coarse aggregates: gabbro, basalt, quartzite, limestone, and sandstone. A LA abrasion and compressive strength test was conducted for each concrete mix with the respective aggregate type. The results obtained from the study showed a strong correlation (R^2 = 0.88) between the aggregate hardness determined using the LA abrasion test and abrasion resistance (Kılıc, et al., 2008). From the results obtained, it can therefore be deduced that the LA abrasion test was shown to be a suitable indicator of the abrasion resistance performance of aggregates.

Furthermore, aggregate crushing values obtained from quarries in Gauteng show that granite aggregates have a higher ACV % when compared to other aggregate types. The Aggregate Crushing Value (ACV) is described as a test that provides a relative measure of the resistance of an aggregate to crushing under a gradually applied compressive load (IS:2386- Part 4, 1963). It is also used to give a measure of the aggregates' abrasion resistance. Lower ACV values should be preferred, therefore, the aggregates mentioned in the study above need to be evaluated.

Table 2.2 shows the aggregate crushing values from a study on AfriSam quarries located in the Johannesburg region. The Los Angeles Abrasion test is also used in this study to determine the hardness properties of the aggregates. The principle of the test is to find the abrasion wear due to the relative rubbing action between the aggregate and the steel balls used as an abrasive charge (Monyakeng, 2022). Aggregates with a lower LA abrasion percentage value tend to have better abrasion resistance than those with a higher value. For this reason, Aggregates with a lower LA abrasion % value (andesite and dolerite) were selected in this study and compared to the granite aggregates which have higher LA abrasion percentage values.

Table 2.2: Holcim Product and properties of Gauteng Aggregates (Holcim, 2004)

Product	Plant rock type							
	Eikenhof andesite	Ferro (Pretoria) meta quartzite	Juskei (Midrand) granite	Olifantsfontein dolomite	Roodekrans granite	Rooikraal dolerite	Sub-Nigel Reef (Nigel) quartzite	Zeekoewater (Witbank) felsite
ACV %	5,9	13,1	21,7	12,8	17,7	12	12,7	13,3
LA Abrasion%	8	25	33	16	-	8	-	16

Evangelista and de Britto (2007) investigated the influence of recycled aggregates and natural virgin fines on the concrete's abrasion resistance. The study involved the replacement of 30% to 100% of the natural fines with recycled aggregates in the concrete mix, and the results show that the abrasion resistance improved by 5% to 30% reduction in abrasion loss for the respective natural fines replaced. This reduction in material loss results from the better bond between the aggregate and the cement paste due to the influence recycled fines have on the concrete matrix. Replacing natural aggregates with recycled aggregates yields the same results where coarse aggregates are concerned. Konin and Kouadio (2012) conducted a similar study on the influence of recycled aggregates on abrasion resistance. It was concluded that recycled coarse aggregates performed better in abrasion resistance when compared to natural aggregates. This performance was also attributed to the improved bond between the aggregate and the concrete matrix (Konin and Kouadio, 2012).

Lastly, Well-graded hard mineral aggregates should be used in severe abrasion-resistant concrete applications, as this improves the density of the concrete, thus benefiting its impregnability and abrasion resistance (Bakke, 2006).

Laplante et al. (1991) carried out an experiment to examine the influence of aggregate properties on the abrasion resistance of concrete; in the study, four different types of coarse aggregates were tested as a portion of an extensive abrasion resistance testing program. The aggregates used in the study consisted of granite, limestone, dolomitic limestone, and trap rock. The concrete samples were tested for abrasion resistance using the ASTM C779. The results obtained from the study showed that concrete with limestone contained the most material loss due to the abrasion test (later called abrasive/material loss), with granite and trap rock aggregates containing the lowest material loss (Laplante, et al., 1991). It was also observed that there is a direct correlation between the aggregate strength and abrasive loss of concrete, which will be discussed in more detail in Section 2.7.4 on page 43.

The softer rock (limestone) experienced more abrasion material mass loss than the concrete samples made from harder granite and trap rock. Thus, it was concluded that the type of aggregate used in the concrete is one of the most influential factors in the abrasion resistance of concrete, which is also supported by other researchers (Alexander, et al., 2009). Figure 2.12 shows the abrasive wear on the various aggregates mentioned above. The results show that the aggregate type significantly influenced the depth of wear experienced by the concrete, at a constant w/c ratio. Indicating an interdependence between aggregate type, and the abrasion resistance of concrete.

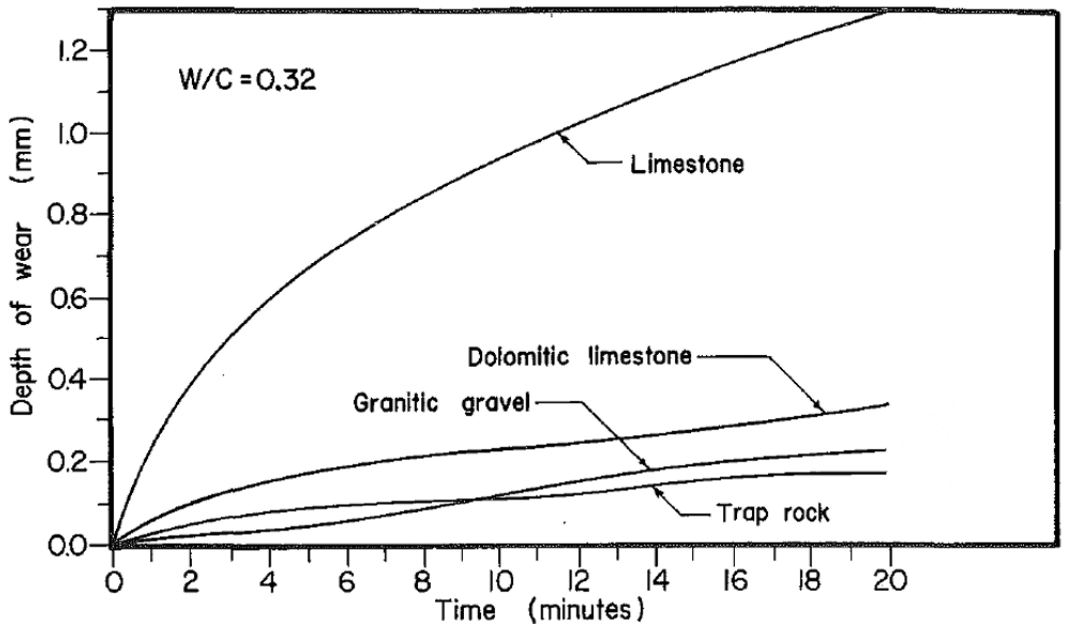


Figure 2.12: Abrasion wear of concrete with various aggregate types adapted from (Laplante, et al., 1991).

2.7.2 The influence of cement content and supplementary cementitious material.

Onur (2004) investigated the influence of varying cement content on compressive strength and abrasion resistance of concrete. This research focused on the effects of increasing the cement content from 200 kg/m^3 to 300 kg/m^3. The increase in cement content from 200 to 300 kg/m^3 showed a rapid increase in strength gain and a reduction in abrasion loss (Onur, 2004). This decrease in abrasion loss is a result of the decrease in the w/c ratio, which will be discussed in detail below. Concerning sustainability, the increase in cement content for a constant w/c ratio is unnecessary, as increasing the cement content results in a larger carbon footprint (Alexander, et al., 2009), even though similar results can be obtained from using supplementary cementitious materials and altering other concrete constituents (Onur, 2004).

Among different concrete constituent materials, supplementary cementitious materials have been highlighted to significantly influence the abrasion resistance of concrete (Alexander, et al., 2009). Yetgin and Cavdar (2011) studied the effects of the pozzolanic compositions and matrix structure or voids on the abrasion resistance of

cement mortars using the Böhme apparatus. The study concluded that there is a relationship between the mineral components of the binder and the concrete's resistance to abrasion. A higher content of clinker, limestone, and silica fume led to a reduction in the abrasion depth of cement mortars after one year. The extremely fine particles of silica occupy the voids between the other binder particles, which is often referred to as a 'fine filler effect'. Incorporating silica fume in concrete significantly improves the pore structure, increasing the concrete density and reducing porosity, thus resulting in better abrasion resistance (Benoy, 2021).

During the cement hydration process, the water in the concrete reacts with the tricalcium silicate (C_3S) and dicalcium silicate (C_2S), leading to the formation of C-S-H and free lime ($Ca(OH)_2$) as a byproduct (Jacobs and Kiliswa, 2021). The presence of pozzolanic materials in the concrete facilitates pozzolanic reactions, which result in the above-mentioned enhancement of the concrete properties. The pozzolanic reactions are as a result of the pozzolans reacting with the free lime ($Ca(OH)_2$) to produce additional C-S-H, which is the main contributing factor to the strength of the concrete (Jacobs and Kiliswa, 2021).

Furthermore, the two major aluminate phases Tricalcium Aluminate (C_3A) and Tetracalcium Alumino-ferrite (C_4AF) phases also contribute minimally to the overall mechanical strength of concrete. Though their contribution to compressive strength is much less than that of C_3S and C_3S, they play a more critical role in controlling the hydration process, setting times and chemical durability (Jacobs and Kiliswa, 2021). During hydration, C_3A reacts with gypsum and water to form the Ettringite (AFt) Phase, which forms as needle-like crystals that help control the early setting of concrete. Similarly, C_4AF follows a similar reaction as mentioned above, which ultimately results in the conversion of the Aft phase into the Monosulfate (AFm) phase, which is the final product of hydration of aluminates in cement (Jacobs and Kiliswa, 2021).

Ismaeil, et al. (2021) studied the mechanisms and influencing variables on the disintegration resistance of concrete. A comparison between 100% PC and a mix with a 7% SF replacement was drawn. The ASTM 1138 abrasion test was conducted on the two mixes above, and it was obtained that the mix with the 7% SF replacement had an 86% increase in abrasion resistance when compared to the control mix (100% PC). This therefore indicates that the use of SF should be a major consideration for the production of abrasion resistant concrete.

Yen, et al. (2007) states that mixes with up to 15% cement replacement by FA had a similar abrasion resistance to those without FA. In the study, PC was replaced by 15%, 20% 25% and 30% FA, and tested at 28, 91, 182, and 364 days. The 28-day abrasion test results are shown in Figure 2.13. The 15% FA replacement was found to be the optimum replacement of PC, this will therefore be considered in this study as an acceptable replacement quantity.

There is a common consensus among authors on the improved abrasion resistance of concrete by the replacement of PC with both fly ash (< 15 % FA) and condensed silica fume (< 7 % CSF) respectively. Fly ash reacts with the calcium hydroxide in the concrete to form calcium silicate hydrate (C-S-H) by converting the weaker crystalline phase to a strong gel-phase that binds the cement particles, and the aggregates together. Thus, resulting in a reduction in porosity and an overall improvement in the mechanical strength of the concrete (Poyo, 2018). This formation of calcium silicate hydrate improves the microstructure of the concrete by forming more cohesive and stable interparticle bonds between the cement particles and aggregate matrix, thus increasing its compressive strength and abrasion resistance (Pierre, 2009). The improvement in abrasion resistance in both cases mentioned above is a result of the reduction in porosity and the formation of stronger bonds at the interfacial transition zone between the aggregates and the cement paste.

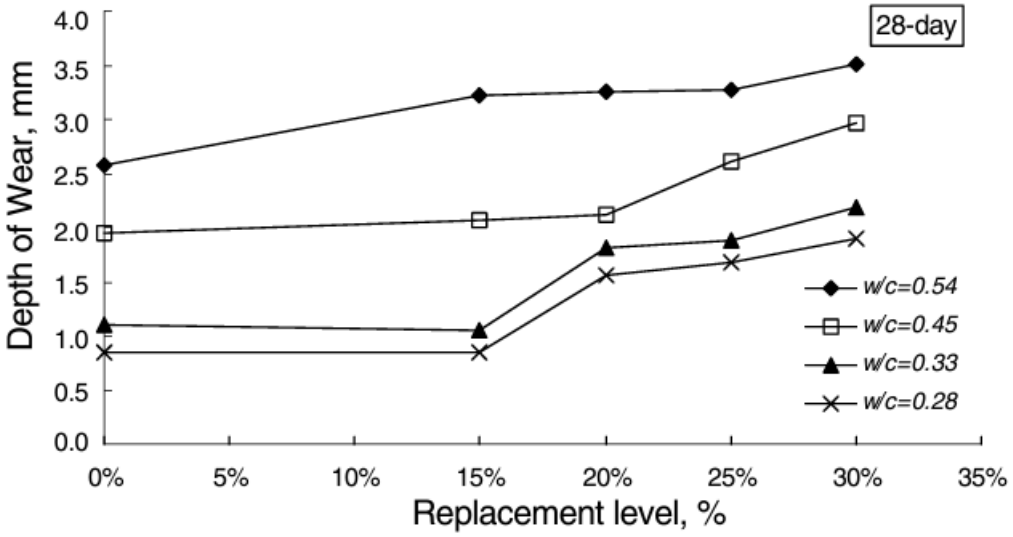


Figure 2.13: Effect of fly ash on the abrasion resistance of concrete at the age of 28 days (Yen, et al., 2007).

Lastly, Naik, et al. (1995) investigated the effects Class C fly ash (FA) has on the abrasion resistance of concrete. The study utilized the ASTM C 944 abrasion test method to evaluate the abrasion resistance performance of the various mix samples. The research focused on substituting PC with FA at replacement levels ranging from 15 % to 70 %. Abrasion tests were conducted at intervals of 28, 91, and 365 days respectively. Contrary to the findings in Figure 2.13 above, the results indicated that the abrasion resistance of concrete with a 15 % to 30 % PC replacement with FA showed a negligible influence on the abrasion resistant properties of the mixes, compared to the reference concrete with 100 % PC. Furthermore, the rest of the concrete mixes with more than a 30% FA substitution were noted to have poor abrasion resistance (Naik, et al., 1995).

Consequently, a comparative analysis of the two studies mentioned above indicates that an 85/15 blend of PC and FA shows the most advantageous ratio of PC substitution that maintains the concrete's abrasion resistance performance across both studies.

2.7.3 The influence of the water-to-cement ratio w/c on abrasion resistance.

Although this section primarily addresses the influence of the w/c ratio on abrasion resistance, it is essential to recognize that the effects of the w/c ratio cannot be considered in isolation from its influence on compressive strength. The strength of concrete is highly dependent on the w/c ratio, thereby establishing a crucial interrelationship between these factors, and their combined effect on abrasion resistance.

The researchers cited in sub-Section 2.7.1 and 2.7.2 above also investigated the effect of varying the w/c ratio on the abrasion resistance of concrete in their respective experiments, and similar conclusions were drawn from their respective investigations. The decrease in the w/c ratio was shown to result in an increase in the abrasion resistance of concrete. Similarly, Liu, et al. (2005) conducted abrasion tests on four concrete samples with different w/c ratios ranging from 0.26 to 0.50, using a non-standard water-jet with sand particles abrasion test. The results showed that the abrasion resistance increased with the decrease in w/c ratio. This result was expected as concrete with a lower w/c ratio has higher strength and lower porosity, resulting in better bonds between the cement paste and the aggregates, subsequently increasing compressive strength (Scott and Safiuddin, 2015). Figure 2.14 on page 42 shows two concrete samples from the above investigation, with a w/c ratio of 0.28 (Left) and 0.36 (Right).

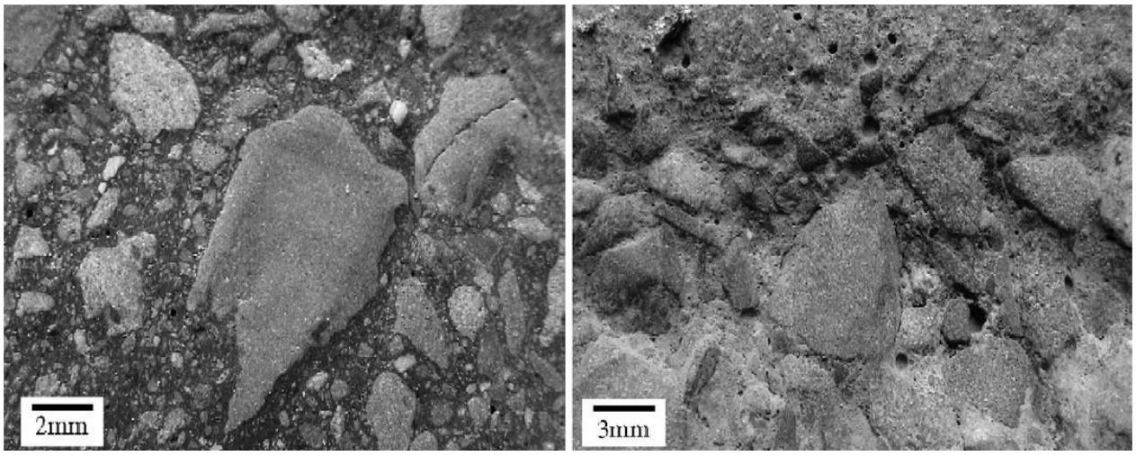


Figure 2.14: Abraded concrete surfaces with varying w/c ratios. 0.28 (left) and 0.36 (right) (Liu, et al., 2005).

The concrete on the left with a 0.28 w/c ratio has a denser and stronger concrete matrix when compared to the sample with a w/c ratio of 0.36. The aggregates in the picture with the 0.28 w/c ratio are more closely packed due to the reduced w/c ratio,

thus revealing less cement paste to be subjected to abrasion, resulting in the sample experiencing the least material loss (Scott and Safiuddin, 2015). Furthermore, the sample on the right experienced 45% more abrasion loss when compared to the one on the left.

Lastly, the ASTM limits the w/c ratio for abrasion-resistant concrete to 0.45 for hydraulic structures; however, there is no mention of w/c ratios for use in silo RC. The SANS require that the w/c ratio range between 0.45 to 0.55 based on exposure conditions. However, as highlighted above, the reduction in w/c ratio results in higher abrasion resistances. This therefore means lower w/c ratios than what is provided by the SANS need to be adopted.

2.7.4 Influence of concrete compressive strength on abrasion resistance

There is a general agreement between researchers on the relationship between concrete strength and abrasion resistance. This is seen in the studies above, where the increase in strength results in a reduction in abrasion loss. Research suggests that the dependence of abrasion resistance on concrete strength follows an asymptotic relationship, where a minimal increase in concrete strength results in a very significant increase in its abrasion resistance (Adewuyi, et al., 2017). However, at compressive strengths above 60MPa, the influence of concrete strength on abrasion resistance becomes less significant (Liu, et al., 2005).

The concrete's compressive strength is a function of the core of the concrete to resist stress while abrasion resistance is a function of the surface of the concrete. In a study on special surface finishing techniques, Papenfus (2003) argues that although abrasion resistance is related to compressive strengths generally, by means of using special surface finishing processes or materials, it is possible to achieve a surface with a higher abrasion resistance using a concrete that has low compressive strength. From the aforementioned statement, it is therefore suggested that it is possible to achieve high abrasion resistance from lower strength concrete, given that good quality surface finishing is undertaken. These techniques will be discussed in sub-Section 2.8.2 on page 45.

As mentioned above, an increase in compressive strength results in a direct increase in abrasion resistance (Warudkar and Elavenil, 2020). However, it is important to note that low strength concrete does not necessarily result in poor abrasion resistance, as strength alone does not serve as an indication of durability, in this case, abrasion resistance (Beushausen, 2005). Other factors include binder and aggregate types as well as the adopted construction methods such as curing, compaction and finishing can also influence the performance of the concrete.

2.7.5 Influence of concrete surface cracks on abrasion

Extensive research on the effects surface cracks have on the abrasion of concrete has shown that the abrasion resistance of concrete decreases with an increase in crack

width (Liu and Pann, 2011). Cracks on the concrete surface permit shearing action to occur as the abrading material wedges into the crack, allowing a larger concrete surface area to be dislodged, thus increasing the rate of deterioration (Scott and Safiuddin, 2015).

In a study investigating the impact of surface cracks on abrasion resistance using the ASTM C 944. It was demonstrated that 1 mm wide cracks resulted in a 100% increase in the loss of concrete due to abrasion when compared to surfaces exhibiting no visible cracking (Liu and Pann, 2011). This finding highlights the significant impact concrete cracks have on the extent and rate of deterioration of concrete due to abrasion. Further to the impact of the abrasive action of ore material on concrete shown in Figure 2.4, high-impact energy from the ores being unloaded into the silos also results in crack initiation and propagation. These cracks thus further influence the rate of deterioration of the internal surfaces of silos.

Crack orientation also significantly affects the rate of abrasion. Cracks that form perpendicular to the direction of abrasion result in more significant wear on the countersurface due to the increased contact length between the particle and the crack. The perpendicular angle between the direction of the abrasive action and the crack orientation maximises the crack width being sheared, resulting in more aggressive abrasion loss on the concrete (Liu and Pann, 2011). This underscores the importance of crack geometry on a concrete surface exposed to abrasion.

Due to the construction methodology of silos discussed in Section 2.8.4 below, surface discontinuities are perpendicular to the direction of abrasive wear, which, as mentioned above, could result in higher rates of deterioration. Therefore, silo construction methodologies could negatively impact the structure's overall durability due to the construction related cold joints forming perpendicular to the direction of abrasive material flow.

2.8 Influence of Construction Practices on Abrasion Resistance of Concrete Structures

In addition to the above-mentioned influence of intrinsic factors on concretes' abrasion resistance, ensuring that principles of producing good quality concrete are adhered to has significance for the overall performance of concrete. The extrinsic factors, production, construction process, and curing that influence the overall abrasion resistance of concrete are discussed below. (Scott and Safiuddin, 2015) considered the attention to surface finishing techniques, moist curing at early ages and the use of surface hardening agents as additional ways of improving the abrasion resistance of concrete and should, therefore, be investigated in more detail.

2.8.1 Workability, placing and compacting concrete on abrasion resistance.

Researchers suggest that no direct relationship between the field performance, workability, and abrasion resistance of concrete exists (ASTM, 2018). However,

increased workability aids in better mixing, placing, compaction and finishing of concrete, indirectly resulting in more homogeneous concrete and better abrasion resistance (ASTM, 2018). Improved workability thus influences the placement of homogeneous, un-segregated concrete, resulting in better abrasion resistance (Razak, et al., 2004). Adequate compaction and vibration is known to significantly improve the density and strength of the concrete matrix by releasing trapped air in the concrete mix, reducing porosity, and increasing density thus positively affecting its abrasion resistance (ASTM, 2018). For vertical slipform sliding applications, a slump range of 120 to 200 mm is deemed acceptable (Hasselqvist and Gegerfelt, 2021).

2.8.2 Surface treatment and near-surface properties on abrasion resistance

Various researchers have identified the surface properties of concrete as the most significant construction related consideration for abrasion resistance (Liu and Pann, 2011). Abrasion is a surface property instead of a bulk property effect like compressive strength. Even though strength is an indicator of abrasion resistance, the quality of the surface-layer or cover concrete (cover-crete) significantly influences the concrete's resistance to abrasive wear (Liu and Pann, 2011). The various ways to increase the abrasion resistance of concrete include; concrete overlays, surface finishing techniques, coatings, and surface treatments.

Concrete surface treatments can be categorized into four distinct types: surface coatings, hydrophobic impregnations, pore-blocking surface treatments, and multifunctional surface treatments (Wu, et al., 2023). Surface coating treatments are the most suitable forms of concrete surface treatments, as they form a protective layer between the abrasive particle and the concrete surface (Wu, et al., 2023). Previous research focused on the other concrete surface treatment methods demonstrated negligible effects on abrasion resistance, suggesting limited efficacy in enhancing the durability of concrete surfaces (Pan, et al., 2017). Thus, surface coatings could yield more desirable abrasion resistance results. However, there is a lack of reliable in-service data and information, therefore, conclusions on the effectiveness of the above-mentioned methods, specifically when applied to silos could not be reached.

Furthermore, surface finishes are also an important consideration for the improvement of abrasion resistance in concrete. (Sadegzadeh, et al., 1987) Investigate the influence of surface finish techniques on the microstructure of concrete. The test program measured the pore volume abrasion loss on the surface of 3 different surface finish types: hand, power, and repeated power finish. The surface treatment brought excess water to the surface of the concrete that eventually evaporated, resulting in a lower local w/c ratio. This loss of surface moisture then led to a reduction in the pore volume, thus increasing the density of the concrete matrix and improving the overall hardness of the concrete (Sadegzadeh, et al., 1987). The repeated power finish improved the abrasion resistance of the specimen by nearly three times that of the hand-finished specimen (Sadegzadeh, et al., 1987). These results are further supported and

recommended by the ASTM, where emphasis is also placed on the importance of a power finish (ASTM, 2018).

In a study on the impact of surface finishes on abrasion resistance development in concrete with varying w/c ratios, the influence of concrete pore volume on abrasion was examined using an abrasion resistance test apparatus with a rotating steel plate carrying three case-hardened steel wheels (Sadegzadeh, et al., 1987). The findings from the study shown in Figure 2.15, indicate a strong linear correlation between the total pore volume and the depth of abrasion, with a correlation coefficient of 0.97. The pore size decreases from a hand finish to a repeated power finish, indicating that a repeated power finish is more likely to reduce abrasion depth.

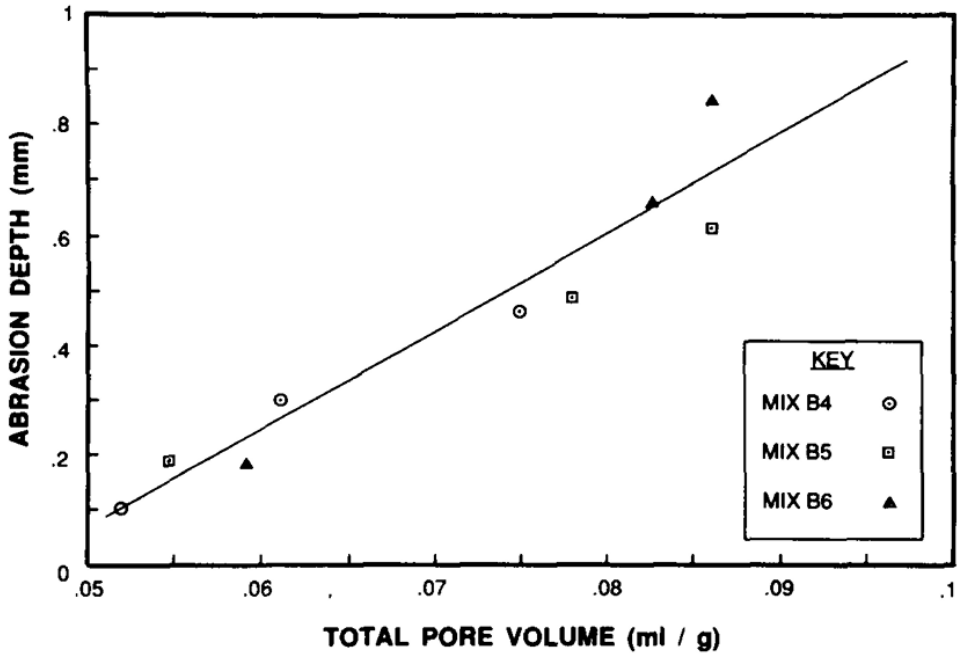


Figure 2.15: Influence of pore volume on the abrasion resistance performance of concrete, where the mix labels B4, B5 and B6 refer to the w/c ratios of 0.44, 0.54 and 0.65, respectively (Sadegzadeh, et al., 1987).

The application of surface treatment, and surface finishing techniques and methodologies falls outside the scope of this research, as the primary emphasis is on the concrete mix design. The application of these surface coatings has limitations such as accessibility, site conditions, and most importantly, come at an additional cost (Luqmaan, 2019). Furthermore, due to a lack of literature and application of these surface methods. Accessing in-service performance data presents significant challenges, and evaluating the correlation between laboratory test results and actual field performance can be complex and nuanced (Luqmaan, 2019). Nevertheless, this exclusion does not diminish the benefits to abrasion resistance attributed to the use of surface treatment methods.

2.8.3 Effects of curing on abrasion

Once the concrete is placed and compacted, it is necessary to immediately protect it from rapidly drying out and maintain its moisture content for the development of the desired hardened concrete properties (Alexander, et al., 2009). Curing is described as the process of ensuring satisfactory moisture content and temperature for a period of time to aid in the development of desired hardened concrete properties such as strength, volume stability, resistance to chemical attack and abrasion resistance (Piplewar, et al., 2014).

Since a low w/c ratio is desired to produce abrasion-resistant concrete (usually less than 0.5), additional water should be provided at the surface of the concrete to reduce the amount of moisture lost at the surface due to evaporation (Alexander, et al., 2009). Water availability at the surface improves the degree of cementing reactions in the concrete, resulting in a cover-crete that can resist chemical and physical attack due to its improved impermeability (Alexander, et al., 2009).

Furthermore, the duration of curing also plays a significant role in achieving the required performance from the concrete. It is important for curing to take place without delay after the concrete has been cast for the preservation of moisture and temperatures both at depth and on the surface of the concrete (Piplewar, et al., 2014). *"Accurately cured concrete has an ample amount of moisture for sustained hydration and growth of strength, volume stability, resistance to freezing and thawing, and abrasion and scaling resistance."* (Piplewar, et al., 2014:119-126).

Kevern, et al. (2009) conducted an investigation to analyze the impact of six distinct curing regimes on the abrasion resistance of concrete, using the ASTM C944 test method. The evaluated curing methods were air curing, moist curing under plastic for 7 to 28 days, soybean oil curing, white pigment curing, and curing with a non-film evaporation retardant.

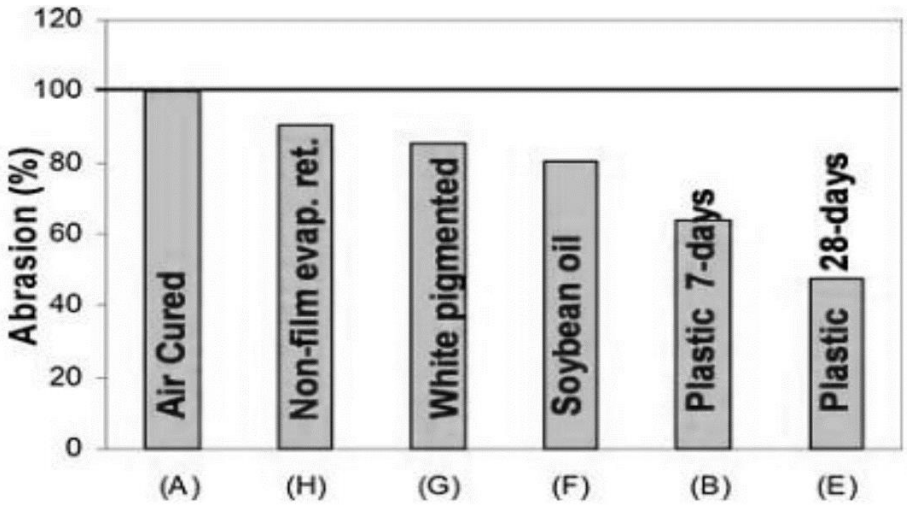


Figure 2.16: Effects of curing regime on concrete abrasion at 28 days (A to E indicates the curing regime) (Kevern, et al., 2009).

The findings revealed that the concrete specimens subjected to moist curing exhibited superior performance with minimal abrasive loss (50% less than that of the air cured specimen), whereas the air-cured specimens experienced the highest degree of abrasion (Kevern, et al., 2009). This resulted from the moisture trapped by the plastic sheet aiding the cementing reactions and producing more dense concrete at the surface. Figure 2.16 depicts the above-mentioned results based on the different types of curing regimes. In addition to the curing regime, the significance of the curing duration on abrasion resistance was investigated by (Dhir, et al., 1991). The concrete specimens were made from the same mix, and cured for 1,4,7 and 28 days. The investigation concluded that the abrasion resistance increases with the increase in moist curing duration (Kevern, et al., 2009).

The air cured sample (A) experienced the most amount of mass loss due to abrasion when compared to the other five samples. Consequently, sample (A) was established as the reference point for the abrasive index, denoted as 100 %. The average abrasion mass loss of mix (A) was 7.37 g, which serves as the benchmark. In comparison, the other samples H, G, F, B and E experienced varying degrees of abrasion mass loss of 91%, 86 %, 82 %, 64 and 55 %, respectively, relative to the reference sample (A). Furthermore, the plastic cured results are also replicated by (Alexander, et al., 2009), where the curing duration is suggested to increase concrete strength and density. The ASTM also recommends that abrasion-resistant concrete be moist cured for 5 to 7 days at 21° Celsius (Bakke, 2006).

Thus, it can be concluded that plastic curing yields superior abrasion resistance in comparison to other curing methods evaluated in this study. Nevertheless, the practical application of this curing method may be limited, particularly in contexts such as silo construction. Hence, the use of curing compounds may be more advantageous in such scenarios, as they are more practical and are shown to have better abrasion resistance, when compared to air-cured specimens.

2.8.4 Industry standard for cylindrical silo construction

Flat bottom silos are generally a lot easier to construct due to the shutter sliding methodology compared to conical bottom silos. Slip-form construction can be likened to an extrusion process. Fresh concrete is poured into the top of the slipforms, and then the formwork acts as dies and shapes the concrete (ACI 313R-97, 1997). After some time, the concrete exits the bottom of the form in its plastic state, with enough stiffness to uphold its weight and maintain its shape, while the forms confer the structure its intended shape. Unlike conventional extrusion, where the concrete is pushed through the die, the slip forms are, in this case, raised upward to receive new concrete at the top (ACI 313R-97, 1997). Movement of the form is accomplished using hydraulic jacks that “climb” on smooth, mild steel rods, which are then left embedded in the hardening concrete. These “jacking rods” are progressively extended by adding additional rods during the progress of the work. The slip-form construction operations

are undertaken continuously, without interruption, ensuring a homogeneous, joint-free structure.

2.9 Existing Abrasion Resistance Tests and Research Methodology

2.9.1 Overall abrasion resistant concrete testing methodology

This sub-Section outlines the effects of the aggregate size and type, w/c ratio, and binder type on compressive strength, abrasion resistance, initial setting time, and workability of concrete used for silo construction. These fresh and hardened concrete properties are considered to be the most influential on concrete quality when it is to be placed using the slip-form method for the construction of bulk storage silos (ACI 313R-97, 1997).

The American Concrete Institute's (ACI) commentary on the design and construction of silos and stacking tubes for storing granular material has a set of recommendations for the constituents of concrete used to construct silos discussed in Section 2.9.2. However, silos constructed with these above-mentioned recommendations tend to wear quite significantly when used in mineral processing, as demonstrated in the silo SIMM inspection report in Appendix C. As a result, it becomes important to re-evaluate the suitability of the recommendations for application in high-impact and abrasion-prone environments that the concrete is exposed to i.e., material storage silos in mineral processing.

Concrete silos experience two modes of mechanical and physical wear; these are impact and abrasion (Heerden, et al., 2005). These wear mechanisms are outlined in more detail in sub-Section 2.3.1 above. These mechanical wear processes result in the damage of concrete at the internal surface, subsequently leading to the loss of concrete cover to the reinforcement at the inner surface of the silo, compromising the durability of the structure. The hardened cement paste usually has a lower abrasion resistance than the aggregates and, in some cases, abrades faster than the aggregates (Concrete Institute, 2013). It has been observed that in certain scenarios, the degree of wear leads to the emergence of aggregates through the concrete, as the mortar encompassing the coarse aggregate is abraded. Such a phenomenon indicates that the mechanical properties and durability of the concrete are closely linked to the constituent materials and their respective interactions. This, therefore, means that the abrasion resistance of concrete is a function of the mortar, and aggregate material properties (Alexander, et al., 2009).

2.9.2 ACI material recommendations for silo construction.

Recommendations for concrete materials used for the construction of silos are as follows (ACI 313R-97, 1997):

R2.2 – Cements: CEM I (with a fineness modulus less than 2000) and CEM II type cements- due to their initial set during a slip form operation.

R2.3 – Aggregates: ACI 313 recommends similar aggregates for aesthetic purposes. Thus, no recommendations are made on strength and size.

R2.2 – Admixtures: ACI 313 recommends controlling only the initial setting time and water reduction.

As discussed in Section 2.7, the concrete strength and abrasion resistance can therefore be improved by specifying harder and more abrasion-resistant aggregates, specifying lower w/c ratios, and using appropriate finishing and curing techniques. However, the ACI recommendations do not emphasize the importance of the above mentioned parameters on the performance of the concrete. This aspect is also going to be looked at in more detail below.

2.10 Modelling and Testing of the Abrasion Resistance of Concrete

Many methods of abrasion testing and modelling have been developed over the years by various institutions and researchers. The American Society for Testing and Materials (ASTM), National Building Research Institute of the Council for Scientific and Industrial Research (NBRICSIR) and South African National Standards (SANS) have developed most of these test methods for abrasion resistant concrete, which will be mentioned and described in detail below.

In an investigation on "*Elements for the effective design of abrasion resistant concretes."* by Heerden, et al. (2005), a relationship between the mechanical strength and abrasion resistance of concrete was identified through laboratory tests. Over a range of compressive strengths, the abrasion resistance increased with the increase in strength, but the strength was not the main contributing parameter (Heerden, et al., 2005). The evaluation of abrasion-resistant concrete requires a different quantitative test method for strength, as it is subjected to a large variety of conditions that can not only be assessed by using the strength of the concrete.

The following abrasion test types in Table 2.3 were obtained from (Heerden, et al., 2005). In addition, the Böhme (DIN 52108) abrasion test method was also added to Table 2.3 and was adopted from a study on testing the abrasion resistance in hydraulic structures.

Table 2.3: Different categories of abrasion test types and methods on concrete (Heerden, et al., 2005) (Kryžanowski, et al., 2012).

Abrasion test type	**Description**	**Test Method**
Abrasion by polishing	A tool forces over the concrete surface a grinding media, either abrasive powder or balls.	Method C ASTM C779
Abrasion by cutting	A tool forces cutting surfaces ('teeth' or blade) over the concrete surface	Method B ASTM C779 and ASTM C994

Abrasion by impact	The concrete surface is exposed to repeated shock of a single mass or from a falling flow of several objects.	SANS 1058
Abrasion by particles	A stream of air charged with abrasive sand is projected onto the concrete surface (Sandblasting).	ASTM C418
Abrasion by grinding	The surface of the concrete is exposed to a rotational grinding disc.	Böhme (DIN 52108
Abrasion by water with particles	A stream of water charged with abrasive sand is projected onto the concrete surface.	Non-standard -The water jet method with abrasive particles (Liu, et al., 2006)
Abrasion by cavitation	Very high velocity and pressure water flow condition induces cavitation phenomenon on the concrete surface.	Non-standard -water jet test method (Liu, et al., 2006)

These tests, however, do not predict the service life that can be expected from a specific concrete but rather show the quality and effectively evaluate how different variables affect the abrasion resistance of concrete (Scott and Safiuddin, 2015). Additionally, a comprehensive review of the literature reveals a lack of references that could provide meaningful comparisons of results between the various other abrasion tests. This, therefore, creates difficulties in the development of abrasion resistance durability specifications and acceptance criteria.

2.10.1 ASTM abrasion test methods

Over the past century, various attempts to reproduce the detrimental abrasion forces on concrete have been made, and various standards of laboratory methods and testing machines have been produced (Bakke, 2006). The ASTM testing methods for abrasion resistance have been adopted worldwide and in design codes such as the CSA A23.2-16A and 17 A Canadian code. Additionally, various other tests have also been developed and adopted in various parts of the world.

There are currently 4 ASTM methods for evaluating the abrasion resistance of concrete subjected to various kinds of abrasive actions. These test methods are as follows: ASTM C418 for abrasive actions under traffic and waterborne abrasive action using sandblasting. Method A ASTM C779 for horizontal surfaces with light traffic using a revolving machine, Method B ASTM C779 for relatively high impact uses a dressing wheel cutter to simulate rolling. Method C ASTM C779 uses a ball bearing machine, and lastly, ASTM C994 uses a cutter machine to determine the abrasion resistance of the mortar on the surface (Bakke, 2006). ASTM C1138 is for modelling the abrasion resistance of concrete used in hydraulic structures.

Table 2.4 summarizes which test should be used for different abrading actions adopted from the ASTM C418, C779, C944, C1138, and the respective references below.

Table 2.4: Application of Tests for abrasion resistance of concrete (Bakke, 2006), (Scott and Safiuddin, 2015)

Type of abrasion	ASTM C418	ASTM C779			ASTM C944	ASTM C1138
		Method A	Method B	Method C		
Foot traffic or light to medium tire-wheeled traffic.	X	X			X	
Forklift, heavy tire wheeled traffic, automobile with chains, heavy steel wheeled traffic or studded tires			X	X	X	
Abrasive erosion of waterborne particles on hydraulic structures	X					X

ASTM C418: Abrasion resistance testing of concrete by sandblasting.
This test method uses silica sand graded to pass through an 850 µm sieve and be retained on a 600 µm sieve to sandblast a concrete surface area. This is done to evaluate the relative resistance of the concrete area to abrasion by sandblasting (ASTM C418-12, 2012). This test method, as mentioned above is designed to simulate abrasive actions under traffic and water borne abrasive particles transported over a concrete surface. Additionally, this method is suitable for testing the abrasion resistance of the weakest link (ASTM C418-12, 2012), i.e. the paste, as the energy of the sand particles is too small to dislodge the aggregates in the concrete (Alexander, 1985). This method is therefore not applicable to this research, as the mode of deterioration or abrasion does not simulate that which is experienced in silos used in dry mineral processing operations.

ASTM C779: Abrasion resistance testing of horizontal concrete surfaces
This test method covers all 3 (A, B, C) methods under ASTM C779 mentioned above, and is used to determine the relative abrasion resistance of horizontal surfaces (ASTM C779 / C779M-12, 2012). These tests are used to determine the effects of the variation in surface properties of concrete but do not give a quantitative indication of the durability of the concrete (Poyo, 2018). The test procedures are, however, limited as they can only be used to evaluate the effects of curing, surface treatment and finishing methods on the abrasion resistance of the concrete. This therefore means that the

effects of the concrete constituents on abrasion resistance cannot be evaluated using this method, thus making this method unsuitable for this research.

ASTM C1138: Abrasion resistance testing of concrete used in hydraulic structures.

This test method was developed for the abrasion resistance evaluation of concrete used in hydraulic structures such as dams, spillways, stilling basins and weirs (Poyo, 2018). "*This test method is intended to qualitatively simulate the behaviour of swirling water containing suspended and transported solid objects that produce abrasion of concrete and cause potholes and related effects."* (ASTM C1138M-12, 2012:1). This method can be used to evaluate the influence of different types of concrete. Furthermore, this test is useful in the selection of concrete materials, concrete mix designs and construction methods where waterborne action is expected (Poyo, 2018). Even though this test evaluates similar requirements as this research, it is only applicable to underwater structures. Modifications could be done to make it suitable for this research.

2.10.2 LASA modified tumbling test method for abrasion resistance.

Most laboratory test methods developed have been developed for general applications. Due to the extremely aggressive abrasion caused by both impact and friction in ore passes and considering the material size circulating through these structures, available test methods are unable to reproduce such conditions (Heerden, et al., 2005).

To better simulate these conditions, LaFarge Aluminates South Africa (LASA) in 2000 developed a modified test procedure called the 'LASA modified tumbling test'. This test is based on the existing SANS 1058 standard test, which induces both impact and friction abrasion on concrete specimens for the construction of pavement slabs. However, this test uses small steel ball bearings, which do not necessarily replicate the aggressiveness of the mine environment. Therefore, the following modifications were made to the existing method to make it more applicable to the mining environment:

i. Change the steel balls from 12 mm to 40 mm.

ii. Add deflector plates to increase the impact component of the test.

The following changes were made because the damage due to impact is more severe when compared to the other contact types (Heerden, et al., 2005). Like the different test methods, the LASA tumbling test does not predict wear life but shows the abrasion resistance performance of different concrete mix designs. This test method however requires modifications to be done to a standardized test method. These modifications could render difficulties as the modifications could be applied differently. Thus, resulting in challenges with the replicability of the test, and obtaining comparable results.

2.10.3 Justification for using the modified SANS 1058 test for this study.

To obtain test results that replicate the performance of concrete exposed to impact and abrasion, it is important that the test method conducted be tribosimulative. When designing a tribosimulation, the foremost concern is to identify the most crucial wear mechanism and develop a test apparatus that yields the same kind of wear response. This enables the researchers to gain valuable insights into the wear behaviour of structural components and in this case, devise effective strategies for mitigating wear-related issues the concrete is exposed to.

There are various abrasion tests that have been developed by researchers over the years as mentioned in Section 2.10.1. However, to achieve more precise and reliable results, it is imperative that one should perform tribosimulative tests, which mimic the real processes as well as possible. A tribosimulative test is a specialized test designed to replicate the operational conditions and environmental factors experienced by a specific structural component (Teeri, et al., 2006). The most crucial concern when designing a tribosimulation is to identify the most significant wear mechanism, and subsequently design a test apparatus that can replicate the same wear response. This approach ensures that the test provides results that better imitate the wear behaviour of materials under various conditions (Teeri, et al., 2006).

Furthermore, it has been suggested in literature that the constituents such as aggregate type size and binder type enhance the abrasion resistance of concrete. However, it is important to note that the research conducted to arrive at this conclusion was carried out using different methods, making it difficult to draw clear comparisons between them. Furthermore, these abrasion resistance test methods do not necessarily simulate the environmental loading conditions that silos in mineral processing are typically exposed to.

In a study on sandblasting and wire-brush concrete abrasion resistance testing, it was concluded that there was a poor correlation between the laboratory test cubes and cores obtained from the structure (Poyo, 2018). This was the case as the abrasion mass loss obtained from the site cores was three times that obtained from the laboratory. This therefore suggests that test methods used in the study do not accurately simulate the real-life environmental conditions. Therefore, it is important that future research endeavours focus on methods that can accurately simulate reality while providing uniformity in the experimental results.

The ASTM C418 and the SANS 1058 tumbling test are the two most commonly used abrasion resistance tests in South Africa. The ASTM C418 has been used by various researchers to determine the abrasion resistance of concrete used to construct spillways (Poyo, 2018), and the SANS 1058 has been utilized in pavement block testing only (SANS 1058, 2021). Additionally, from the research conducted in this study, the Böhme was identified to be a relatively commonly used abrasion test in

South Africa. These tests are widely accepted in the industry, and the test apparatus is also relatively easily accessible.

The DIN 52108 abrasion test uses an abrasive wheel method for testing the behaviour of inorganic materials when subject to wear caused by grains sliding (DIN 52108, 2002). Furthermore, the prevailing deterioration process simulated by the Böhme test is abrasion through grinding (Kryžanowski, et al., 2012). This method would be applicable in the case where abrasive action is more prevalent when compared to impact. However, as presented in Section 2.5, the silo wall is exposed to both impact and abrasion, where deterioration due to ore impact on concrete is more severe. This was also observed to be the case as shown in the silo inspection report in Section 3.5 on page 74 of this report. This therefore limits the tests' ability to fully simulate the exposure conditions, specifically the deterioration due to impact.

The SANS 1058 tumbling test provides tribological contact types that are comparable to those experienced due to the impact of ore bodies on the silos' concrete walls. As discussed in Section 2.3, the deterioration of the silo concrete wall is a function of a harder material impacting a softer material. This test therefore simulates the above-mentioned contact conditions, as the hardness of the steel balls used is greater than that of concrete.

Lastly, this test allows for replicability as there is adequate test information available, and the apparatus is locally obtainable. However, its applicability to concrete for structural purposes has not been explored. Therefore, an investigation into the suitability of various concrete mix designs for applications requiring abrasion resistance is required.

2.11 The Structural Inspection, Maintenance and Management Guidelines for Plant Structures

The Anglo-American SIMM guideline is a South African mining and mineral processing plant best practice guideline used for early identification and rectification of structural deterioration (Krige, 2006). This guideline offers a complete description of what must be visually investigated during a visual inspection of a plant and provides a schedule of recommendations to ensure there are proper inspections at appropriate intervals.

Following an inspection, the condition of the structure is reported and recorded. The structure's condition is recorded in 6 different categories from 0 to 5, where 5 indicates severe deterioration, rendering the structure with no useful strength. Table C 1 in the appendices shows a typical report matrix for this research during the Silo SIMM inspection. Non-destructive tests such as measurement and penetration tests for cracks and hardness are also used during the inspection to understand the structure's condition better.

The main purpose of the inspection is to do a nominal integrity assessment. This is done to bring forth any major problems, such as significant design errors or severe deterioration of the structure. This can be due to spalling, cracking, corrosion, and mechanical damage (Krige, 2006).

2.12 Literature Review Summary

To develop a comprehensive understanding of the durability of RC silos, a thorough understanding of the abrasive exposure environment is required. In Section 2.1, causes of silo failures are reviewed. This section highlights the gaps in literature, and the oversimplification of the environmental loading when silo design is undertaken. Emphasis is drawn on the fact that materials flow knowledge and the abrasiveness of the stored bulk material is often underestimated; thus, not much emphasis is placed on the abrasion-wear resistance requirements. Furthermore, Section 2.2 gives a brief overview of durability design requirements, where the need to develop performance-based design considerations is briefly outlined.

The difficulty in quantifying and qualifying the aggressiveness of the exposure environment has resulted in a lack of comprehensive literature on the influence of impact and abrasion-wear (exposure environment) on silo concrete in mineral processing plants. Thus, Section 2.3 of this literature review draws focus on the development of a comprehensive understanding of the mechanisms of concrete deterioration due to the stored bulk solids. This section outlines the differences between the tribological contact types and their influences on concrete deterioration.

Section 2.4 delves into the characterisation of the abrasive particles, specifically ores in mineral processing. This section looks at the influence of hardness and size on the severity of abrasion. Additionally, the influence of upstream processes on the resultant tribological contact types are also outlined in this section.

Material flow design in bins and silos is mainly based on the mineral processing requirements. However, the flow of material through the silo influences how the abrasive particles interact with the internal silo wall. Section 2.5 outlines the ways in which stored material interacts with the silo. In this section, impact caused by the discharge of material through the silo, and abrasion wear on concrete as a result of material mass flow is discussed. Additionally, when considering the exposure environment, other material storage alternatives, such as stockpiles, are briefly considered. Even though these storage methods are also used in processing plants, their applicability is limited as they have significant disadvantages.

Significant research has been conducted on the improvement of the abrasion resistance properties of concrete over the years. A comprehensive review of the influence of microstructural characteristics, mix composition, and the various construction practices on the abrasion-wear resistance performance of concrete was reviewed in Section 2.7 and 2.8, respectively. These sections outlined the influence of

various concrete constituents on abrasion-wear resistance, together with the extrinsic factors that influence the overall performance of the concrete.

Section 2.9 and 2.10 reviews the existing industry standards for the design and construction of silos, and further discusses abrasion resistance test methods, applications and limitations. Various tests have been established by researchers. However, the majority of these tests use different tribological contacts to those experienced by silos in mineral processing. Furthermore, these tests are shown to have limitations in reproducing synergistic interactions as experienced by these silos. Additionally, Section 2.10 provides a justification for the use of the SANS tumbling test in this study.

Lastly, Section 2.11 briefly overviews the use of the Anglo-American SIMM guidelines for carrying out structural inspections in mineral processing. This guideline was adopted and used for the inspection of a platinum processing plant silo, as discussed in Section 3.4.2.

CHAPTER 3

3 METHODOLOGY

This chapter outlines the details of the structural inspection and laboratory procedures performed during the study.

3.1 Introduction

The laboratory experiments carried out in this study consist of 18 different mixes cast with a w/c ratio of 0.4, and a permutation of binder types (100% PC, 75/15 PC/FA, 7.5/92.5 PC/CSF), aggregate types (andesite, granite and dolerite), and aggregate sizes (13.2 and 19 mm). More details regarding these mixes are provided in Table 3.3 on page 68.

Even though silos are constructed with a concrete compressive strength of ±40 MPa (Ferreira, 2021), higher compressive strengths were adopted in this study to capitalize on the superior abrasion resistance performance related to higher compressive strength concrete as outlined in sub-Section 2.7.4. For this reason, the above-mentioned mixes were all cast with a characteristic compressive strength of 80 MPa.

The concrete compressive strength, SANS abrasion, setting time, and slump tests were conducted to evaluate the performance of the various mixes with respect to their applicability in the construction of a bulk storage silo, using the slip-form construction method. Furthermore, each of the mixes were assessed to determine their appropriateness for the intended structural application, i.e., their abrasion resistance performance, and concrete compressive strength gain requirements.

Lastly, to provide a benchmark of the real-life performance of the mixes, three additional norite mixes selected for the construction of a RoM silo at a platinum processing plant were cast with a characteristic compressive strength of 40 MPa as indicated by the structural designer. Comprehensive details regarding the mix designs are provided in Appendix A. These mixes were not used to analyse the influence of concrete constituents on the abrasion resistance performance of the concrete, as they are only used as a benchmark for the industry standards adopted in this case.

The main aim of this study was to conduct a laboratory investigation of the influence that different concrete constituents have on the strength and abrasion resistance properties of concrete. This approach intends to deliver a comprehensive understanding of performance-based design considerations for abrasion-resistant concrete, tailored for silos used for material storage within the mineral processing industry. Figure 3.1 represents the overall methodology adopted in this study.

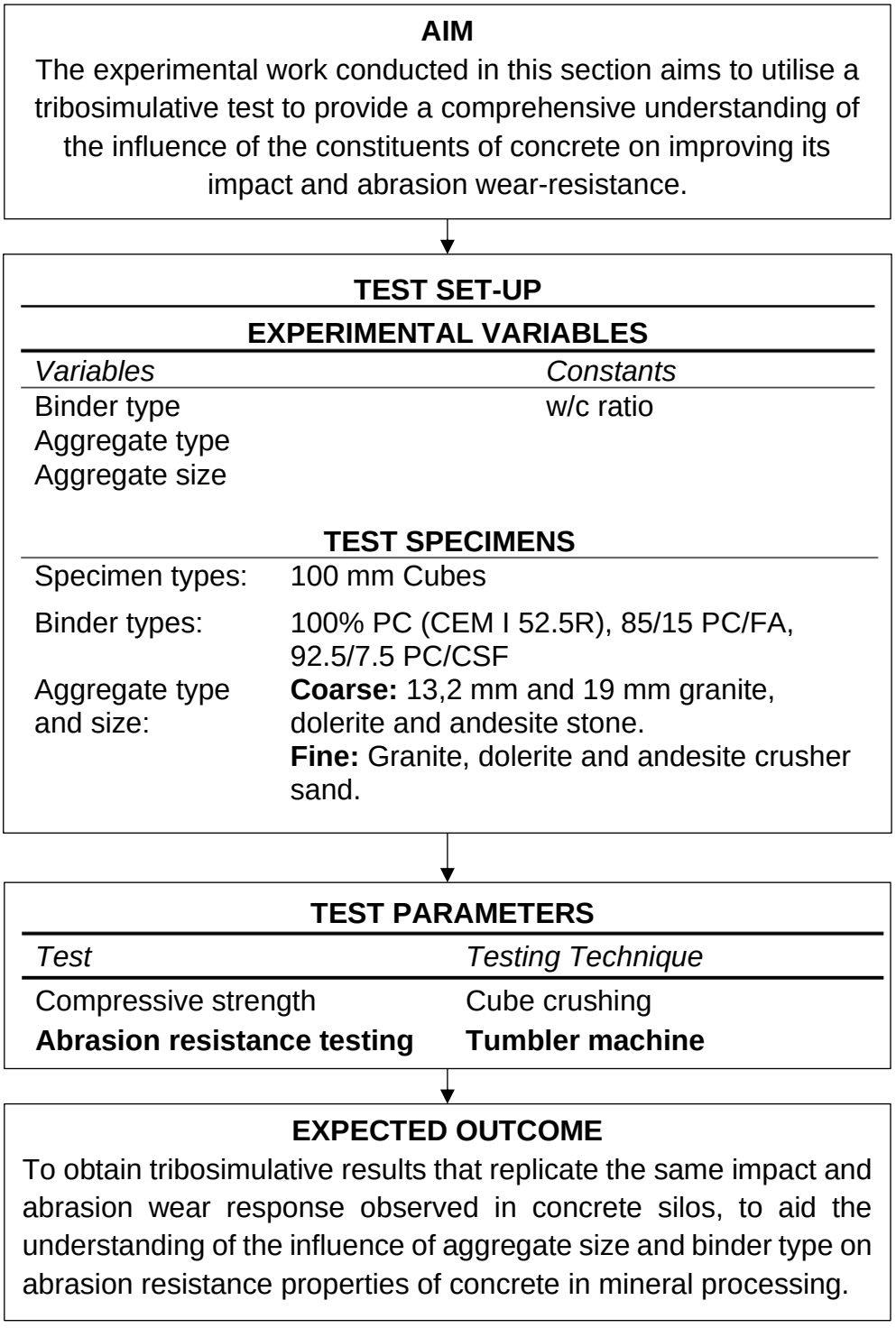


Figure 3.1: Experimental Methodology flow chart.

The second phase of the study was to conduct a structural inspection according to the Anglo-American standard for performing structural inspections to assess the deterioration of concrete silos. This was conducted to evaluate the causes, mechanisms, and the extent to which the deterioration occurs. The findings were then used in conjunction with the abrasion test, to inform the performance-based design considerations proposed in Section 5.1 on page 104.

3.1.1 Experiment set-up

As per the findings of a study conducted by (Scott and Safiuddin, 2015) highlighted in Section 2.4, to determine the abrasion resistance of concrete, it is crucial to consider the constituents of concrete that have the most significant impact on abrasion resistance.

The three main factors considered in this research are, the influence of aggregate size, concrete compressive strength, and binder type on the abrasion resistance of concrete. The concrete properties mentioned above were varied to assess the preferred binder combination, and the most dominant synergic influences on abrasion resistance obtained from the variations.

The aggregate type was also varied as andesite and dolerite aggregates have already been established in sub-Section 2.7.1 to be the hardest and most abrasion resistant when compared to the other aggregate types. The performance of these aggregate types was compared against granite aggregates, as granite aggregates have also been mentioned to perform best with respect to abrasion resistance (Laplante, et al., 1991). This, however, contradicts the information obtained from Table 2.2, as these had the least desirable aggregate properties. This is discussed in detail below.

As per the ACI 313R-97 (1997) recommendations, together with consensus amongst industry experts, to mitigate risks associated with silo slip form construction, it is recommended to adhere to specific fresh and hardened concrete properties. These are as follows:

1. Workability should range between 100 to 140 mm slump.
2. Initial set of the concrete should be within +/- 1 hour.
3. 28-day compressive strength ≥ 40MPa.
4. Relatively high rate of compressive strength gain.

As mentioned above, the mixes in Table 3.3 on page 68 were cast with higher concrete compressive strengths. The justification for using higher concrete compressive strengths has been provided in detail in Section 3.2 below. Furthermore, the suitability of these samples for silo slipform construction (workability and setting times), compressive strength, and abrasion resistance performance was then compared against the recommendations by the ACI and industry experts mentioned above. This was conducted to gain better insights on the improvement of the concrete's performance, without affecting the salient construction requirements as outlined in Section 2.9.2.

3.2 Concrete compressive strengths used in this study

Section 2.7 of the literature review emphasizes that the increase in concrete compressive strength, together with the use of harder aggregates, results in a notable improvement in the overall hardness of concrete. This increase in concrete hardness is beneficial to the improvement of the abrasion resistance of the concrete, as discussed

in Section 2.3.1. The ability of a material to abrade a surface depends on the comparison between the surface material hardness (the concrete) and the abrasive hardness of the ore material, represented by the hardened steel balls in this case (see Section 3.4.6 for more information on the hardened steel balls). Increasing the material hardness will result in the reduction in abrasion- wear, thus, increasing the concrete's compressive strength should result in better abrasion resistance performance.

In this context, the concrete compressive strengths used in the experiment, which exceed 80 MPa, significantly surpass the minimum standards established for structural design, where a compressive strength of 40 MPa is specified as outlined by the ACI recommendations and the industry standards discussed above. This increase in concrete compressive strength is expected to improve the overall abrasion resistance performance of the concrete.

3.3 Constituent materials

3.3.1 Binder Type

Various studies discussed in Section 2.4 have revealed that supplementary cementitious materials such as CSF and FA can reduce the abrasion loss in concrete, thus improving its abrasion resistance. However, the extender content should not be greater than 30% (Heerden, 2021).

The binders used for this study consist of PC (CEM I 52,5R), FA, and CSF. These binders are selected as they have the highest influence on improving the abrasion resistance of concrete (Benoy, 2021). The cement chosen in this study complies with SANS: 50197-1 and 2 requirements. Additionally, the binders used in this study also comply with the SANS mentioned above, including SANS: 55167-2, SANS: 50450-1, SANS: 50450-2, SANS: 53263-1, and SANS: 53263-2.

As mentioned above, abrasion resistance is a function of concrete strength, while constructability is a function of the rate of strength gain and other fresh concrete properties. CEM I 52.5R was selected as the preferred binder due to its compressive strength gain rate. It was also selected as it is compositionally similar to PC and its minor constituent content not exceeding 5%. CEM I 52.5R is more suitable where faster demolding times are required, as well as higher slipform sliding rates, which makes it more ideal for silo sliding operations during construction (AfriSam, 2021).

Among the different concrete constituent materials, supplementary cementitious materials have been highlighted to also influence the abrasion resistance of concrete. Additional economic and sustainability benefits can also be derived from using blended cements when compared to 100% PC (Heerden, 2021). For this reason, the binders used in the other concrete mixes were substituted by volume as follows: 85/15 PC/FA and 92.5/7.5 PC/CSF, respectively.

Research has shown that the substitutions mentioned above provide the best performance concerning abrasion resistance (Laplante, et al., 1991:Naik, et al., 1995). The typical chemical composition of the binders is shown in Table 3.1.

Table 3.1: Chemical composition of binders (PPC, 2019) (AfriSam, 2021).

Oxide	% Composition by mass		
	PC	FA	CSF
CaO	63,0 - 69,0	4,0 - 7,0	0,3 - 0,6
SiO_2	19,0 - 24,0	48,0 - 55,0	85-97
Al_2O_3	4,0 - 7,0	28,0 - 34,0	1,0-1,5
Fe_2O_3	1,0 - 6,0	2,0 - 4,0	1,0-1,6
SO_3	-	-	-
MgO	0,5 - 3,6	1,0 - 2,0	0,6 - 0,8
H_2O	-	-	1,2 - 2,0
K_2O	-	-	1,2 - 0,8
$Na_2O + 0,658\ K_2O$	-	1 - 2	-

The replacement percentage of 15 % FA is based on the study shown in Figure 2.13 of the literature review. Where the replacement of up to 15 % FA was seen to slightly reduce the abrasion wear depth at w/c ratios lower than 0.45 (Yen, et al., 2007). Furthermore, this selection is supported by another study conducted on the replacement of PC with FA ranging from 15 % to 70 %, where a 15 – 30 % replacement was considered to have a negligible influence on abrasion resistance, and replacement > 30 % negatively impacting the abrasion resistance performance (Naik, et al., 1995). Thus, when the two studies were contrasted, the 15 % FA replacement can be seen to be the most optimum.

The replacement of 7.5 CSF is based on the study on the influence of SF on abrasion resistance outlined in Section 2.7.2, where a comparison between a mix with 100 % PC, and a mix with a 7 % SF replacement was drawn. It was obtained that the mix with the 7 % SF replacement had an 86 % increase in abrasion resistance when compared to the control mix (100% PC) (Ismaeil, et al., 2021).

3.3.2 Binder Content

To obtain high strength at a low w/c ratio, a high binder content is required; this binder content is typically greater than 400 kg/m^3 (Mehta and Monteiro, 2006). The benefits of reducing the w/c ratio are discussed in Section 3.3.3. Thus, the binder content used in this study was greater than 400 kg/m^3 and in compliance with the guidelines set forth by SANS.

3.3.3 Water/cement (w/c) ratio

The SANS 10100-2 (2014) code requires that the w/c ratio for conventional concrete lie between 0.45 and 0.55 based on exposure conditions. In conventional concrete, the interfacial transition zone (ITZ) between the aggregate and cement matrix is often the weakest link in terms of compressive strength. Thus, the reduction in the w/c ratio below 0.4 and the use of cement extenders such as FA and CSF tend to strengthen the ITZ (Beushausen and Dehn, 2009).

The research outlined in Section 2.7.3 also shows that as the water/cement ratio decreases, the abrasion resistance tends to increase. It is important to note that the optimal water/cement ratio recommended by SANS may not suffice in specific scenarios. As such, it becomes necessary to explore the possibility of decreasing the said ratio even further in order to achieve the desired durability performance.

For this study, a w/c ratio of 0.4 was selected for the various mixes respectively. A w/c ratio of 0.4 has been widely acknowledged to be typical for high-strength concrete (Beushausen and Dehn, 2021), which is expected to also have a positive effect on abrasion resistance. This is because lower water-cement (w/c) ratios lead to reduced porosity, which in turn promotes the formation of stronger bonds between the cement paste and the aggregates at the interfacial transition zone (ITZ). As a result, the formation of stronger bonds leads to the enhancement of the desirable mechanical properties, improving abrasion resistance.

3.3.4 Water

The water used shall be free from any impurities that might impair the strength or durability of the concrete, as established in SANS 51008: 2006. This was achieved by using potable water for concrete mixing.

3.3.5 Aggregates

To ensure optimal performance and availability of the aggregates, it is imperative that aggregates conform to the requirements outlined in SANS 1083. By adhering to these standards, the likelihood of adverse outcomes such as excessive shrinkage, creep, and alkali-aggregate reaction is greatly minimised. It is important to note that aggregates which comply with this code have undergone rigorous testing to ensure their resilience to these adverse effects. The three aggregates used in this study are the Eikenhof andesite, Juskei (Midrand) granite and Rooikraal dolerite. The selection justification and criteria will be discussed in detail below. More information on the aggregate properties can be obtained in Appendix D.

The aggregate densities were measured using an Anton Paar Ultrapyc 300 gas pycnometer, which uses helium gas to measure the true density of solid materials. The resulting data is presented in Appendix D. The results obtained were utilized to investigate the correlation between aggregate density and the abrasion resistance of concrete for the various aggregate types.

Coarse aggregates

The superiority of granite aggregates when compared to other aggregate types regarding abrasion resistance is well recognized and documented by researchers (Laplante, et al., 1991). These aggregates have also undergone extensive research, and their use is permissible as per SANS 1083. As established in Section 2.4 in the literature review, when the binder type is kept constant, the aggregate size and type are the most contributing factors to the reduction in abrasive loss. In this case, granite coarse aggregates have been selected as they are the best-performing aggregates regarding aggregate abrasion resistance compared to other aggregates (Laplante, et al., 1991). These aggregates are compared against the performance of dolerite and andesite aggregates.

Aggregate crushing values obtained from quarries in Gauteng show that granite aggregates have a higher ACV % when compared to other aggregate types. The Aggregate Crushing Value (ACV) is described as a test that provides a relative measure of the resistance of an aggregate to crushing under a gradually applied compressive load (IS:2386- Part 4, 1963). It is also used to give a measure of the adequacy of the abrasion resistance of an aggregate.

Lower ACV% values should be preferred as a fairly strong correlation between ACV and aggregate compressive strengths has been obtained in literature (Weinert, 1998). Furthermore, the aggregate compressive strength has been established to improve the overall abrasion resistance of concrete. Therefore, the aggregates mentioned in the study above need to be evaluated. Table 3.2 below shows the aggregate crushing values from a study on AfriSam quarries located in the Johannesburg region. The aggregate properties in bold in Table 3.2 refer to the aggregates used in this study.

Table 3.2: Holcim product and properties of Gauteng aggregates (Holcim, 2004)

Product	**Plant rock type**							
	Eikenhof andesite	Ferro (Pretoria) Meta quartzite	**Juskei (Midrand) granite**	Olifantsfontein dolomite	Roodekrans granite	**Rooikraal dolerite**	Sub-Nigel (Nigel) Reef quartzite	Zeekoewater (Witbank) felsite
ACV %	**5,9**	13,1	**21,7**	12,8	17,7	**12**	12,7	13,3
LA abrasion%	**8**	25	**33**	16	-	**8**	-	16

The literature presented in Section 2.7.1 indicates that the preferred aggregates with respect to abrasion resistance are granite and quartzite. However, the granite and quartzite (specifically, granite sourced from Midrand and Roodekrans, as well as quartzite) exhibit Aggregate Crushing Value (ACV) percentages of 21.7%, 17.7%, and

12.7%, respectively. In contrast, dolerite and andesite demonstrate significantly lower ACV percentages of 8.9% and 5.9%.

This suggests that dolerite and andesite possess superior resistance to crushing and fracturing compared to the aforementioned aggregates. This leads to a discrepancy in alignment with the conclusions reached in Section 2.7.1 and results in conflicting views on the selection criteria of aggregates for abrasion resistance. This research aims to use the granite aggregate to benchmark results obtained from literature against the performance of the dolerite and andesite aggregates.

The Los Angeles Abrasion test is also used to determine the hardness properties of the aggregates. The LA abrasion test is highly correlated to ACV%, thus should both produce similar selection criteria (Ajagbe, et al., 2015). The principle of the test is to find the abrasion wear due to relative rubbing action between the aggregate and the steel balls used as an abrasive charge (Monyakeng, 2022). Aggregates with a lower LA abrasion percentage value tend to exhibit better abrasion resistance than those with a higher value. For this reason, aggregates with a lower LA abrasion % value were selected in this study. The abrasion resistance properties of these aggregates contribute to the overall performance of the concrete.

The aggregate size also plays a significant influence on the overall abrasion resistance of the concrete; therefore, 13,2 mm and 19 mm of dolerite, granite and andesite coarse aggregate were selected for this study. (Liu, et al., 2005) conducted a study where the increase in aggregate size was shown to contribute significantly to the overall increase in the abrasion resistance of the concrete. This was attributed to the decrease in the surface area of the exposed mortar due to the increase in the exposed aggregate surface area. It is also important to note that more energy is required to dislodge larger aggregates when compared to smaller coarse aggregates (Liu, et al., 2005). Figure 3.2 shows a picture of the three aggregate types used in the study. The grading results are also shown in Appendix D.



Figure 3.2: 19 mm andesites, dolerite and granite aggregates used in the study.

Fine aggregate

Unwashed dolerite, granite and andesite aggregate from the same parent rock as the coarse aggregates were used for this study. The purpose of using a coarse and fine aggregate from the same parent rock is to obtain the same inherent characteristics and properties as the parent rock from which the sand will be produced (Grieve, 2009).

Crusher sand produces concrete with a water content requirement lower than that of concrete made with pit sand (Grieve, 2009). This allows for a further reduction in the w/c ratio, ultimately improving the abrasion resistance of concrete (Scott and Safiuddin, 2015). The reduction in water content could also result in the reduction in cement content required, subsequently reducing the overall mortar volume. The reduction in mortar volume will result in the reduction of the surface area of mortar exposed to abrasion, resulting in a higher coarse aggregate surface area exposed to abrasion, thus improving the overall abrasion resistance of the concrete mix as established in Section 2.7.

Admixtures

A Sika Viscocrete 3088 superplasticizer was incorporated into the design to improve the workability of the mixes. The superplasticizer is made from an aqueos solution of modified polycarboxylate.

3.4 Laboratory tests and procedures

The flow chart presented in Figure 3.3 outlines the mix design procedure followed.

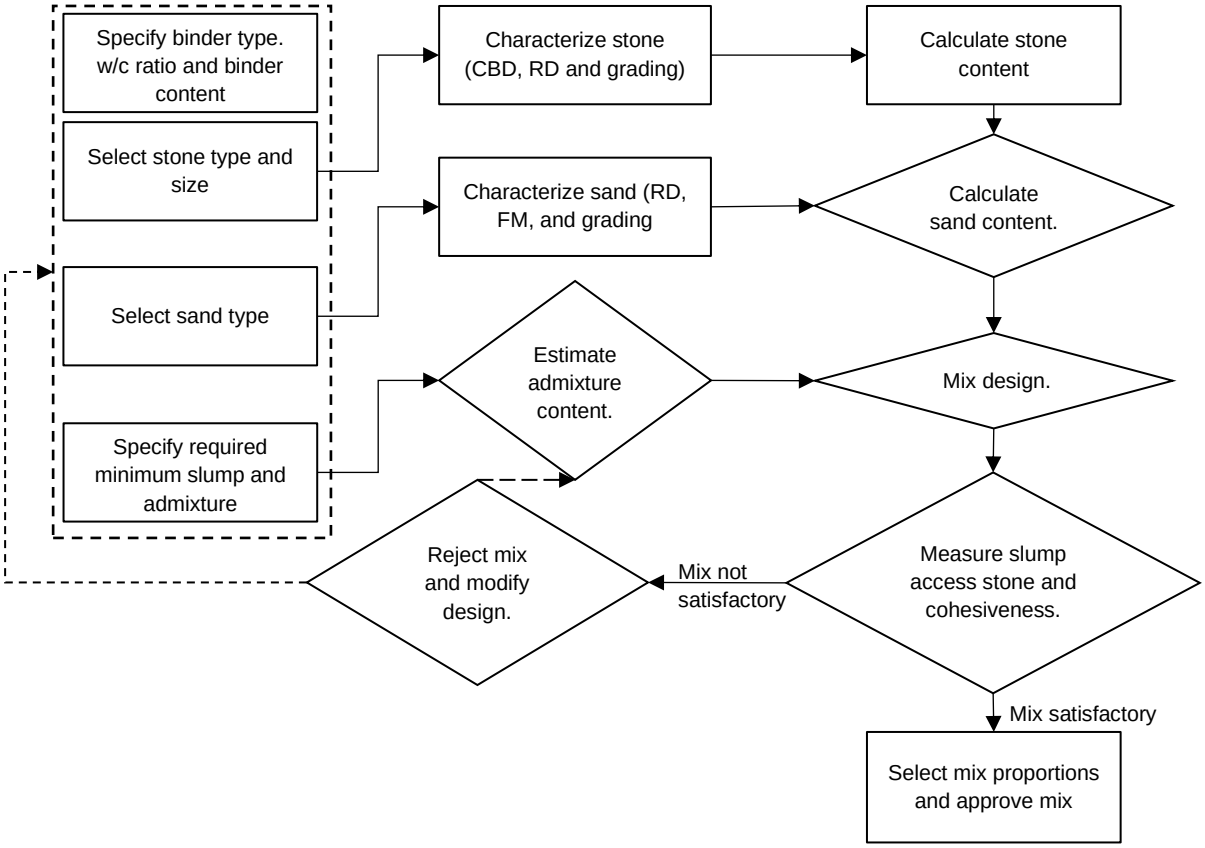


Figure 3.3: Concrete mix design flow adaptation (Addis and Goodman, 2009).

The Concrete Institute of South Africa's volumetric mix design method was adopted in the study (Concrete Institute, 2013). The fresh concrete was prepared using a pan mixer and compacted with a vibrating table. The dry ingredients were combined and mixed thoroughly, and then the water was gradually added to the mix. The mixture was then blended until a uniform consistency free of lumps was achieved.

3.4.1 Concrete mix Proportions

Table 3.3 on page 68 shows the mix proportions used in this research. This approach is based on the requirement that the absolute volumes should equate to the total volume of the concrete.

3.4.2 Test specimens

i. Number of specimens per test

The compressive strength test required three 100 mm cube specimens per mix, equating to a total of 162 cubes. Furthermore, the abrasion resistance test also required three 100 mm cube tests per mix, equating to 162 tests for cubes. The total number of cubes cast for both compression and abrasion testing equates to 324 cubes, a breakdown of the above mentioned is shown in Table 3.4 and Table 3.5 on page 69.

ii. Curing of Specimens

Curing is defined as providing adequate moisture, temperature, and time to allow concrete to achieve the desired properties for its intended use (Owens, 2013). Immediately after casting, the specimens were covered with polyethylene sheets for a 24-hour period at room temperature to prevent moisture loss, then placed into a water bath at 23 ± 2° C for curing. These cubes were cured for 3, 7, 14 and 28 days to obtain compressive strength and abrasion resistance testing respectively.

It is acknowledged that additional benefits of SCMs can be viewed later than 28 days, and that the 28-day compressive strength and abrasion resistance performance of the mixes with SCMs can be slightly inferior to the ones with 100% PC. However, for concrete mixes with small SCM replacement quantities (< 20 %) the 28-day results provide a sufficient and reliable indication of performance (Yaseen, et al., 2024), as relatively small increase in compressive strength is obtained between the 28- and 56-days results (Yaseen, et al., 2024).

iii. Number of specimens per aggregate type and size

Table 3.5 shows a breakdown of the number of specimens per aggregate type. The total number of cubes per aggregate size and type is 54, while the total number for the entire experiment is equal to the total number of cubes mentioned above, 324.

Table 3.3: Summary of concrete mix proportions cast with a 0.4 w/c ratio

Binder Type	Aggregate type	Aggregate size	Mix identifier	Water (kg/m^3)	PC (kg/m^3)	FA (kg/m^3)	CSF (kg/m^3)	Stone (kg/m^3)	Sand (kg/m^3)	Superplasticizer (%)	Approx. ratio
PC	Andesite	13,2mm	APC13	195	488	0	0	975	850	0.65	1:3:9
		19mm	APC19	195	488	0	0	1125	770	0.8	1:3:10
	Dolerite	13,2mm	DPC13	195	488	0	0	875	1065	0.65	1:3:10
		19mm	DPC19	195	488	0	0	975	920	0.65	1:3:10
	Granite	13,2mm	GPC13	195	488	0	0	975	750	0.65	1:3:9
		19mm	GPC19	195	488	0	0	1075	605	0.65	1:3:9
PC/FA 85/15	Andesite	13,2mm	AFA13	195	414	73	0	975	825	0.65	1:3:9
		19mm	AFA19	185	393	69	0	1125	745	0.8	1:3:10
	Dolerite	13,2mm	DFA13	185	393	69	0	825	1090	0.65	1:3:10
		19mm	DFA19	185	393	69	0	975	945	0.65	1:3:10
	Granite	13,2mm	GFA13	185	393	69	0	975	770	0.65	1:3:9
		19mm	GFA19	185	393	69	0	1075	630	0.65	1:3:9
PC/CSF 92,5/7,5	Andesite	13,2mm	ASF13	195	450	0	37	975	840	0.65	1:3:9
		19mm	ASF19	185	427	0	35	1125	760	0.8	1:3:10
	Dolerite	13,2mm	DSF13	185	427	0	35	825	1105	0.65	1:3:10
		19mm	DSF19	185	427	0	35	975	960	0.65	1:3:10
	Granite	13,2mm	GSF13	185	427	0	35	925	785	0.65	1:3:9
		19mm	GSF19	185	427	0	35	1075	640	0.65	1:3:9

Table 3.4: Breakdown of cubes per test type

Test type	PC						PC/FA 85/15						PC/CSF 92.5/7.5					
	APC13	APC19	DPC13	DPC19	GPC13	GPC19	AFA13	AFA19	DFA13	DFA19	GFA13	GFA19	ASF13	ASF19	DSF13	DSF19	GSF13	GSF19
Compressive Strength	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9
Abrasion Test	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9
Total per mix type	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18
Total per binder type	**108**						**108**						**108**					

Table 3.5 Number of cubes per aggregate size, type, and binder type.

Test type	APC13	APC19	DPC13	DPC19	GPC13	GPC19	AFA13	AFA19	DFA13	DFA19	GFA13	GFA19	ASF13	ASF19	DSF13	DSF19	GSF13	GSF19
Andesite	18	18					18	18					18	18				
Dolerite			18	18					18	18					18	18		
Granite					18	18					18	18					18	18
Total	**324**																	

3.4.3 Workability

The workability of the concrete is influenced by factors such as water content, binder content, aggregate properties, cement types and the presence of admixtures (Kellerman and Crosswell, 2009). A reduced water content results in poor workability, and since a reduced water content is desirable for abrasion-resistant concrete, workability is a significant consideration. Concrete with poor workability can affect the handling, placing and compaction, increasing the possibility of poor production quality. Workability also indicates the stiffness of the mix and its ability to maintain shape under its self-weight. This is a very important consideration for slip-form construction.

This study is based on the variation of w/c ratio, aggregate size, and binder type, which all have a significant influence on workability. Larger aggregates tend to reduce the overall workability of a concrete mix, while binder types such as FA and CSF less than 5 % by mass tend to improve the overall workability. A reduction in the w/c ratio may also negatively influence workability without introducing a plasticizer. This, therefore, requires that a slump test be conducted on the specimens and the results recorded to ensure that the concrete mix is workable enough to be handled, placed, and compacted for silo sliding. This was also used to assess the effect of varying the aggregate size and binder type on the concrete mix's workability.

With respect to the slump records, no significant differences were obtained. All the 18 mixes had a slump range of 140 to 165 mm. A breakdown of all the slumps obtained is shown in Table B 1 in the appendices. Even though the ACI recommends that slumps should range from 100 to 140mm, the slump records obtained from the 18 mixes were deemed to be acceptable, as a slump range between 120 to 200mm is deemed to be acceptable for vertical slipform sliding (Hasselqvist and Gegerfelt, 2021). The slump requirements vary based on the ambient site conditions; thus, the slump requirement could easily be varied by varying the superplasticizer content to suit.

3.4.4 Initial Set

The initial and final setting times were established as per SANS 50197-1, which requires the use of a Vicat apparatus and makes a mechanical determination of the initial setting time for a given cement paste (Giaccio, et al., 2019). Figure 3.4 shows the Vicat apparatus used in this study. The information obtained from this study is used to ensure proper handling, placing and finishing of concrete.

After the concrete has been mixed and placed, it remains plastic and workable for some time, then gradually, the concrete starts to set, changing from a plastic material to a weak solid (Kellerman and Crosswell, 2009). This transition period from the liquid phase to the solid phase is referred to as the initial set, and the time taken is referred to as the initial setting time. The initial setting time is essential to silo sliding construction as cold joints form when the elapsed time between placing two

consecutive layers of concrete exceeds the initial setting time of fresh concrete (Piyasena, et al., 2023).

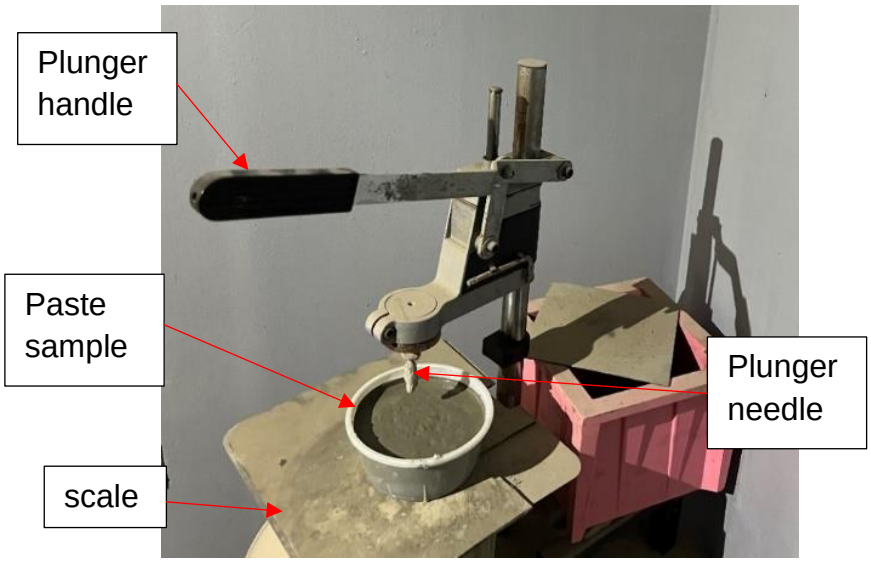


Figure 3.4: Vicat Setting time test apparatus.

For silo sliding, the newly cast concrete that is exposed at the base of the mould will typically be four to five hours old, during which the initial setting process has commenced. At this stage, the concrete maintains its shape independently of the mould structure (Middel and Burwitz, 2021). It is important for the pace of construction to be synchronized with the setting rate of the concrete, a phenomenon that is influenced by various factors, including ambient temperature (Middel and Burwitz, 2021). Should the concrete undergo premature stiffening while still confined within the forms, there exists the potential for horizontal uplift cracks to develop due to the formwork movement, as shown in Figure 3.8 on page 76. This occurrence is attributed to the frictional forces between the concrete and the mould surfaces. Figure 3.5 shows the various setting times obtained in the experiment.

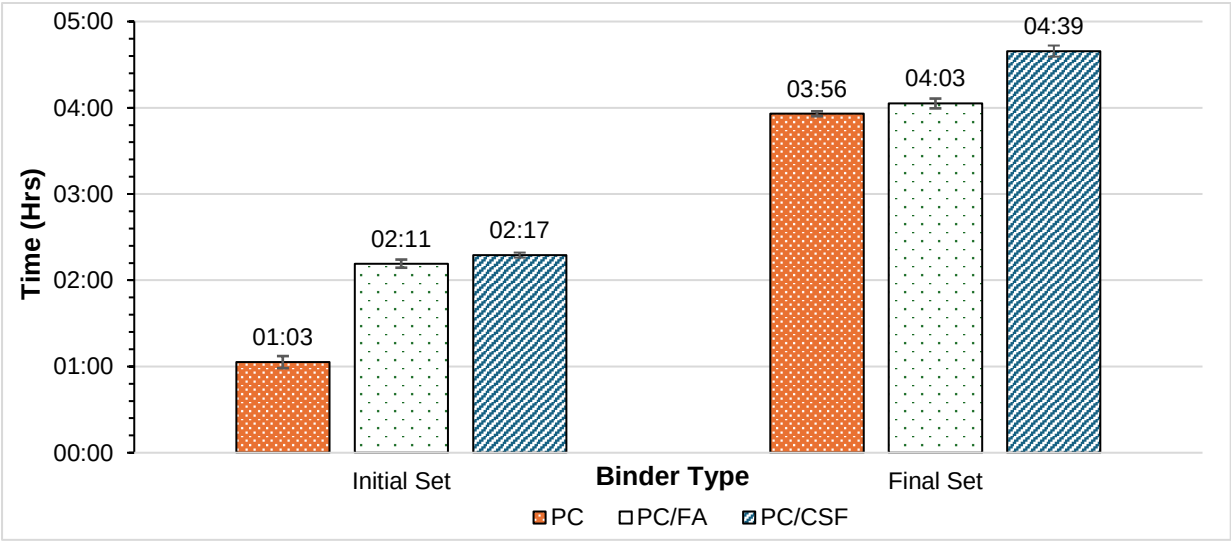


Figure 3.5: Average setting times for the various binder types.

It is evident from Figure 3.5 that the reduction in w/c ratios, and the use of PC significantly reduced both initial and final setting times obtained in the experiment. The initial setting times obtained fall within the ACI recommendations of +/- 1 hour, as outlined above. However, care should be taken as setting times should be based on the site-specific requirements. This is to allow for transporting, placing and compaction of the concrete. As established in Section 2.8.1, placing, compaction and consolidation have a significant influence of the overall abrasion resistance of the concrete. The use of retarders could be introduced into the mix to make it more suitable for sliding applications, where required.

3.4.5 Concrete compressive strength testing

The concrete compressive strength tests were conducted according to SANS 5863: 2006. These tests consisted of three test specimens (3 x 100 mm test cubes). Specimens were crushed at 3, 7 and 28 days, and a concrete cube strength was determined for each test. The average of the three test determinations was calculated as one test result.

As per SANS, all tests were performed using an automated hydraulic compression machine with a 2000 kN capacity, at a loading rate of 3 kN per second up to failure. The cubes were placed at the center of the machine to ensure uniform load is applied to the specimen, and the load was applied to the faces perpendicular to the direction of casting. A detailed summary of the compression results is found in Appendix E.

3.4.6 Abrasion Resistance Testing

The abrasion test was conducted according to a SANS 1058: 2012. The test requirements, including general acceptance criteria, are outlined in the above code. The acceptance criteria is based on the maximum mass loss (m_L) allowable.

Where:

$$m_L = m_{before} - m_{after} \quad \text{Equation 6}$$

m_{before} = mass of sample before abrasion test (oven dry sample) measured in grams (g)

m_{after} – mass of sample after abrasion test measured in grams (g).

According to the code, this result should not be greater than 15 g for pavements. The abrasion resistance tests were conducted at 7, 14, and 28 days to analyse the influence of the above-mentioned concrete constituents on the results over time. Figure 3.6 below shows the Tumbling test machine used in this study. A detailed summary of the compression and abrasion test results is shown in Appendix E.

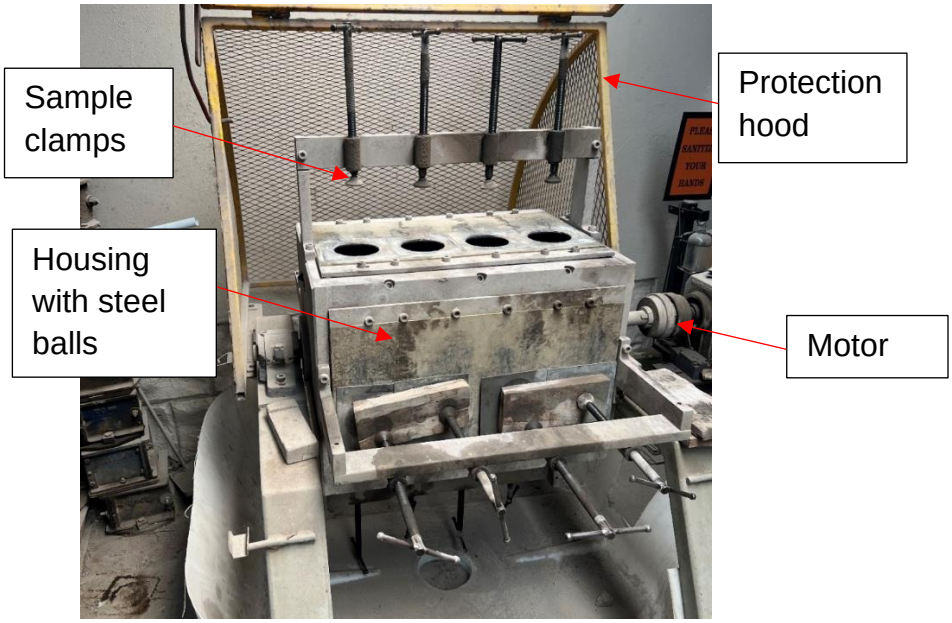


Figure 3.6 Tumbling abrasion test machine.

The abrasion resistance tests were carried out to give an indication of the most suitable concrete mix from the above concrete constituents to wear from impact and abrasion. The purpose of this test is to quantify the abrasion loss (in grams) on each of the concrete samples from the 18 different concrete mixes. These tests can, therefore, be used to assess the potential abrasion resistance performance of as-built concrete structures in future. Depending on the environmental exposure of the concrete, the test results can, in future, be used to assess the durability of the concrete and determine the concrete's potential lifespan referenced back to the abrasive loss during the time of testing.

Abrasion resistance test apparatus:

1. **Drying Oven:** must be well-ventilated with a cubic capacity at least three times greater than the cumulative volume of the specimens being dried. Must also be capable of maintaining a consistent temperature of 110 °C ± 8 °C.
2. **Analytical Scale:** must possess adequate capacity and precision, with an accuracy tolerance of ± 0.1 g.
3. **Tumbler Machine:** Equipped with a rectangular steel container. Incorporates angle plates positioned at each corner of the interior to effectively deflect the ball bearings. The driving mechanism must facilitate rotation at a speed of 60 r/min ± 1 r/min. See Figure 3.6.
4. **Steel Ball Bearings:** A total of 600 hardened steel ball bearings required. Each ball bearing should have a diameter of 12.9 mm ± 0.1 mm, a mass of 16.2 g ± 0.2 g and a density of +/- 13 800kg/m^3.

More information about the tumbling test can be obtained from SANS 1058: 2012.

3.5 Silo SIMM Inspection

3.5.1 Introduction to SIMM inspection

This sub-Section looks at the SIMM inspection carried out on an existing silo discussed in Section 2.11, outlining the impact of abrasion on concrete used in mineral processing. The findings are outlined below. The Anglo-American SIMM guideline is a South African mining and mineral processing plant best practice guideline used for early identification and rectification of structural deterioration (Krige, 2006). The main objective of this inspection was to evaluate the current condition of the structure and deterioration mechanisms. This together with the abrasion test is used to inform the performance-based design considerations proposed in this study.

The structural assessment is carried out by assigning a deterioration rating on a scale of 0 to 5, where 0 indicates that the structure is in excellent condition and 5 indicates severe deterioration, rendering the structure with no useful strength. Appendix C shows the report matrix for the Silo SIMM inspection.

The fundamental aim of the visual inspection is to carry out a nominal integrity assessment. The primary objective of this assessment is to bring forth any major problems, such as significant design errors or severe deterioration of the structure related to impact and abrasive action. The secondary objective of the inspection was to explore the effects different ore sizes have on the internal face of the concrete silo. The silo stair tower was used to provide safe access to perform a close-up inspection of the internal and external walls. Images were taken as evidence of wear on the silo wall due to impact and abrasion.

The mine manager also provided a history of all modifications done on the silo during the visual inspection. This was in the form of a record of changes or modifications of the structure or the equipment on the structure and/or approved general arrangement drawings confirming the adequacy of the structure where modifications have been made.

3.5.2 Conditional categories

All the findings from this research are described using the deterioration conditions listed in Appendix C. Findings related to structural deterioration were recorded, and no comments were made on structural elements found to be in good condition.

3.5.3 Visual structural inspection report

A general written report is provided, in which the condition of the inspected structure was recorded photographically and descriptively. These photographs are clearly labelled to identify typical members and show their conditions. This report indicates the conditional categories mentioned above and highlight portions of the structure where deterioration is assessed as 3 or 5.

3.5.4 Salient crusher plant and silo information

A SIMM inspection of the RoM silo at a platinum crusher plant was carried out on the 9th of November 2023 During a short maintenance shutdown. The inspection was carried out in general compliance with the Anglo-American best practice guidelines AA-BPG-S03.

The RoM silo was commissioned in 2006 and has a live material capacity of 5000 tons. At the time of inspection, the silo had a total throughput of approximately 34 926 073 tons of ore with a maximum feed material size of 420 mm. The RoM silo was constructed in 2005 and commissioned in 2006. The wall is 300 mm thick with an internal diameter of 15 000 mm. The overall height of the concrete silo is 31 340 mm above surface bed level. The depth of ore containment is 22 260 mm with two ore discharge openings in the 1 000 mm thick suspended slab.

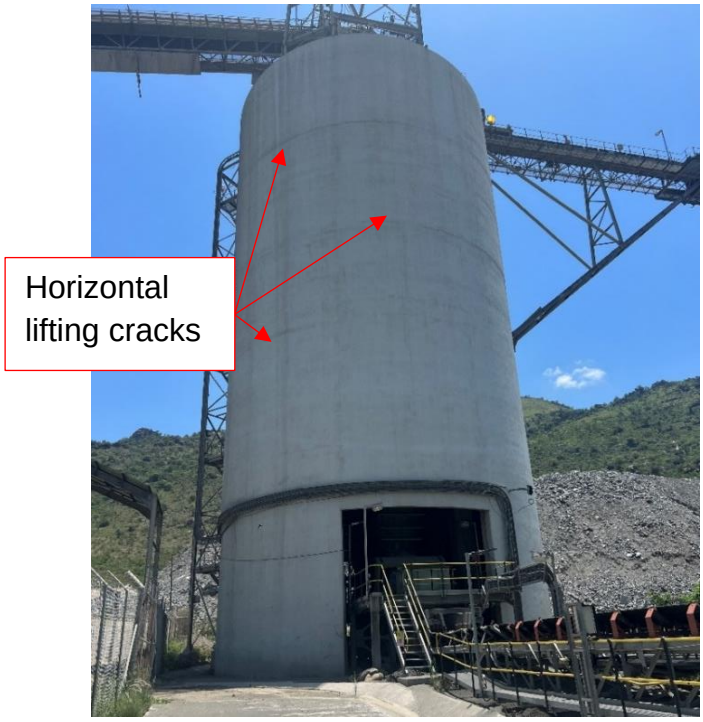


Figure 3.7: Picture showing the eastern external face TRP UG2 RoM silo.

The wall was constructed of 40 MPa concrete with a 90 mm cover-crete (40 mm cover + 50 mm sacrificial cover) to the internal wall reinforcement over the full material containment height. A sacrificial shotcrete liner was also installed over and above the 90 mm cover on the internal face of the silo wall, extending to the top of the wall. However, no details of the shotcrete were shown on the engineering drawings, as the shotcrete liner was installed after commissioning. A steel staircase with intermediate landings provides access to the roof level. A picture of the silo elevation is shown in Figure 3.7.

3.5.5 Conditional report – general history

The silo was previously repaired in 2007 when horizontal cracks were identified on the internal and external surfaces of the silo. An investigation conducted in the same year concluded that the cracks were construction-related and of a non-structural nature. The horizontal constructional movement cracks typically form when the concrete sticks to the slipform during a lifting event, and from friction forces that develop between the shutter and the setting concrete lifting (Middel and Burwitz, 2021). These horizontal cracks the develop due to the formation of cold joints, which are also a result of delay in placement to allow for bonding of the newly placed concrete with the concrete from the previous slide event (Piyasena, et al., 2023). These construction stoppages occur during rebar fixing, placing and compaction of new concrete. The picture in Figure 3.8 shows a close-up picture of the cracks mentioned above.

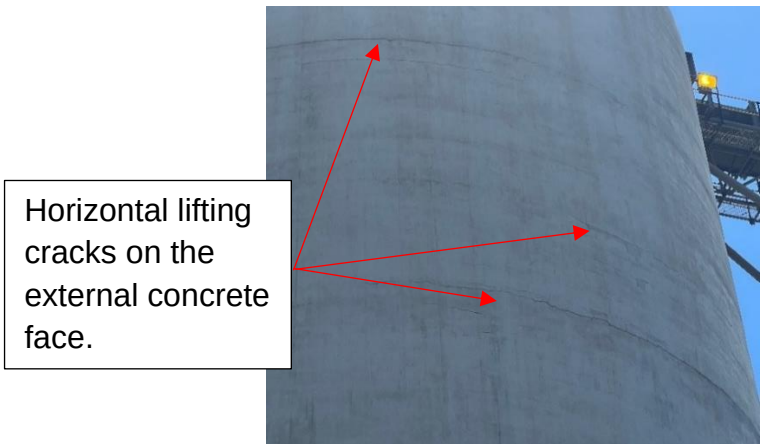
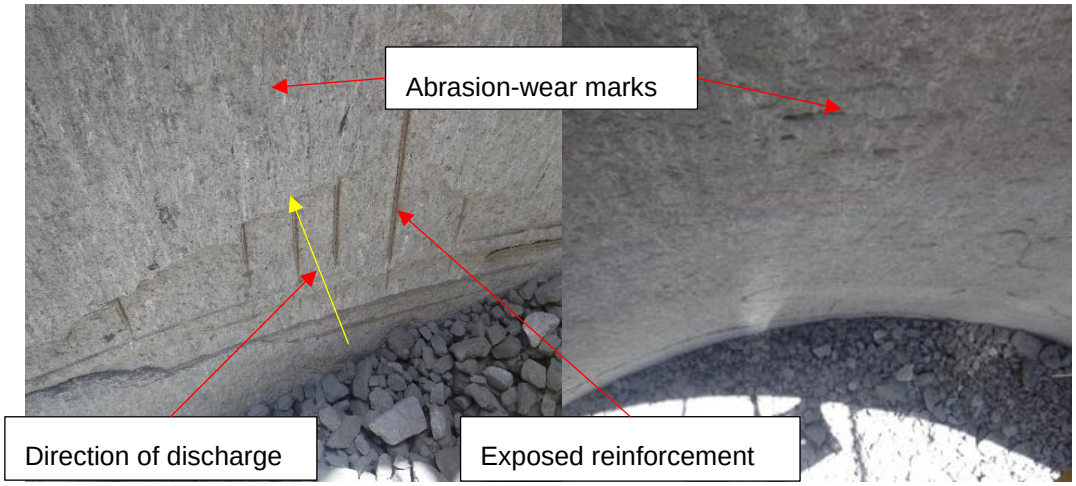


Figure 3.8: Picture of silo showing horizontal cracks on the external wall.

As mentioned above, there are no details of the shotcrete liner shown on the original design drawings and it is furthermore unclear when this sacrificial liner was installed. It was, however, mentioned that this was done due to the high abrasive nature of the platinum ore. No other modifications or additions were made to the structure besides the above-mentioned sacrificial liner. Figure 3.9 shows the abraded internal walls of the RoM silo mentioned above. It can be seen that the concrete cover has significantly been abraded in some areas, leading to the exposure of the reinforcement.

The sacrificial shotcrete liner and cover-crete on the inside face of the wall is in some places completely worn away. Structural reinforcement is exposed at the lower portions of the western wall adjacent to the discharge into the silo as shown in Figure 3.9 (a). This is due to the material being discharged directly onto the wall, and/or material overrun as discussed in Section 2.5 above. Furthermore, the zone depicted in Figure 3.9 also coincided with the zone where the discharged ore material impacts the silo's internal concrete wall as discussed in Section 2.5.1 above.



(a) Western wall (b) Eastern wall

Figure 3.9:RoM silo internal wall (a) Western wall - wall adjacent to the discharge, (b) Eastern wall - on the side behind the discharge chute.

It should be noted that at the time of the inspection, the silo was not completely empty, but it was observed that one of the horizontal hoop reinforcement bars were damaged and effectively compromised the strength of the wall. The white marks on the wall are a result of mass flow conditions. As the material moves as a mass, it abrades against the silo wall, ploughing through the surface of the concrete, leaving behind marks as shown in Figure 3.9(a). The pictures also contextualize the particle size of the stored material. In this case, the material hardness is lower than the abrasive hardness of the surface. Therefore, micro-cutting or scratching of the surface takes place. However, in Figure 3.9(a), the abrasive material hardness is higher than the hardness of the surface; therefore, clear removal of the surface is taking place, and the process has the nature of fatigue. The rate of wear is further increased by the particle mass and angularity, therefore further increasing the rate of deterioration on the internal surface of the silo. The sequence in which the loss of mass on the silo wall occurs is shown in Figure 2.4 in the literature review.

The general conditional category of the internal wall is 3 for wear and abrasion, and 1 for cracking. It is also important to note that as wear on the surface increases, the rate of abrasion increases, due to a prying action that forms between the counterface and the abrasive material. This would therefore result in a rapid increase in concrete deterioration. Additional category breakdowns and pictures of the internal wall can be found in the report in Appendix C.

3.5.6 Schedule of Findings and SIMM Inspection Summary

Table 3.6 summarizes all the findings obtained from the SIMM inspection report in the appendices, the deterioration conditional categories related to the findings are also given below. Table 3.6 clearly indicate that the abrasion wear is the most significant contributing factor in influencing the overall deterioration of the structure.

Table 3.6 Schedule of findings and deterioration conditional categories

Finding	**Deterioration Condition Category**
Silo General	
Poor drainage around the silo.	1
Silo Concrete	
Severed abrasion wear of sacrificial shotcrete liner to inside of bin wall. Exposed and damaged wall reinforcement on the lower section of the western wall.	3
Diagonal hairline cracks below the main steel girder supports are deemed to be serviceability cracks	1
Horizontal cold joints or lifting cracks. Not of structural nature.	1 to 2
Minor horizontal and vertical hairline cracks on the external face of the silo wall.	1
Mechanical damage at soffit and side of wall opening.	1
Damaged joint sealant	1
Moisture seepage at soffit of suspended slab.	1 to 2

There are diagonal hairline cracks at the steel girder support positions at the top of the silo wall. Visible efflorescence is observed in some of the cracks. This indicates that these are likely old cracks. These cracks all measure less than 0,2 mm in width. A hammer survey was performed by striking the concrete along the crack with a hammer. This revealed that the concrete was firm and solid with no signs of delamination or spalled concrete. Considering that silo was commissioned over 17 years ago and in its current condition, these cracks are all less than 0,2 mm wide with no visible signs of delamination or spalling, these cracks are therefore not considered to significantly affect the integrity of the wall.

Lastly, the most influential factor in the overall deterioration of the silo was the due to the abrasion of the internal wall caused by the ore material as shown in Figure 3.9. This therefore further reinforces the need to evaluate the influence of suitable performance-based specifications for the design, modelling, testing and test acceptance criteria for abrasion-resistant concrete used for material storage structures in minerals processing.

To gain more insight into the abrasion resistance of the silo concrete cores would be required and an abrasion test would be carried out. The results obtained would therefore be contrasted against the results obtained in the experimental work. This would aid in providing an understanding of the long-term abrasion performance of the concrete, relative to its design specifications, which would aid in the development of

abrasion performance models. However, the silo was in use at the time of the study. Therefore, concrete cores could not be drawn.

3.6 Overall Research Methodology

Figure 3.10 shows an overall research methodology and a brief description of the activities.

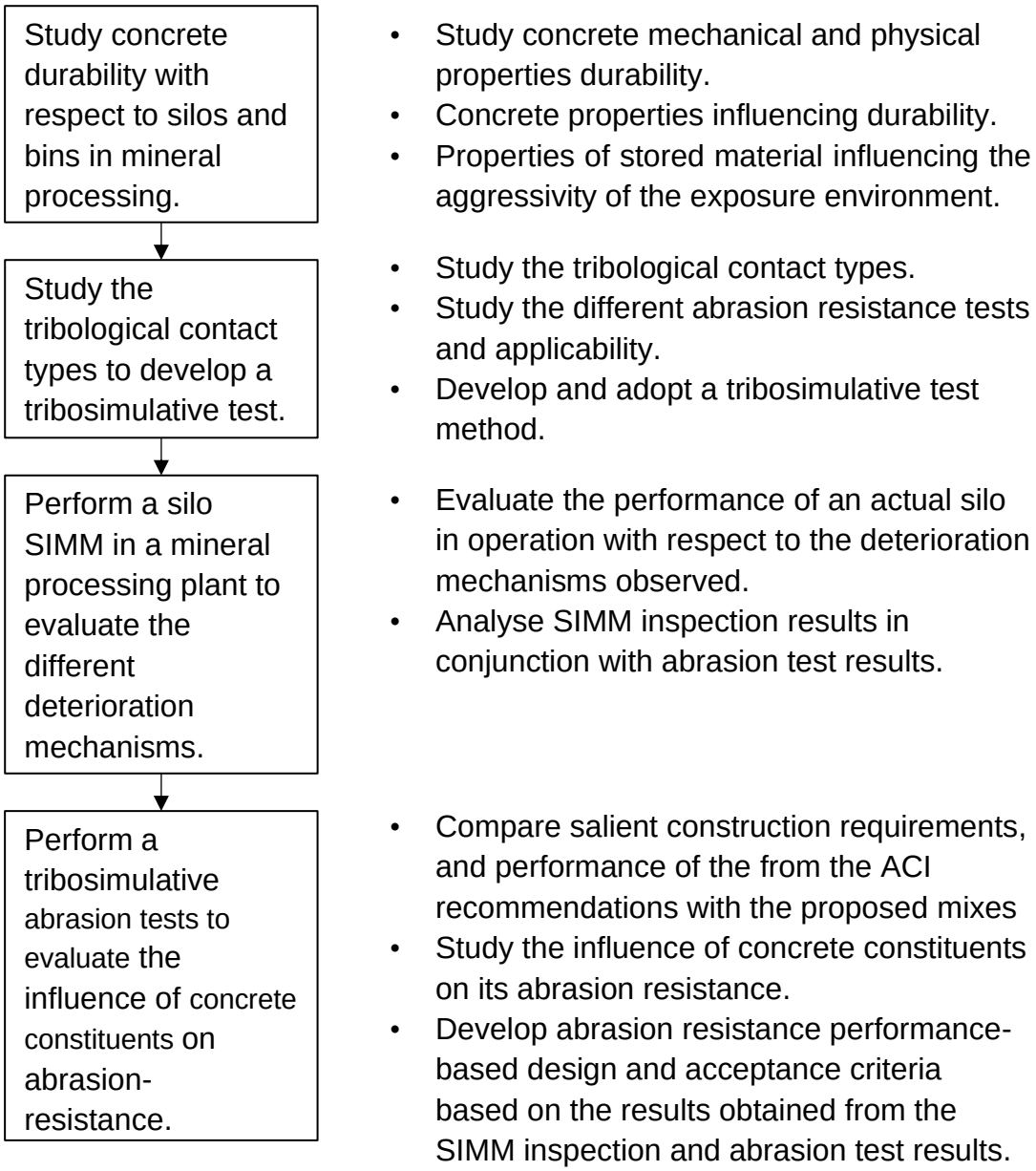


Figure 3.10: Overall Research Methodology Flow Chart

CHAPTER 4

4 RESULTS AND DISCUSSION

This chapter presents the results from the experimental work carried out in this research as outlined in Chapter 3. The abrasion and compression strength test results were evaluated at 7, 14, 28 and 3, 7 and 28 days respectively. The tests were carried out to facilitate the comprehensive study of the effects of the aggregate type, size, and binder types on the compressive strengths and ultimately, abrasion mass loss on the concrete. More details on the data and analysis can be found in Appendix E. Table 4.1 shows the mix identifier naming convention used throughout this section.

Table 4.1: Mix identifier breakdown for the various concrete mixes cast with a 0.4 w/c ratio.

Binder Type	Aggregate type	Aggregate size	Mix identifier
PC	Andesite	13,2 mm	APC13
		19 mm	APC19
	Dolerite	13,2 mm	DPC13
		19 mm	DPC19
	Granite	13,2 mm	GPC13
		19 mm	GPC19
PC/FA 85/15	Andesite	13,2 mm	AFA13
		19 mm	AFA19
	Dolerite	13,2 mm	DFA13
		19 mm	DFA19
	Granite	13,2 mm	GFA13
		19 mm	GFA19
PC/CSF 92.5/7.5	Andesite	13,2 mm	ASF13
		19 mm	ASF19
	Dolerite	13,2 mm	DSF13
		19 mm	DSF19
	Granite	13,2 mm	GSF13
		19 mm	GSF19

The error bars presented in the figures (where applicable) below serve as a representation of the standard deviation of the underlying data, thereby indicating the degree to which the accurate measurement of the reported values may deviate. These error bars indicate the extent to which the individual data points might lie from the reported average values.

4.1 Concrete compressive strength test results

Figure 4.1 below shows the time development of compressive strength for all the 18 mixes. A 95% confidence interval was used for the concrete compressive strength test. As expected, the concrete compressive strength of all the mixes increased with the increase in age. The results show a significant increase in the early age strength for all the mixes, from 3 to 7 days, which then increased at a decreasing rate between 7 and 28 days. This is as a result of concrete produced with lower w/c ratios having higher rates of hydration, even when normalized to the 28-day compressive strength (Domone and Illston, 2010). Generally, all 18 mixes achieved their expected 28-day compressive strength expectations, with minimal standard deviation.

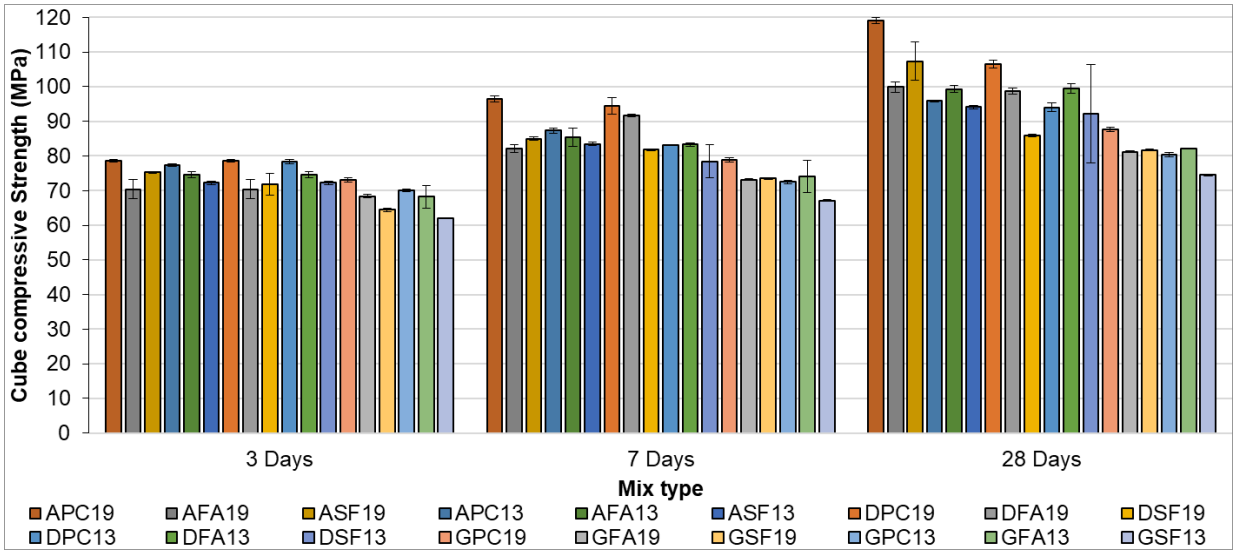


Figure 4.1: Average 3-, 7- and 28-day compressive strengths for all 18 concrete mixes.

At lower w/c ratios, the distance between the cement particles decreases, leading to the reduction in the distance between the hydrating particles. This phenomenon then contributes to the formation of a denser hydrated cement microstructure. Conversely, the increase in w/c ratio results in larger inter-particle spacing, thus causing the hydration products to interact over larger distances. Ultimately, this results in the formation of less dense hydrated cement microstructure, resulting in lower concrete compressive strengths (Du Preez, 2019).

With respect to the influence of supplementary cementitious materials (SCMs), the rate and 28-day strengths differed slightly for the mixes, across all the respective aggregate types. Typically, mixes with PC had the highest 28-day compressive strength, and rate of strength development for each respective aggregate type. The use of SCMs dilutes the cement available for hydration with slower reacting pozzolanic materials which initially delay the rate of strength gain but matures over time. The use of cement extenders is known to reduce the amount of calcium hydroxide available for the formation of the calcium silicate hydrate, which is essential to early age concrete strength (Angelucci, 2013).

APC19 (andesite, PC, 19 mm) was observed to have the highest rate of strength and overall strength gain when compared to the other 20 concrete mixes. This superior compressive strength performance was also observed with respect to AFA19 and ASF19. With the increase in concrete compressive strength, the mechanical properties of the aggregate were observed to be of increasing importance, as the mix compressive strength attained varied with the variation in aggregate type. The mixes with granite aggregates showed the least strength gain and overall 28-day strength when compared to the other mixes. This was expected as for high-strength concrete (f_{cu} > 60 MPa), the aggregate compressive strength becomes increasingly significant to the concrete compressive strength performance (Beushausen and Dehn, 2021).

The 28-day compressive strength of the mixes with granite aggregates was comparatively lower, as they have a 10% FACT value of 162 kN, whereas the other mixes (mixes with andesite and dolerite aggregates) have 10% FACT values of 564 kN and 296 kN respectively. Concrete mixes with aggregates that have higher 10% FACT values are expected to have higher overall compressive strengths; therefore, it follows that the granite aggregate mixes have significantly lower compressive strength when compared to the andesite and dolerite mixes (Beushausen and Dehn, 2021).

The mixes with dolerite aggregates (13,2 and 19 mm) had the lowest amount of fines with 4.4% passing through the 0.150 mm size sieve, and a Fineness Modulus (FM) of 4.07, which is the highest amongst all the 18 mixes. This uniqueness did not, however, reflect in a variation of compressive strengths, as the compressive strengths of the mixes with the dolerite aggregates were comparable to that of the andesite. For the design of HSC in South Africa, preference is usually given to crusher sand with a FM of 2.7 to 3.0 (Addis, 2001). However, the effects of utilizing crusher sand with a higher FM on both compressive strength and abrasion resistance were not immediately evident. The relationship between compressive strength and abrasion resistance is outlined in the subsequent sections below.

Generally, all the mixes met their specified characteristic 28-day compressive strengths, with relatively high strength margins. Thus, the compressive strength design aspect for silo concrete was not considered to be an issue for all the various mixes. Additional information can be obtained in Appendix E.

4.2 28-day abrasion mass loss results and analysis

Figure 4.2 shows the 28-day abrasion mass loss results for all 18 mixes. The error bars below show a deviation from the average abrasion mass loss results, thus indicating how far the data points lie from the presented averages and, thus, the level of variability in the data.

It is plausible that the element of variability exists due to the differences in near-surface properties of the concrete samples (Liu and Pann, 2011). These surface properties are affected by the random placement, distance, and orientation of aggregates near the surface of the concrete. As mentioned above, the aggregate has a higher abrasion

resistance when compared to the cement paste, therefore, more abrasion mass loss will be observed for concrete samples with relatively lower aggregate to cement paste surface area ratios.

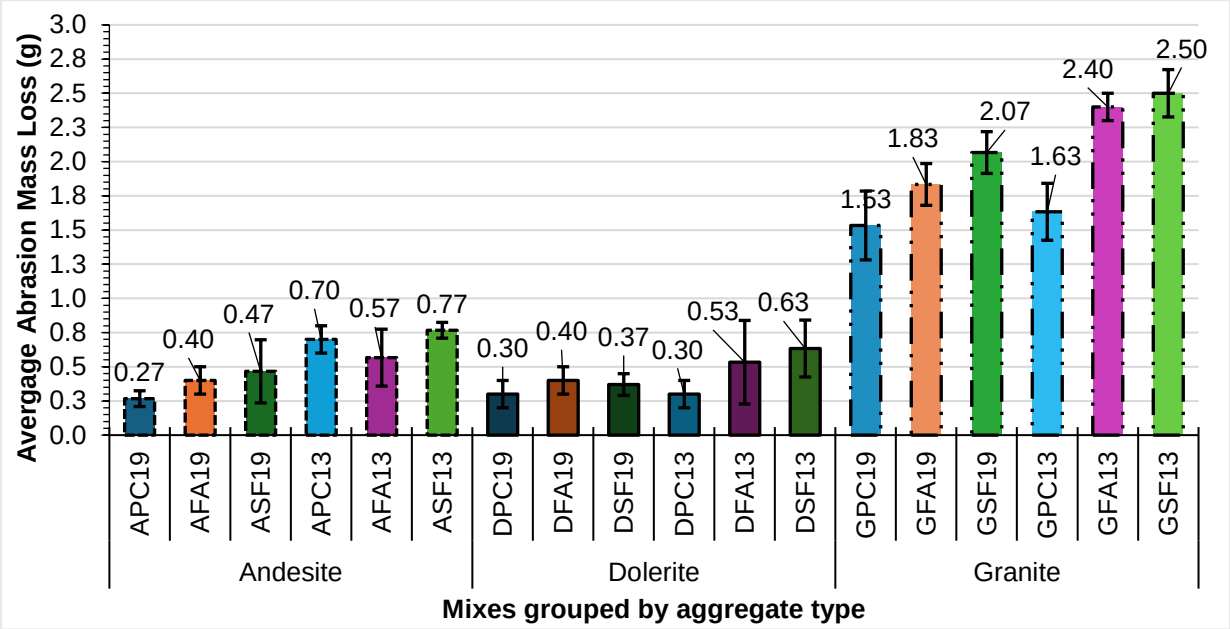


Figure 4.2: 28-day comparison of the abrasion mass loss values for the various mixes.

The results also demonstrate that the concrete mixes with a 100% PC blend (APC, DPC, GPC both 19 and 13,2 mm) showed a superior performance with respect to the concrete abrasion resistance at 28 days, when compared to the other blended cement mixes (PC/FA and PC/CSF). Furthermore, relatively low w/c ratios used in the study also contributed significantly to the high compressive strength, which ultimately resulted in the low 28-day abrasion mass loss observed.

Blended mixes PC/FA and PC/CSF (19 and 13,2 mm, respectively), except for APC13, demonstrated significantly lower abrasion resistance development and overall abrasion resistance at 28 days when compared to concrete mixes with 100% PC, for each respective aggregate type. This is due to the reduced PC content for the blended cements, which results in slower rates of strength gain, as discussed in sub-Section 2.7.2. Both PC/FA and PC/CSF binder type mixes were not observed to have a significant effect on the 28-day abrasion resistance, as their performance varied with respect to aggregate type and size. As mentioned above, the 28-day results alone cannot be used to conclude on the overall influence of these blended mixes as they are pozzolanic and should be tested after longer curing periods. However, these results can be used as a comparison between the performance of the various mixes at 28 days, as the later age abrasion resistance and strength properties are not expected to change significantly at lower replacement levels.

The mixes with dolerite aggregates were observed to have the least average abrasion mass loss when compared to the various aggregates for the mixes. On average, the andesite aggregates were also observed to have a lower abrasion mass loss when

compared to the granite aggregate, but slightly higher than the abrasion mass loss of the dolerite aggregates. The average mass loss measured at 28 days was 0.53 g, 0.42 g and 1.99 g for the andesite, dolerite and granite aggregates respectively.

The 19 mm aggregates were observed to have relative superiority with respect to abrasion resistance when compared to the 13,2 mm aggregates for all the 18 concrete mixes. This result was expected as a similar phenomenon has been observed in literature, as discussed in Section 2.7.1. This is due to the increase in aggregate:paste surface area ratio exposed to abrasion at the face of the concrete test cube.

Some of the results obtained have a relatively high standard deviation for the abrasion mass loss observed. This is a result of the variation in surface properties of the concrete due to the heterogeneous nature of concrete's surface properties, as mentioned above. Furthermore, the orientation of the aggregate relative to the concrete face also plays an important role in abrasion mass loss, as flat-faced aggregates relative to the surface will expose less of the cement paste to the abrasive action. Thus, less cement paste will be abraded. Various permutations showing the relationship between binder types, aggregate types and sizes can be found in Appendix B.

4.3 Effect of the concrete compressive strength on abrasion resistance

Figure 4.3 shows the relationship between concrete compressive strength and abrasion mass loss for all the concrete mixes at 28-days. An empirical correlation between concrete compressive strength and abrasion resistance was established with respect to both the 13,2 and 19 mm aggregates respectively. The trendlines shown in Figure 4.3 show a linear, inversely proportional relationship between compressive strength and abrasion mass loss, where the increase in concrete compressive strength leads to a decrease in observed abrasion mass loss, regardless of the aggregate, and binder types. This result can be translated to the increase in abrasion resistance of the concrete with the increase in compressive strength. This was expected, as it is also mentioned in Section 2.7.4 in the Literature Review.

In the context of the correlation between concrete compressive strength and abrasion resistance, a weaker correlation between the compressive strength and abrasion mass loss was observed on the mixes with the 19 mm aggregate when compared to the mixes with the 13,2 mm aggregate for each respective aggregate type. Correlation coefficients of 0.84 and 0.59 were observed for both the mixes with 13,2 and 19 mm aggregates respectively. A similar phenomenon was also observed with respect to each aggregate type, where the mixes with the 19 mm aggregates had a lower correlation to compressive strength when compared to the 13,2 mm aggregate mixes.

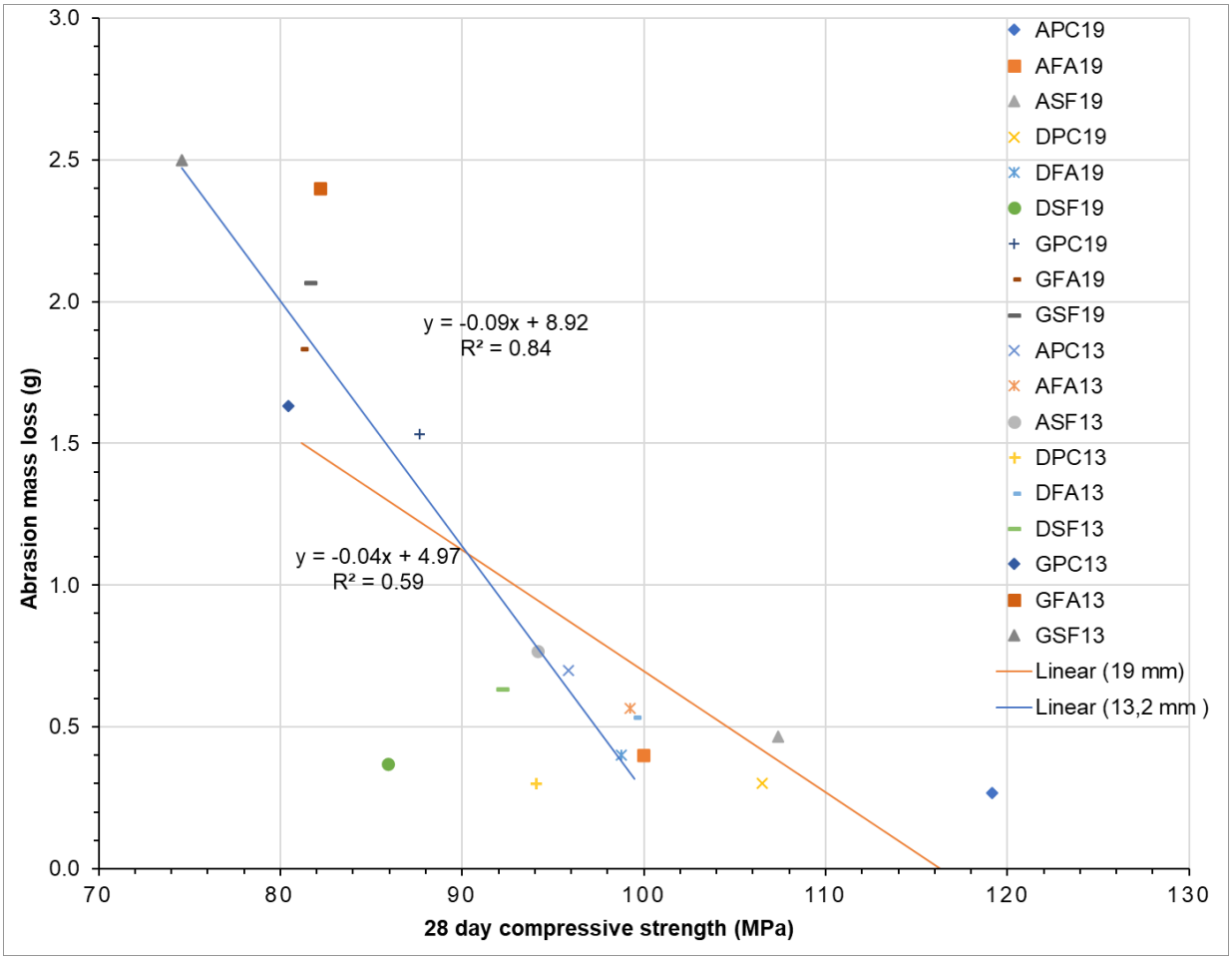


Figure 4.3: Comparison between compressive strength and abrasion resistance of concrete for both 13,2 and 19 mm aggregate mixes at 28 days.

Based on the obtained correlation coefficients, it could be argued that the influence of concrete compressive strength on the mixes with a 13,2 mm aggregate was significantly greater when contrasted with the compressive strength influence on the mixes with 19 mm aggregates. This statement is supported by the 0.8 correlation coefficient obtained as indicated above. This observed result may be due to the mixes with the 19 mm aggregate having a higher aggregate:paste ratio at the surface, when compared to the 13,2 mm aggregate mixes. This, in turn, reduces the influence of binder compressive strength on abrasion resistance, therefore resulting in a lower correlation between the abrasion resistance and compressive strength on the 19 mm aggregate mixes.

A better understanding of the relationship between concrete compressive strength and abrasion resistance could be established with the introduction of more mixes with varying compressive strengths other than those considered in this study. However, based on the behaviour of the various mix types shown below, inferences can be drawn on the abrasion resistance of different concrete mix types at higher and lower compressive strengths than those represented below.

Further to the evidence above on the influence of concrete compressive strength on abrasion resistance, it could be argued that the increase in compressive strength of the

concrete with a 13,2 mm aggregate will result in better abrasion resistance performance when compared to 19 mm. With the 19 mm aggregate, there is a weaker dependence on the compressive strength of the concrete when considering its abrasion resistance. This is evident as poor correlation between strength and abrasion mass loss was obtained from the 19 mm aggregate, when compared to the 13,2 mm aggregate.

It is stated in literature that at compressive strengths above 60MPa, the influence of concrete strength on abrasion resistance becomes less significant (Liu, et al., 2005). However, this was not observed to be the case in this study as the abrasion mass loss reduced quite significantly at compressive strengths greater than 60MPa. The influence of concrete compressive strength could possibly be less significant to abrasion resistance for a particular aggregate type, rather than for all aggregate types. This could be the case as the abrasion mass loss observed is a function of the aggregate type and concrete compressive strength. Thus, when the aggregates used in this study are concerned, the above-mentioned argument does not hold true.

The slope of the 13,2 mm aggregate mixes is steeper than that of the 19 mm. This therefore indicates a higher sensitivity to change in concrete compressive strength on abrasion mass loss for the 13,2 mm mixes when compared to the 19 mm mixes. This is also supported by gradients on the equations presented in the figure above. This is plausibly due to the aggregate:paste surface area ratio exposed to abrasion for the 13,2 mm mixes being greater than that of the 19 mm mixes. Thus, the abrasion mass loss of the 13,2 mm will highly depend on the compressive strength of the paste, which directly influences its abrasion resistance, when compared to the aggregate's abrasion resistance. It has been established in literature that the compressive strength of the aggregate is far more than that of the cement paste, thus the cement paste is expected to abrade more than the aggregates, see Figure 2.4 in the literature review for a visual representation of the abrasion sequence in concrete.

Figure 4.3 also shows the abrasion mass loss at a particular 28-day compressive strength in all three tests for a respective aggregate type and size. The graph also shows a similar correlation between the compressive strength and abrasion resistance for each respective aggregate type comparison, where the increase in compressive strength, results in the decrease in abrasion mass loss observed. As mentioned above, the sensitivity to compressive strength for the 13,2 mm aggregate is still higher when compared to the 19 mm for each of the 3 tests of similar aggregate type and size.

Downward trendlines for all the various aggregate types and sizes with relatively high correlation coefficients were obtained in this study, which can be seen in Figure B 8 in the appendices. It is obvious that the aggregate does not increase in compressive strength over time but rather the cement paste does. This therefore further strengthens the argument that the abrasion resistance of the concrete is highly influenced by the increase in compressive strength of the cement paste.

Lastly, the graphs in Figure 4.2 and Figure 4.3 alone are not fully indicative of the other factors that contribute to the abrasion resistance. The abrasion resistance of concrete is a function of a synergy of the influence of intrinsic factors such as aggregate type, size, density, and concrete density, which will be discussed below.

4.4 Time-dependent development of abrasion resistance of concrete

The compressive strength has been established to have a significant influence on the abrasion resistance of concrete, where the increase in concrete compressive strength results in an increase in the concretes' abrasion resistance (Beushausen, et al., 2021b). This relationship was also established in this study as shown in Figure 4.3. Thus, to obtain a better understanding of the influence of the other factors on abrasion mentioned above, further analysis is required. Figure 4.4 shows the time dependent development of abrasion mass loss for the 18 concrete mixes, normalized with respect to concrete compressive strength.

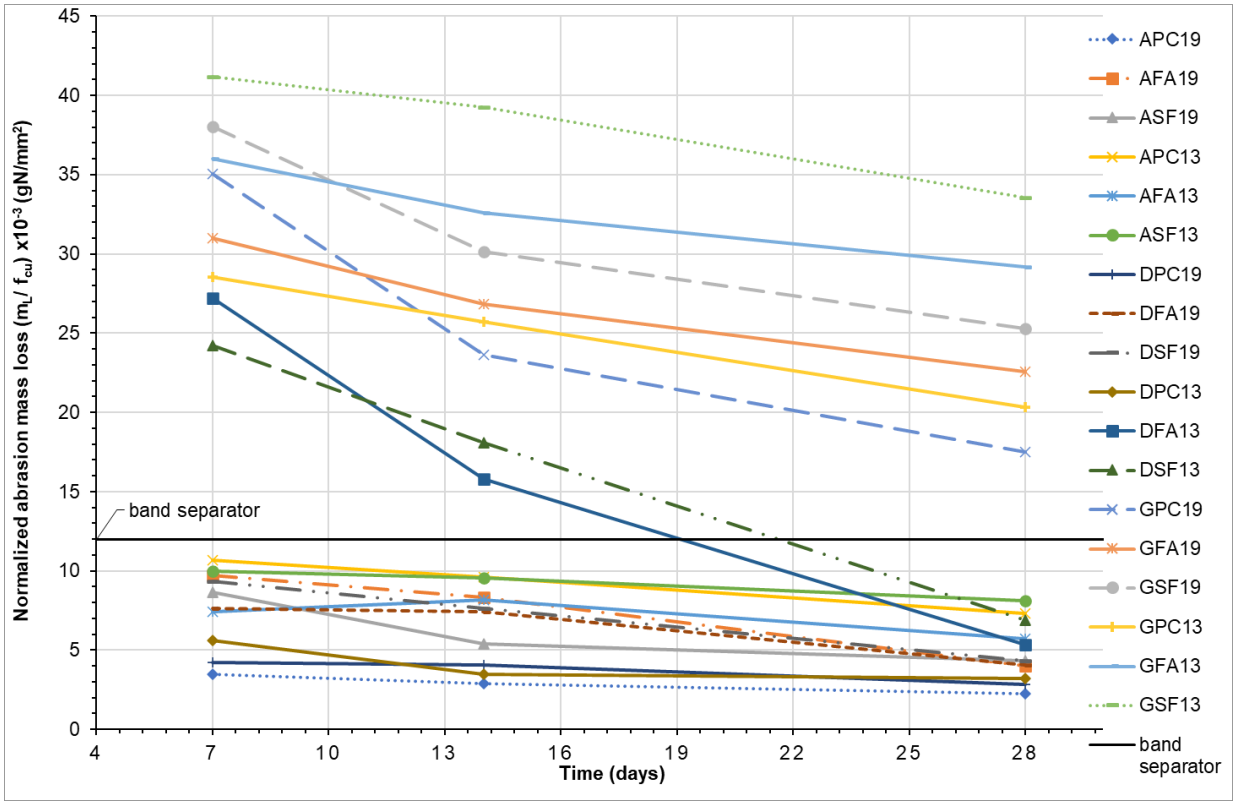


Figure 4.4: Normalized time dependent development of abrasion resistance.

It is observed that there is a distinct trend of decreasing abrasion mass loss with increasing concrete age from 7 to 28 days. The observed trend clearly indicates an increase in the abrasion resistance of the concrete over time. This phenomenon appears to be independent of the influence of compressive strength over time, as the results were normalized with respect to their respective compressive strengths.

The normalized abrasion mass loss results shown in Figure 4.4 were obtained by dividing the abrasion mass loss m_L (g) observed at time (t) with the respective compressive strength f_{cu} (N/mm^2) obtained at time (t). Figure 4.4 also shows 2 distinct

trends of abrasion resistance development obtained. Mixes with a normalized abrasion mass loss (m_L/f_{cu}) lower than 12 x 10^{-3} g/N/mm^2, and those with a m_L/f_{cu} higher than 12 x 10^{-3} g/N/mm^2 throughout the 28-day test period. These mixes are separated using an arbitrary band separator, as shown in the figure above, to aid the discussions. The lower band excludes the six mixes cast with granite aggregate (GPC, GFA, and GSF, both 19 and 13 mm), and two mixes with dolerite aggregate (DFA 13 & DSF 13). However, the DFA 13 & DSF 13 mixes fall lower than 12 x 10^{-3} g/N/mm^2 at 28 days.

The analysis also reveals a slightly higher overall abrasion mass loss difference between 7 and 14 days for the samples with a m_L/f_{cu} higher than 12 x 10^{-3} g/N/mm^2 when compared to the samples with a m_L/f_{cu} lower than 12 x 10^{-3} g/N/mm^2. This, therefore, alludes that the rate of abrasion resistance development in concrete reduces over time. Thus, the age of abrasive loading on the concrete will plausibly influence its overall abrasion resistance performance.

However, DFA 13 and DSF 13 did not conform to the above-mentioned results, as they had a significantly higher mass loss between 14 and 28 days, when compared to their 7 and 14-day mass loss values. This result was not expected, as the influence of FA on the development of concrete compressive strength can be observed later than 28 days. Thus, the normalized mass loss difference exhibited by the DFA 13 and DSF13 mixes do not correlate with the literature reviewed in this study. This anomaly was not expected, as the benefits of using FA were expected to be seen later than 28 days. The performance of these mixes was considered outliers since the other mixes did not exhibit the same behavior.

CSF is known to have a significant influence on the early (< 7 days) development of the mechanical properties favourable to abrasion resistance, by contributing to the densification of the concrete microstructure, and the formation of stronger interfacial bonds between the concrete and aggregates, and the cement particles respectively at early ages (Beushausen and Dehn, 2021c: AfriSam,2021:58). However, this was not observed to be the case, as the DSF 13 mix had an increased abrasion mass loss difference between 14 and 28 days when compared to the 0 and 14 day normalized abrasion mass loss results. This anomaly is also seen to be the case with respect to the concrete compressive strength results, where the influence of CSF on the early age strength development was not observed, as is stated in the literature review.

The rate at which the abrasion mass loss for the mixes with a m_L/f_{cu} lower than 12x10^{-3} g/N/mm^2 decreases with time was similar between 7 -14 days and 14 to 28 days. However, with respect to the concrete mixes with a m_L/f_{cu} greater than 12 x 10^{-3} g/N/mm^2, the rate of reduction in mass loss between 7 and 14 days is significantly higher than that of the 14 to 28 days, as it is observed to have decreased between 14 to 28 days. This, therefore, alludes to the fact that the normalized abrasion resistance development is somewhat similar or correlated to the abrasion resistance development.

Lastly, the settlement of the aggregates in the concrete during vibration is random. Thus, the placement and distance of the aggregate from the surface will not always be the same for every mix. This heterogeneity resulted in some of the test cubes plausibly experiencing higher abrasion mass loss resulting from the volume of the paste at the surface exposed to abrasion being higher than that of the aggregate for that particular test cube (Liu, et al., 2005). This can also be visually observed on Table 4.2. The abrasion test result standard deviation values can be obtained in Appendix E.

4.5 Influence of concrete density on abrasion resistance

Figure 4.5 presents a comparison between the average concrete density, and abrasion mass loss observed for all the 18 mixes, normalized with respect to concrete compressive strength. Even though the results have been normalized with respect to strength, Figure 4.4 shows that there are other contributing factors to abrasion resistance outside of compressive strength. This is the case as the abrasion mass loss is observed to decrease even though the abrasion mass loss results are normalized to remove the influence of compressive strength on the observed abrasion mass loss. The influence of concrete density is shown to be one of these influential factors, which is discussed below.

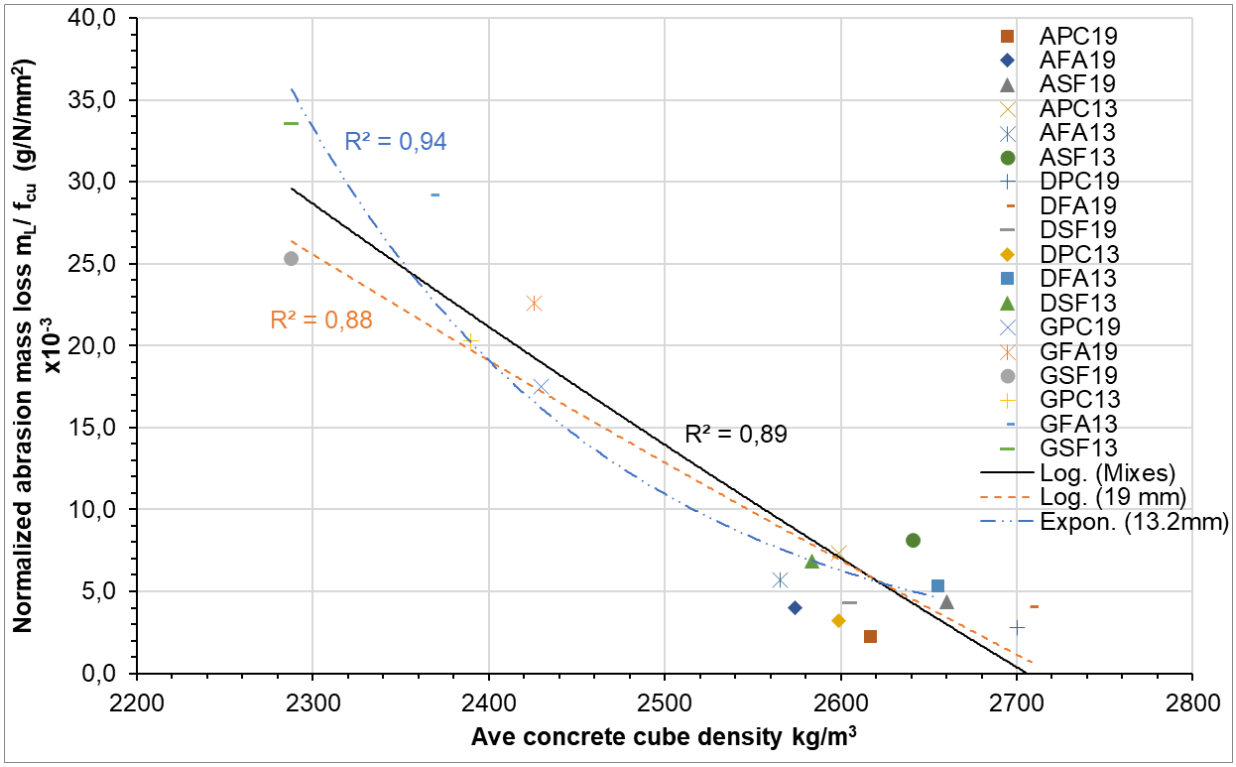


Figure 4.5: Normalized comparison of average concrete density and abrasion mass loss.

An inverse exponential and logarithmic mathematical relationship between abrasion mass loss and concrete density for the 13,2 and 19 mm aggregates, respectively, was established. The 13,2 and 19 mm aggregates both show a direct and strong relationship between the increase in the concrete cube density and the reduction in abrasion mass loss. The data analysis indicates that the 13,2 mm aggregate trendline had a coefficient

of correlation of 0.94, while the 19 mm stone showed a coefficient of correlation of 0.88. These relatively high correlation coefficients thus show a strong relationship between the data sets and the trendline, thus validating the observed relationship.

Furthermore, a negligible difference between the two trendlines was observed, as the data points lie relatively close to each other, an overall coefficient of correlation of 0.87 was observed when the entire data set is considered. This indicates that there is a negligible influence of aggregate size on the abrasion mass loss when concrete density is considered. This result also indicates that the influence of aggregate size on the abrasion mass loss is negligible, when considering the influence of concrete density on normalized abrasion mass loss.

The 19 mm andesite and dolerite aggregate have a Relative Density (RD) of 2.90, and 2.97, respectively, while granite has a RD of 2.63 as shown in aggregate grading results in Appendix D. The RDs were obtained using a gas pycnometer as discussed in Chapter 3. The results, therefore, show that the concrete with dolerite and andesite has a higher density than that of concrete cast with granite aggregates, given that they have a relatively similar stone content volume of 1125 kg/m^3, 975 kg/m^3, and 1075 kg/m^3 for the andesite, dolerite and granite aggregates respectively.

A similar trend is observed with respect to the 13,2 mm aggregate, where andesite and dolerite aggregates have RD values of 2.85, 2.96 respectively, and granite aggregates with an RD of 2.61. This trend is further observed with the fine aggregates as well. The lack of fines in the dolerite aggregates was expected to negatively influence the packing density of the concrete, thus increasing the abrasion mass loss observed. However, the effects were negligible, as the aggregates used still produced relatively dense, and abrasion resistant concrete.

Further to Figure 4.5, Figure 4.6 below shows the influence of the aggregate type on the average concrete cube density at 28 days. The aggregate types with the highest average concrete cube densities resulted in lower abrasion mass loss. Furthermore, the 19 mm mixes resulted in a higher concrete density when compared to the 13,2 mm mixes. This was not expected as literature suggests that the reduction in aggregate size contributes to the aggregate packing density, resulting in high concrete densities (Beushausen and Dehn, 2021).

An argument could also be made that the higher density aggregates require more energy to dislodge them from the concrete matrix, thus improving the abrasion resistance of the concrete. Thus, specifying aggregates with a higher specific gravity results in higher abrasion resistance as established by (Liu, et al., 2005).

Lastly, no correlation was observed between the abrasion mass loss normalized with respect to strength, and concrete density normalized with respect to aggregate density. The data points showed no distinct trend, thus indicating that the aggregate density influences the overall concrete density. This therefore shows that the aggregate density

is an important aspect to consider when designing for abrasion-resistant concrete, see Figure B 7 in the appendices below for more details.

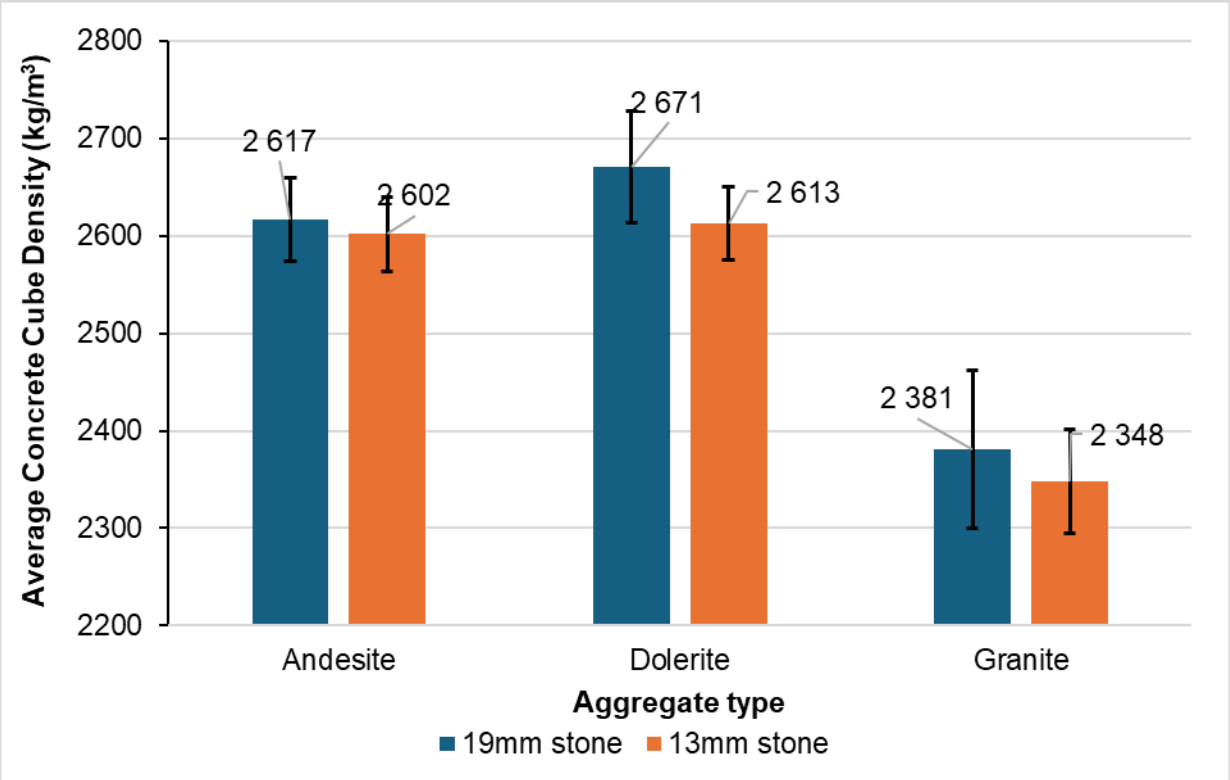


Figure 4.6: Comparison between aggregate type and average cube density at 28 days.

4.6 Effect of aggregate type, density, and size on abrasion resistance

Inferring from Figure 4.5 and Figure 4.6 above, on the influence of aggregate type on concrete density and the overall abrasion mass loss observed, a conception can be drawn on the direct influence of aggregates on abrasion resistance. From the information above, even though indirect, it can be inferred that aggregate types have an influence on the concrete density, which has an influence on abrasion mass loss and, thus, the abrasion resistance of the concrete. Figure 4.7 shows a direct relationship between the aggregate type and abrasion mass loss at 28 days.

It is stated in the literature that in conventional normal strength concretes (concrete with compressive strengths below 60 MPa), the hardened cement paste has an abrasion resistance lower than that of most aggregates, therefore the abrasion resistance of this type of concrete will be highly influenced by the properties of the cement paste rather than the hardness and quality of the aggregates (Beushausen, et al., 2021b), which can be seen in the pictures shown in Section 4.9. However, a different phenomenon was observed with respect to the results obtained in this study, where the aggregate properties had a very significant influence on the development of abrasion resistance, throughout the 28-day test period. A stronger influence of the aggregate properties is observed when the compressive strength of concrete is increased from 80 to 100 MPa, as shown in Figure 4.7 below.

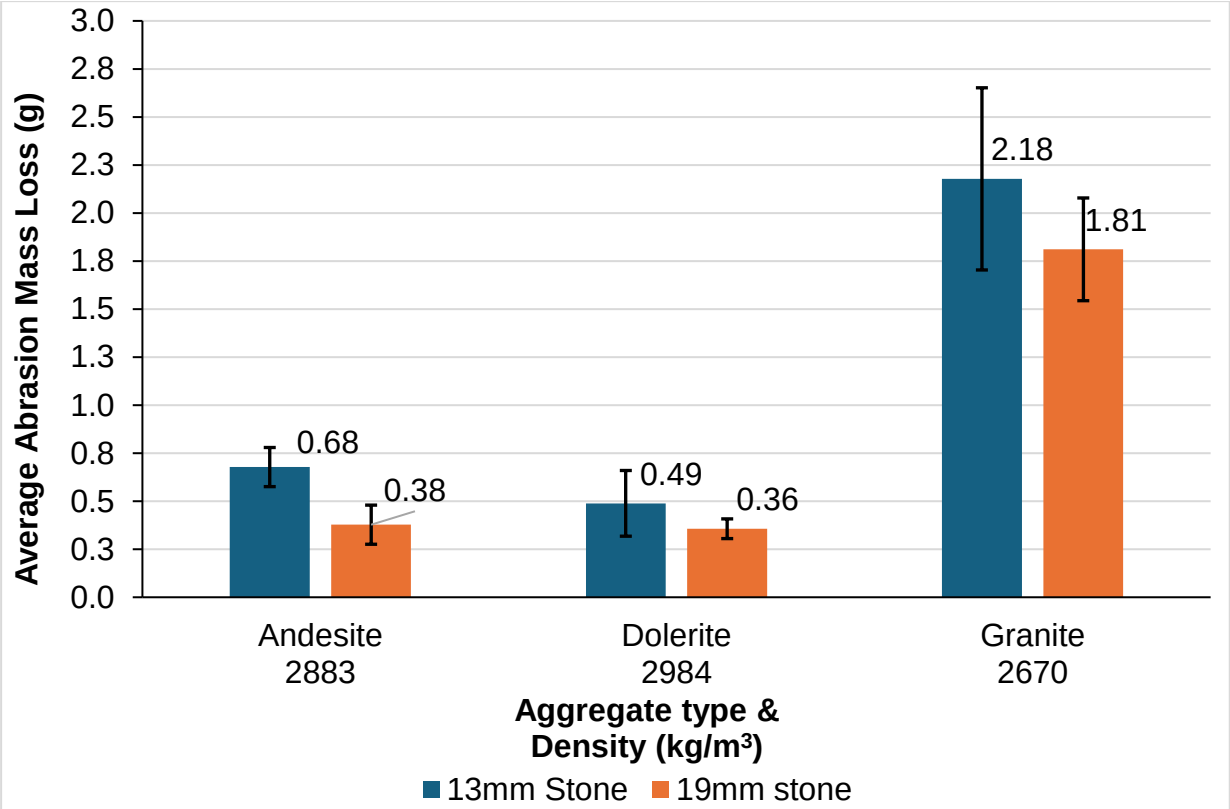


Figure 4.7: Abrasion mass loss comparison for various aggregate types and size at 28 days.

As expected, andesite 19 mm had the least abrasion mass loss when compared to the other aggregate types and sizes. This result trend obtained below is directly related to the aggregate crushing values (ACV%) and LA abrasion values shown in Table 3.2 on page 64. Andesite and dolerite, with ACV% values of 5.9% and 12%, both experienced the least amount of mass loss when compared to granite, with an ACV of 33%. A similar result was observed where aggregates with a lower LA abrasion % value resulted in concrete with lower overall abrasion mass loss. Andesite and dolerite aggregates both had LA abrasion values of 8%, while granite had a LA abrasion value of 33%. The results, therefore, demonstrate that the abrasion resistance of concrete is highly dependent on both the ACV and LA abrasion results of the aggregates.

Further to Figure 4.7, Figure 4.8 shows the 7, 14 and 28-day abrasion mass loss observed in relation to the aggregate densities of each respective aggregate type used to produce the various mixes. These aggregate densities were obtained using a gas pycnometer. The Data points at a particular x co-ordinate indicate a specific aggregate type, where the aggregate densities for each data point on the x-axis are 2670 kg/m^3, 2883.2 kg/m^3, and 2984 kg/m^3 for the granite, andesite, and dolerite aggregates respectively.

Figure 4.8 shows an inversely proportional relationship between abrasion mass loss with respect to aggregate density. Where the mass loss observed decreases exponentially as the aggregate density increases. This phenomenon was expected as

a similar effect was observed with respect to the concrete density. Furthermore, a similar relationship was observed for the 7, 14, and 28-day abrasion mass loss trendlines. The trendlines also showed a relatively high correlation of 0.98, 0.96 and 0.97 for the 7, 14, and 28-day results, respectively. It can, therefore, be interpreted that an increase in aggregate density results in an increase in the abrasion resistance of concrete.

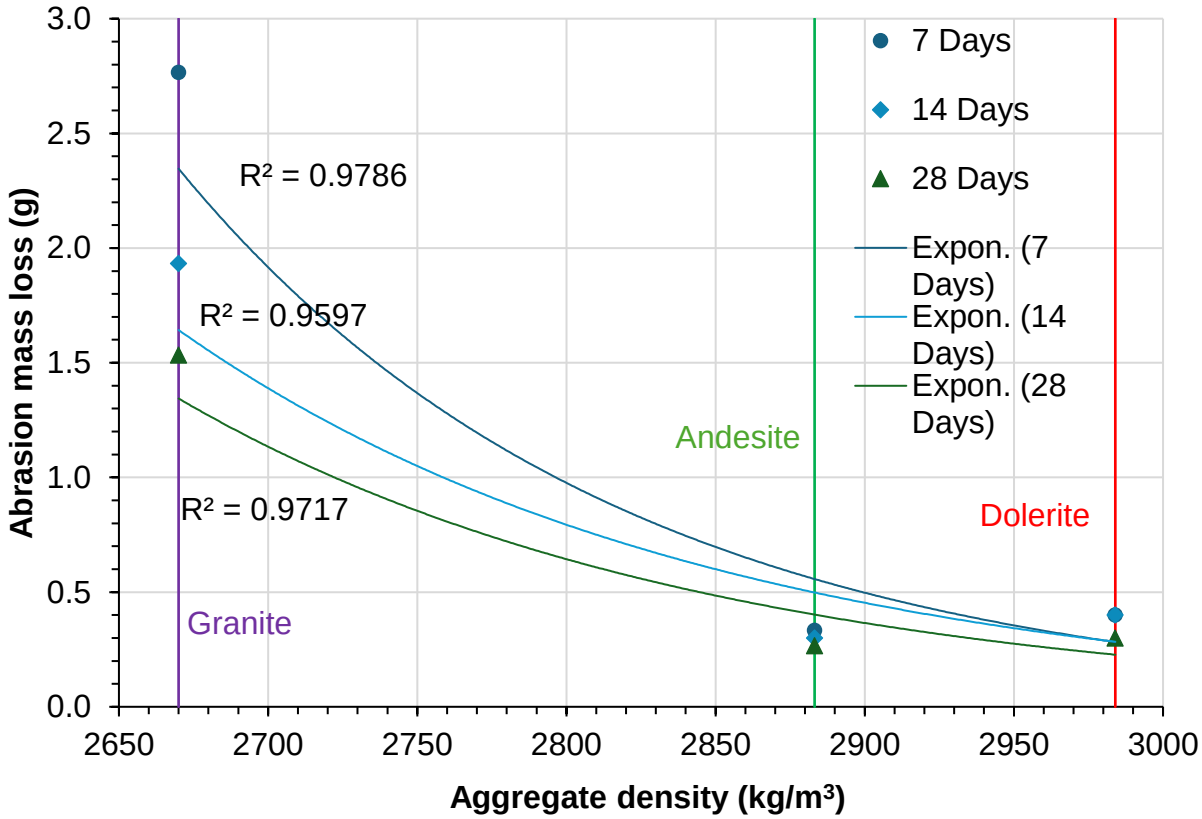


Figure 4.8: The abrasion mass loss measured at 7,14, and 28 days in relation to the aggregate densities of each respective aggregate type used to produce mixes with a 0.4 w/c ratio.

Furthermore, Figure 4.8 also depicts the exponential curves showing a gradual decrease for the 7, 14, and 28 days respectively. This indicates that there is an external influence in abrasion mass loss other than the aggregate density. As mentioned above, this is a result of the increase in compressive strength over time, thus reducing the abrasion mass loss observed, as compressive strength is inversely proportional to abrasion mass loss. This further strengthens the argument that a synergy between aggregate type and paste strength contributes to the abrasion resistance of concrete.

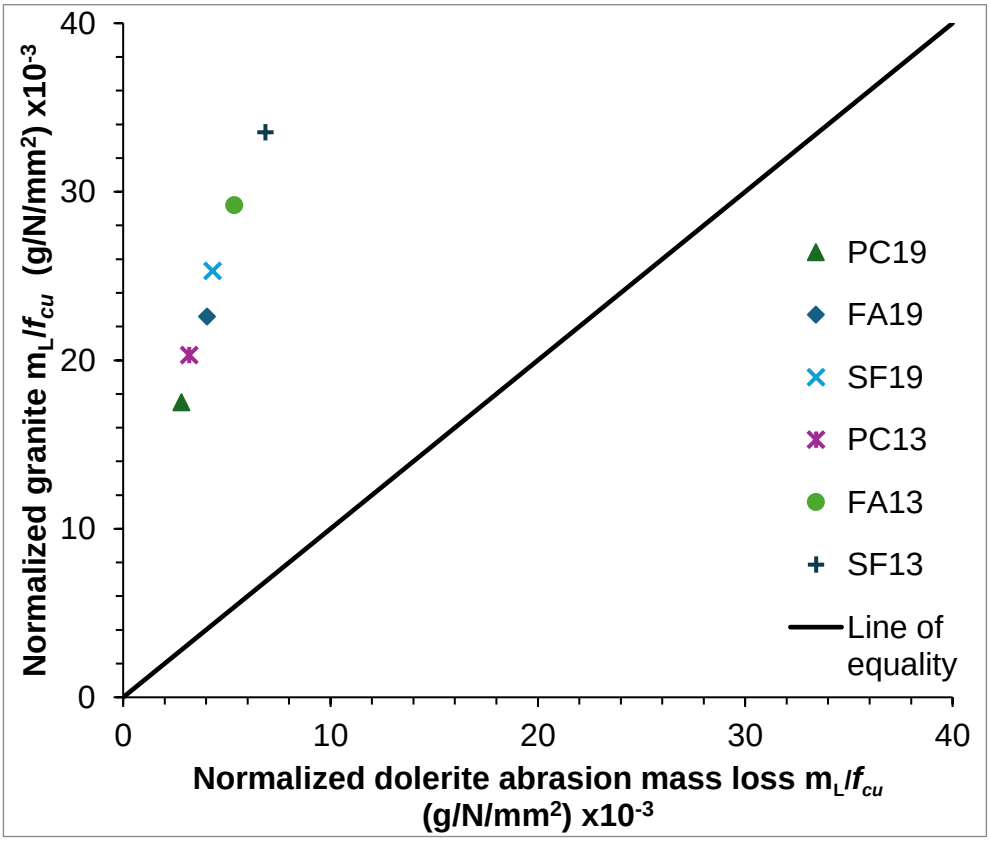
It is suggested in literature that the selected aggregates for concrete exposed to abrasion should have a 10% FACT value in excess of 110 kN (Boshoff, et al., 2021). This selection criterion has a significant influence on the overall enhancement of the abrasion resistance properties of the concrete. The results obtained from this study show that a further improvement in the 10% FACT value results in a decrease in observed abrasion mass loss, thus the increase in abrasion resistance of concrete. Andesite and dolerite both had 10% FACT values of 564 kN and 344 kN, respectively,

while granite had the lowest at 162 kN. Thus, concrete made from aggregates with a higher 10% FACT was shown to have a higher abrasion resistance.

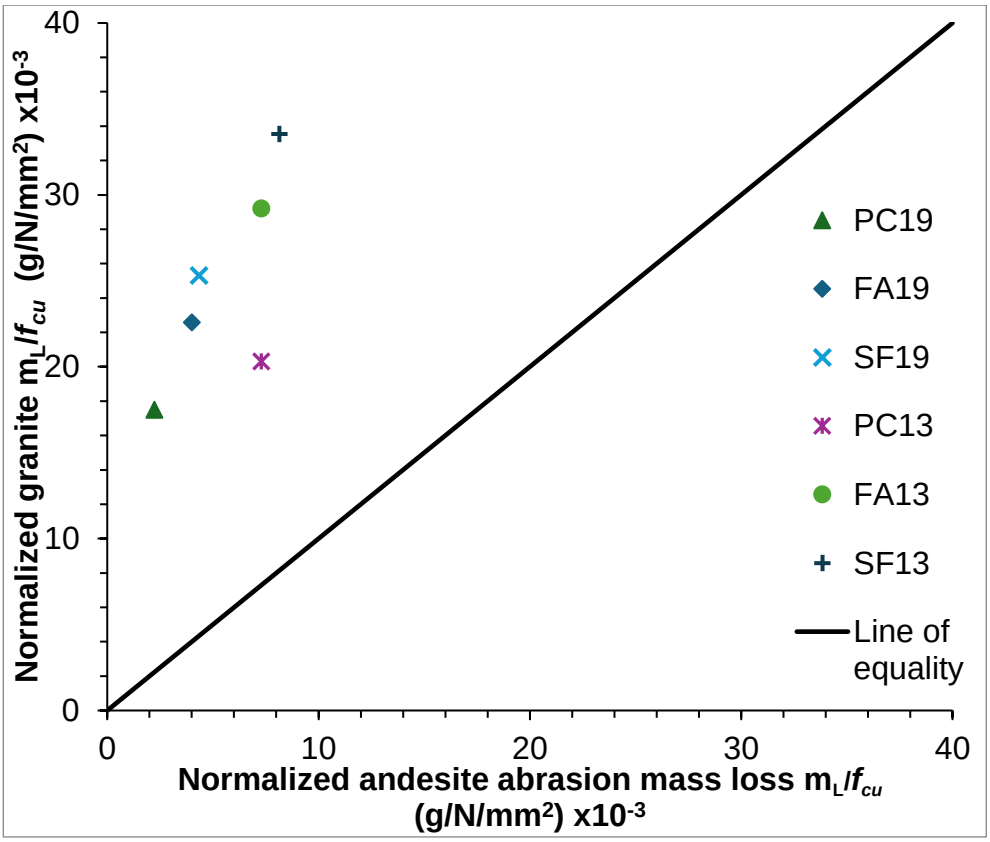
The abrasion resistance performance can therefore be determined by not only the strength and hardness of the aggregate but also the aggregate-cement paste bond, which is indirectly represented by the compressive strength of the concrete (Beushausen, et al., 2021b). This is evident as the granite aggregate mixes exhibiting relatively lower compressive strengths and poor abrasion resistance performance, particularly due to the aggregate properties mentioned above. It could also be argued that as the concrete strength is increased, the aggregate properties become more influential with respect to abrasion resistance.

4.6.1 Comparison of the influence of aggregate type on abrasion resistance

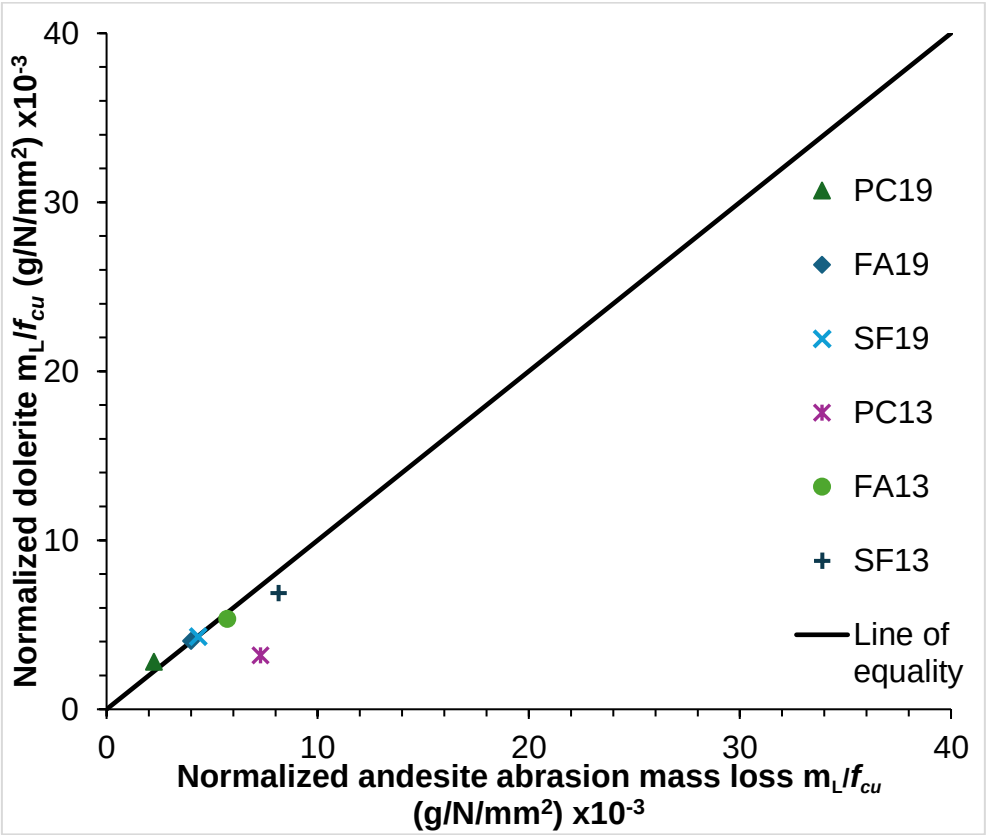
Figure 4.9 on page 94 and 95 depicts a comparison between the aggregate type on the abrasion mass loss observed at 28 days for all the mixes, normalized with respect to concrete compressive strength. With respect to aggregate type, three comparisons are drawn, granite and dolerite (4.9 i), andesite and granite(4.9 ii), and dolerite and andesite (4.9 iii). Intuitively, both graphs with the granite comparisons had data points which lie above the line of equality. This indicates that the granite aggregate had a significantly higher abrasion mass loss observed when compared to the other aggregate types, with a 96 and 111 % difference in abrasion mass loss observed between the andesite and granite, and the dolerite and granite mixes respectively.



4.9 i: Normalized dolerite and granite abrasion mass loss comparison at 28 days



4.9 ii: Normalized andesite and granite abrasion mass loss comparison at 28 days



4.9 iii: Normalized andesite and dolerite abrasion mass loss comparison at 28 days

Figure 4.9: Effect of aggregate type on abrasion mass loss at 28 days, normalized with compressive strength.

Lastly, the dolerite and andesite 4.9 iii comparison had data points which lie relatively close to the equality line. This indicates that there was somewhat of an increase in abrasion resistance with the use of the dolerite aggregate. Thus, the dolerite aggregates had a negligibly superior abrasion resistance when compared to the andesite aggregate. This was deemed negligible, as the majority of data points are positioned closely to, or directly align with, the line of equality.

4.6.2 Influence of aggerate size on abrasion resistance

Figure 4.10 shows a line of equality graph for the abrasion mass loss observed for the various aggregate types with respect to aggregate size, normalized with strength. All the data points fall slightly above the equality line, which indicates a slightly higher abrasion mass loss observed for the 13,2 mm aggregate when compared to the 19 mm aggregate. This was expected, as it was also the case in the graph shown in Figure 4.6.

As discussed in the literature review, the aggregate size has a significant influence on abrasion resistance. Larger aggregates require more energy to be dislodged from the concrete matrix and make up a larger aggregate:paste area ratio at the surface. This therefore leads to the aggregate taking up more of the abrasive forces when compared to the paste. The result below therefore confirms the argument by Dhir, et al. (1991) that the aggregate size plays a significant role in the abrasion resistance.

Lastly, the graph below shows all the various data points representing the binder types lying above the line of equality. This therefore indicates that the 13,2 mm aggregates mixes experienced a higher mass loss when compared to the 19 mm aggregate mixes for all the various binder types at 28 days. It could also be argued that the degree to which the aggregate size influenced the abrasion resistance of the various binder types is relatively small, as most of these data points lie close to the line of equality, indicating the relatively small influence of aggregate size on abrasion mass loss for the various mixes. The DPC mix, however, lies on the line of equality, indicating that for that particular mix type, there was no influence of the aggregate size and binder type on the abrasion mass loss observed.

It is noted in literature that the aggregate volume also has an influence on abrasion resistance (Adewuyi, et al., 2017). However, this could not be recreated in this study as the aggregate contents for each respective aggregate type was not varied significantly as it ranged between +/-65% of the concrete volume. Analysis into the influence of aggregate content by volume could have been achieved by introducing a larger aggregate content range which was not the main aim of this research.

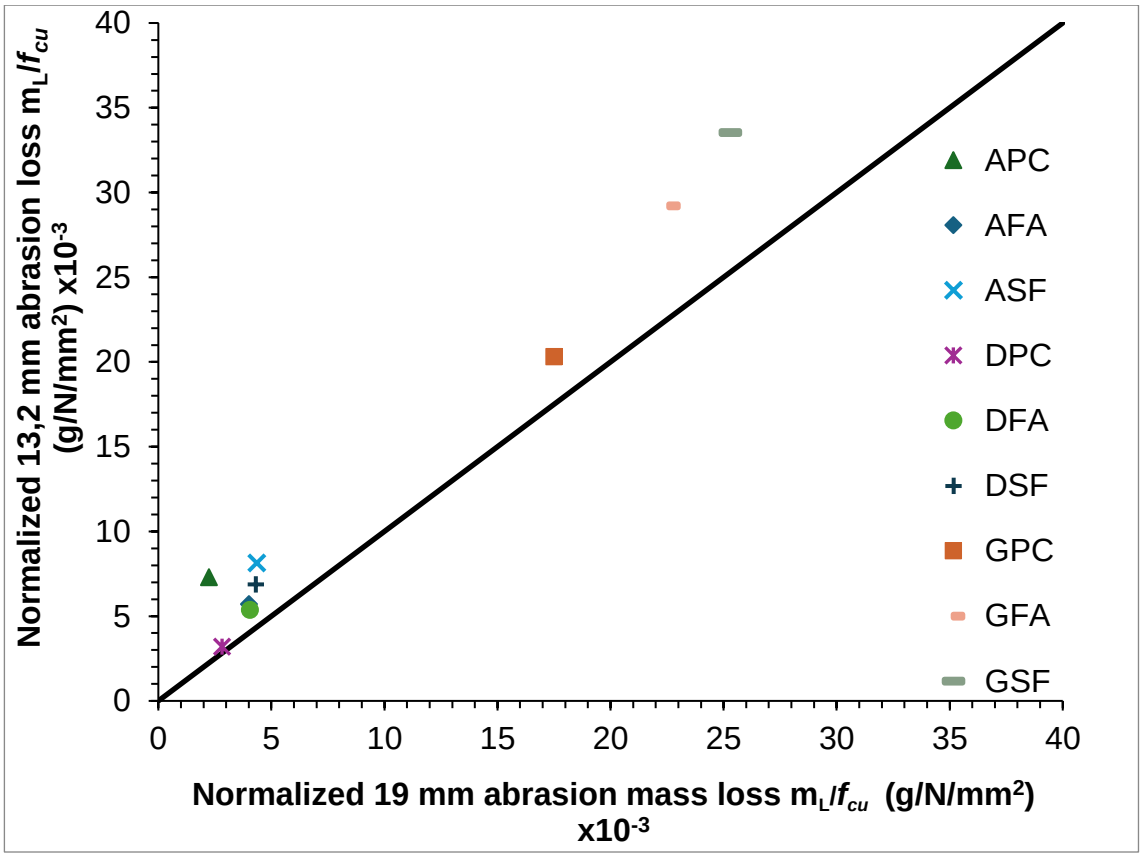


Figure 4.10: Effect of aggregate size on abrasion mass loss at 28 days for different aggregate types, normalized with strength.

Furthermore, the aggregate content (%), both fine and coarse respectively, was also expected to have an influence on the abrasion resistance. Other researchers have shown a linear relationship between the aggregate content and abrasion depth, where the increase in aggregate content resulted in the increase in abrasion depth (Adewuyi, et al., 2017). However, as mentioned above, a study of the influence of aggregate content variation with respect to a particular aggregate type was not the main objective in this study.

4.7 Effect of aggregate grading on abrasion resistance

The slightly inferior abrasion resistance performance of the dolerite aggregates in some cases (DFA13 and DSF13), can also be attributed to the lack of fines in the crusher sand used as shown in Figure D 9 in the appendices. As shown in 4.9 iii above, the physical properties of the dolerite and andesite aggregates was relatively similar. These two aggregates had similar ACV%, LA abrasion Loss (%) values, thus the abrasion mass loss obtained was expected to be similar. Furthermore, the dolerite crusher sand used in this study was a washed sand. This therefore resulted in a significant reduction in the aggregate fines, thus leading to a relatively high Fineness Modulus (FM) of 3.94. Generally, sand with a FM above 2.9 is regarded to be coarse sand (Bonser and Alexander, 2021a). However, the effects of using a washed sand were not immediately apparent, as the abrasion mass loss of the dolerite was comparable to that experienced by the andesite concrete mixes.

The lack of fines in the mixes cast with the dolerite stone therefore resulted in a relatively harsh mix and which was expected to have a lower concrete density due to a lower packing density when compared to the other mixes. Since concrete density is related to the abrasion mass loss observed. The lack of fines was expected to slightly impair the performance of the dolerite aggregate. However, an insignificant influence on the abrasion resistance was observed.

4.8 Effect of supplementary cementitious materials on abrasion resistance

Figure 4.11 shows a comparison of the effect of the binder type for the various aggregate types on the abrasion mass loss observed at 28 days, normalized with compressive strength. The error bars in the figure show a small degree of variability in the data, thus indicating the high reliability of the data.

According to the findings Figure 4.11 when only considering the average mass loss values (PC = 8,9 g/N/mm^2, PC/FA = 11.2 g/N/mm^2 and PC/CSF = 13.75 g/N/mm^2). Concrete with PC had the most superior abrasion resistance when compared to concrete with PC/CSF and PC/FA blends. This result can be attributed to the high rate of strength gain of PC and the relatively slower rate of pozzolanic reactions related to mixes with PC/FA. This, however, was not expected for mixes with CSF, as literature suggests that mixes with CSF have higher rates of early strength gain. For all the mixes, the mixes with CSF had the least 28-day strength when compared to the other mixes with PC and PC/FA. A similar phenomenon was observed with respect to abrasion resistance, where mixes with CSF had a relatively higher abrasion mass loss when compared to the other mix types.

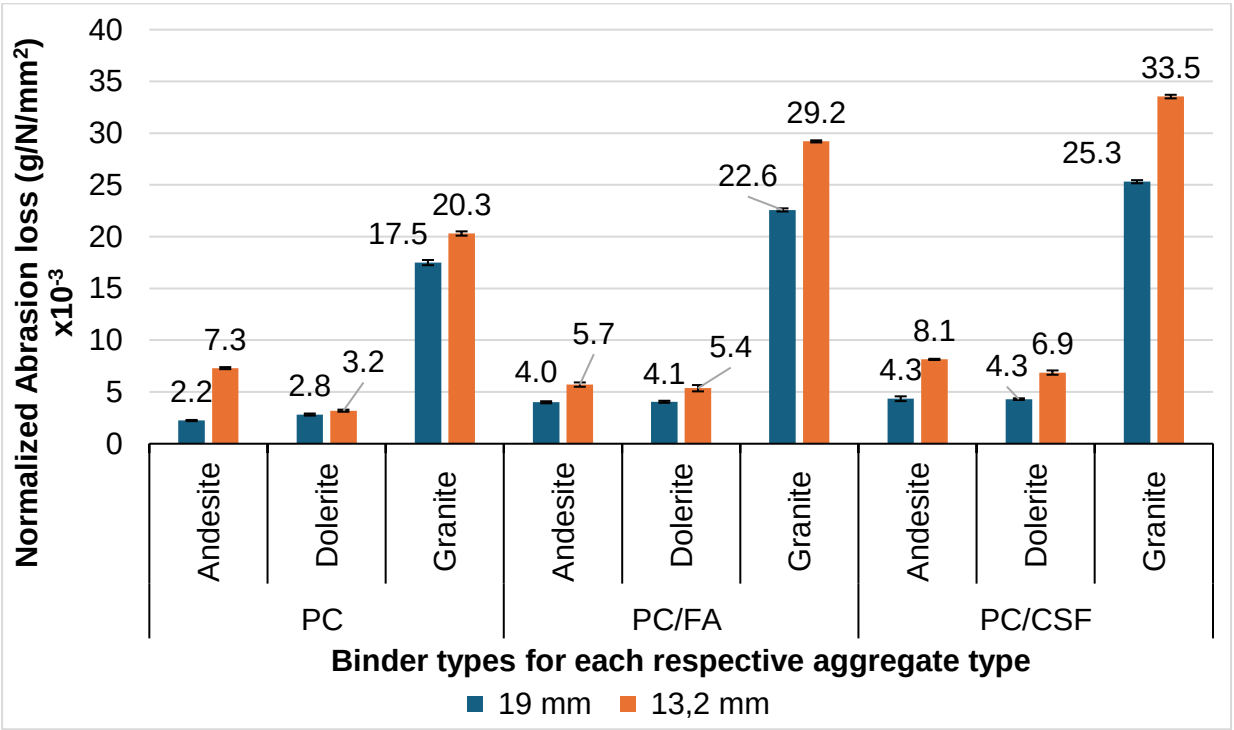
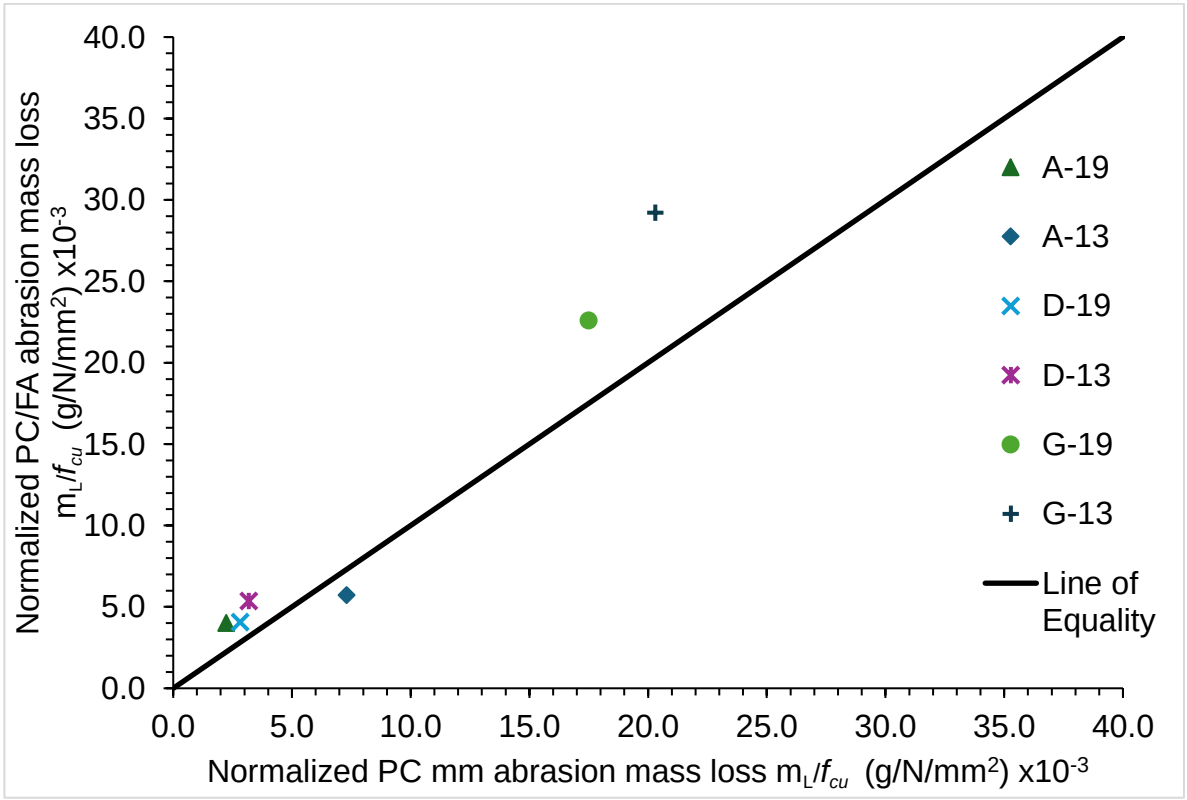


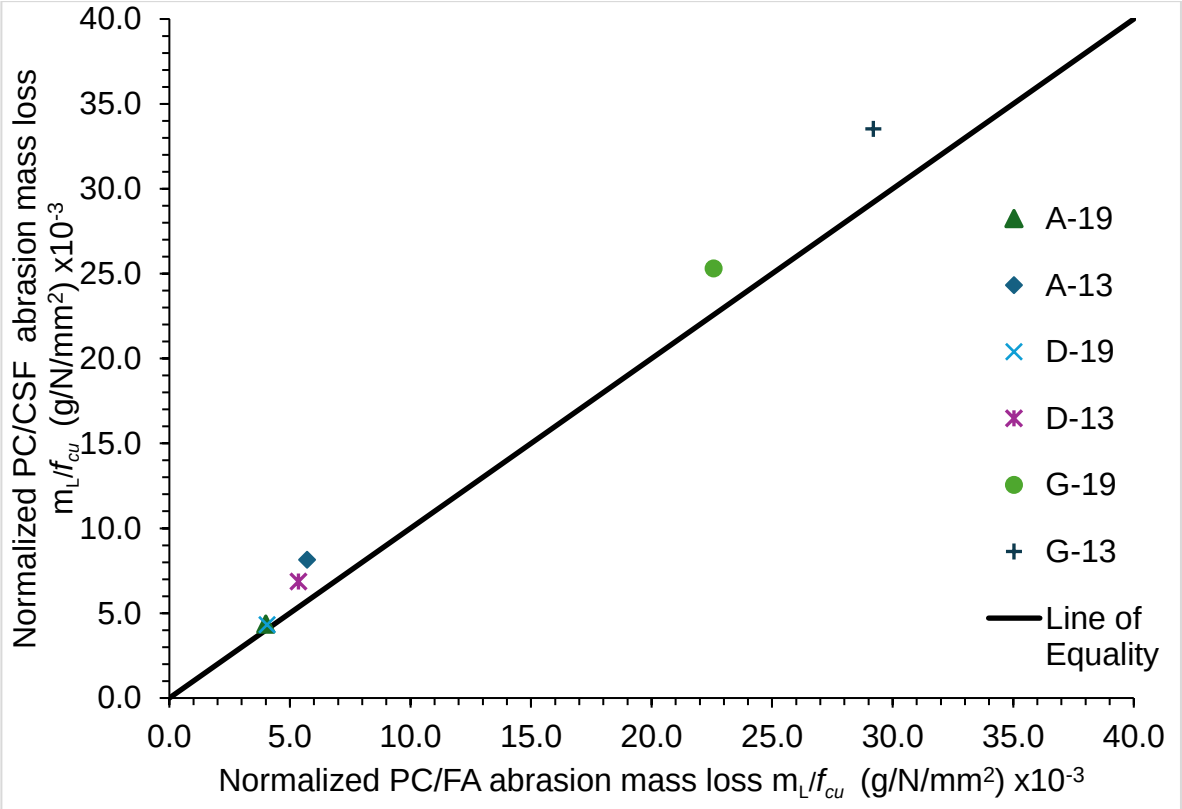
Figure 4.11: Effect of binder type on the average abrasion mass loss measured at 28 days, Normalized with compressive strength.

Furthermore, a similar phenomenon is observed with respect to the abrasion mass loss for each aggregate type. With respect to the binder type, PC had the least abrasion mass loss observed at 28 days. Figure 4.11 also indicates the synergic value to abrasion resistance obtained from the best performing aggregate type, size and binder type. The APC19 mix had the lowest abrasion mass loss, as shown below, and has been analysed throughout the subsequent sections of this research to constitute the best-performing strength, aggregate type and size when compared to the other mixes discussed in this study. Lastly, it is acknowledged that the findings presented in Figure 4.11 should not be regarded as a definitive long-term performance metric for abrasion resistance when evaluated at 28-days. However, these results are instrumental in facilitating comparative analyses of the development of abrasion resistance concerning different binder types at 28 days.

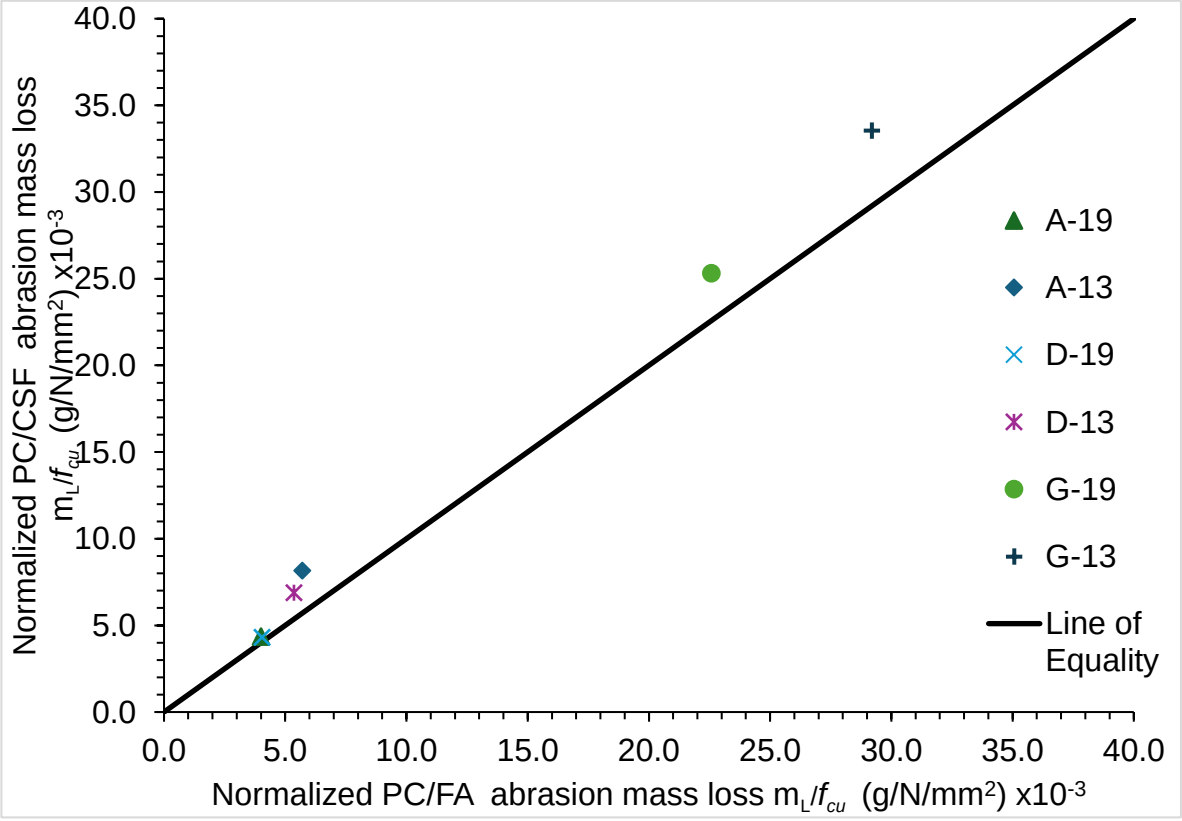
As shown in Figure 4.12 on pages 99 and 100, the normalized abrasion mass loss at 28 days for the various mixes have data points in relatively close proximity to the line of equality. This further shows a relatively minuscule influence of these binder types to abrasion resistance for all the three comparisons. Thus, the result obtained clearly supports that minimal correlation was obtained with respect to the binder type influence on abrasion resistance at 28 days. The 100% PC and PC/FA binders however do show insignificant superiority over PC/CSF; however, the influence is considered to be minimal.



4.12 i: Normalized PC and PC/FA Comparison



4.12 ii: Normalized PC and PC/CSF comparison



4.12 iii: Normalized PC/FA and PC/CSF abrasion mass loss comparison

Figure 4.12: i, ii and iii Effect of binder type on abrasion mass loss at 28 days for different aggregate types and sizes, normalized with strength.

Lastly, as alluded to above, the 28-day results provided in this section do not yield indicative results on the long-term performance of the blended concrete mixes. This is due to the use of pozzolanic supplementary cementitious materials such as FA. The PC/FA mixes are expected to continue to gain the desired mechanical properties of concrete later than 28 days, which would also plausibly contribute to the concrete's abrasion resistance. CSF, however, was expected to yield a relatively low early age abrasion mass loss, due to its contribution to early strength development. This however was not the case, as the 28-day compressive strength for all the mixes with CSF were lower than those in their respective aggregate type and size groups. Interestingly, the aforementioned result holds true for the abrasion mass loss as well, where mixes with CSF had higher abrasion mass loss.

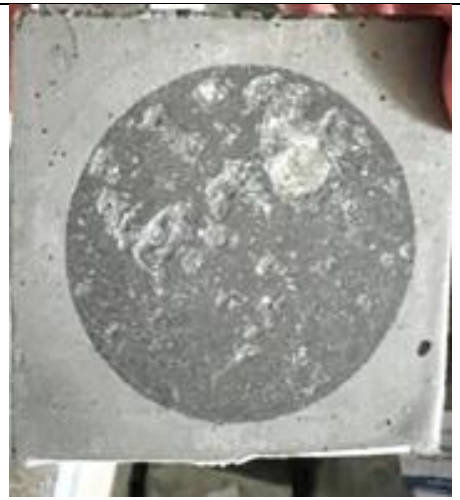
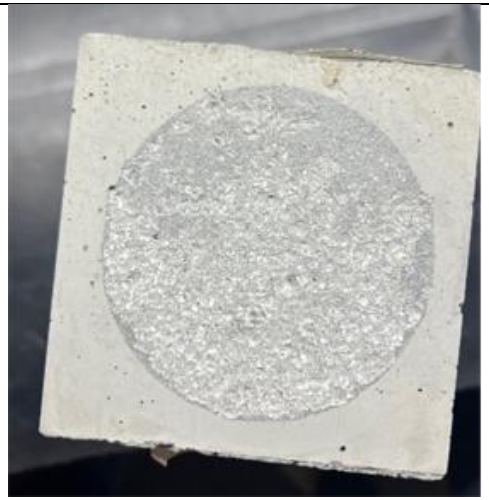
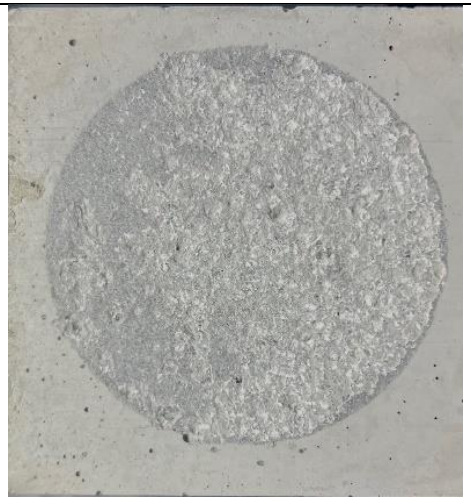
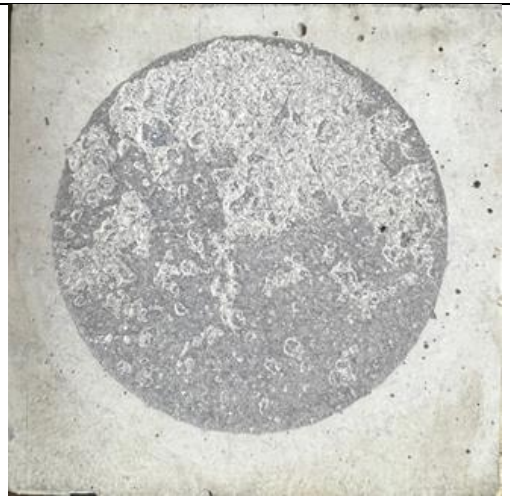
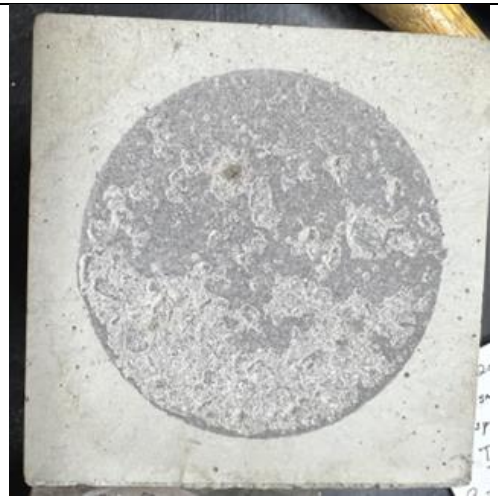
4.9 Visual assessment of the abraded concrete sample surfaces

Table 4.2 visually represents the various 19 mm aggregate 100x100x100 test cube's 28-day abrasion test results, for the different aggregate and binder types. The attached photographs clearly illustrate a considerable difference on the abraded surfaces for the various mix types, where the granite mixes had the most abraded surfaces when compared to the dolerite and andesite mixes. Furthermore, minimal differences can be observed with respect to the binder type comparison, which was expected as the influence of binder type was less significant to abrasion resistance when compared to the aggregate type at 28 days.

Similar visual trends were observed with respect to the 13,2 mm aggregate mixes, where the granite aggregate mixes had the most aggressively abraded surface when compared to the andesite and dolerite mixes. Similar to the pictures below, no visual differences were found with respect to the binder types.

Lastly, some of the pictures (APC 19 and GPC19) clearly depict the abrasion sequence, as highlighted in Figure 2.4 in the Literature Review, where the paste abrades around the aggregate due to its relatively weaker abrasion resistance, leaving the more abrasion resistant aggregate exposed to abrasion (Scott and Safiuddin, 2015). Furthermore, the APC19 had the highest concrete compressive strength, which resulted in a more abrasion resistant paste. This is also evident in the pictures below, as the face of the APC19 sample had the least abraded surface when compared to the other abraded surfaces.

Table 4.2: Visual comparison of the 19 mm abrasion test results at 28 days

Mix Type	100% PC	85/15 PC/FA	92.5/7.5PC/CSF
Andesite	 Abrasion mass loss: 0.27g	 Abrasion mass loss: 0.40g	 Abrasion mass loss: 0.47g
Dolerite	 Abrasion mass loss: 0.30g	 Abrasion mass loss: 0.40g	 Abrasion mass loss: 0.37g

Granite	 abrasion mass loss: 1.53g	 abrasion mass loss: 2.07g	 abrasion mass loss: 1.63g

CHAPTER 5

5 PERFORMANCE BASED DESIGN CONSIDERATIONS FOR ABRASION-RESISTANCE

From the abrasion resistance tests carried out in this research, it was evident that the development of abrasion resistance in concrete is a time-related process, where the abrasion resistance increased at a decreasing rate with age. In this chapter, the 28-day abrasion resistance results, together with the analysis of typical concrete silo environmental exposure conditions, are then used to provide deemed to satisfy design considerations for the design of impact and abrasion resistant concrete.

Similar experiments using different test methods such as the wire brush, sandblasting, and various ASTM methods also yielded results consistent with those observed in this research. Although there were nuances with respect to research methodologies and the aims of the various studies, the findings suggest that the 28-day results can be deemed to be a reliable primary benchmark indicator of the concrete's performance. This reliability is further underpinned by the relatively low percentages of PC substituted with FA and CSF respectively. Nevertheless, the following discussions below factor in the potential development of abrasion resistance beyond 28 days for the mixes with FA and CSF substitutions, based on the results discussed above.

5.1 Performance based design considerations for abrasion resistant concrete

Performance based design (PBD) is a structural design approach that focuses on achieving specific performance criteria (Beushausen, et al., 2021b). This design methodology systematically addresses critical issues pertaining to the durability and reliability of concrete structures, with the aim of improving structural performance, extending lifespan, and optimizing the overall life cycle costs related to the rehabilitation and maintenance of structures.

In relation to the abrasion resistance of concrete in silos, no comprehensive performance-based designs have been implemented previously. As such, the considerations given below are based on the *deemed to satisfy rules* of PBD. These deemed to satisfy provisions and guidelines act as prescriptive benchmarks, of which designs that comply with these benchmarks are expected to reach the required performance targets. These *deemed to satisfy rules* can then be integrated into a *fully probabilistic approach* over time, as reliable statistical data from research becomes available. The following considerations should be addressed when carrying out a performance-based design for abrasion resistant concrete.

5.1.1 Development of tribosimulative testing

To adequately test for the abrasion resistance of concrete accurately, a simulative test must be conducted, and should model the contact type, condition, and severity of the exposure environment. In the case of material silos and bins in mineral processing, the simulative action from the test should mimic the abrasion of the internal silo wall due to the stored material impacting and abrading the internal concrete surface as established in Section 2.5 in the Literature Review. Thus, for the tribosimulative testing of bins and silo concrete in mineral processing, the SANS 1058 tumbling test is identified to be the most suitable test.

In a study on the impact and abrasion wear of ore passes, it was found that the tumbling test best simulated the exposure environment (Heerden, et al., 2005). The tumbling test simulates the effect of 'hard' ore material impacting and abrading on the internal surface of the silo, as the solid hardened steel balls from the test apparatus collide with the exposed face of the concrete sample.

It is important to note that the contact type of abrasion differs from other types of abrasion induced by foot traffic, rubber on concrete, or the flow of water with suspended solids, as established in Section 2.10. Therefore, to obtain uniformity in results for the development of a fully probabilistic approach, uniform and simulative tests should be conducted, and core samples be obtained from structures to measure and contrast lab results against the real-life performance of the structure. This will assist in the creation of wear life prediction models for the development of a fully probabilistic approach.

5.1.2 Establishing the required performance parameters

The performance-based design guidelines adopted below are based on the mechanisms of concrete deterioration, the influence of particle size on impact and abrasion, and the characterization of abrasive ore particles reviewed in the literature review. Furthermore, the 28-day abrasion mass loss results of the ACI mix recommendations in Figure B 2 in Appendix B are then used to establish a benchmark for results deemed to satisfy the performance requirements for severe exposure as outlined below.

Table 5.1 on page 106 shows the proposed abrasion severity rating based on the contact types, material size and hardness. Furthermore, Table 5.2 shows the proposed acceptance criteria, based on the above-mentioned severity rating using a weighted decision matrix approach. The required abrasion resistance performance is referenced to the structure, and the environment the structure is used in (rows a to c). Row d shows cumulative severity rating (based on rows a to c), which dictate the associated desired level of durability(e), which is discussed in detail below.

Table 5.1: Impact an abrasion severity rating based on contact type, material size and hardness.

CRITERIA		SEVERITY RATING				
		1	2	3	4	5
a	Tribological contact type (Figure 2.2) & (Table 2.1)	Low friction abrasion	Abrasion	Abrasion and impact	Impact and abrasion	Heavy Impact
b	Material top size (mm) (Figure 2.3)	< 4	> 4 ≤ 22	> 22 ≤ 80	> 80 ≤ 1000	<1000 >100
c	Stored Material Mohs hardness (Figure 2.5)	< 2	>2 ≤ 3	> 3 ≤ 5	> 5 ≤ 7	> 7

Table 5.2: Abrasion mass loss acceptance criteria at 28-days with respect to the relevant exposure conditions and severity ratings.

		Condition of exposure				
		Mild	**Moderate**	**Severe**	**very severe**	**extreme**
d	Resultant Severity Rating	≤ 3	>3 ≤ 6	>6 ≤ 9	>9 ≤ 12	>12 ≤ 15
e	**Acceptable m_L (g)**	**$20 > m_L \geq 15$**	**$15 > m_L \geq 7$**	**$7 > m_L \geq 3$**	**$3 > m_L \geq 2$**	**$m_L < 2$**
f	**Design life**	**50 years**				

Classification of the environmental exposure conditions (rows a to c)

The aggressiveness of the exposure environment has been comprehensively reviewed in Section 2.3. It has been established that the severity of the concrete deterioration is dependent upon several factors, including the tribological contact type, as well as the size and hardness of the stored ore material. These factors serve as the foundation for classifying the conditions of exposure, as detailed in rows a) to c) of Table 5.1.

The criteria shown in row a) is based on the literature reviewed in sub-Section 2.3.1, on the various tribological contact types observed in silos used in mineral processing. Various researchers concluded that impact loads have been identified to have a dominant influence on the wear of silo internal concrete walls when compared to abrasion (Heerden, et al., 2005). For this reason, the ‘extreme’ classification of the exposure conditions is placed on ‘heavy impact’ loading, whereas wear caused by low-friction abrasion is categorized as a mild exposure condition. These parameters can be further refined to consider the particle impact energy, and impact angle as shown in Table 2.1 on page 24.

Furthermore, the criteria shown in row b) is a function of the stored ore material top size (mm), which is discussed in sub-Section 2.3.2 in the literature review. The material top size ranges shown in row b) are then linked to the tribological contact type, and exposure as shown in Figure 2.3 and Table 2.1, obtained from a study on the relationship between ore top size and tribological contact types (Metso, 2011).

The material hardness shown in row c) is based on the classification and characterization of abrasive ores in bulk materials stores as discussed in sub-Section 2.4.2. Where hardness is established to play a critical role on the rate, and extent of concrete deterioration (Kulu, et al., 2008). A strong correlation between abrasive particle size and hardness has been established by various researchers (Chotěborský, et al., 2009). This correlation has been used to link the material hardness in row c), to the ore size in row b), for the determination of the severity of the exposure. The Mohs hardness values used in row c) are referenced from Figure 2.5, which show the relationship between hardness and stored material top size.

Development of the acceptance criteria (row e)

The concrete's durability is assessed by means of an abrasion mass loss value (m_L), which quantitatively measures the abrasion resistance performance of the concrete. The value of m_L can be obtained as shown in Section 3.4.6. Row e) on Table 5.2 outlines the acceptance criteria based on the summation of the severity rating of the exposure conditions (rows a to c), and should hold true for all various mix designs, regardless of the aggregate properties, binder types and w/c ratios. A more in-depth assessment of the influence of the concrete constituents on abrasion resistance is highlighted in Section 5.2 on page 108.

The norite trial mix results in Table A 1 were used to establish a benchmark for a 'very severe' exposure environment. These mixes were all deemed to have an acceptable abrasion mass loss for the construction of the RoM silo (categorized as very severe exposure in Table 5.1), as they had abrasion mass loss values < 3 g at 28 days. Furthermore, the silo is exposed to PGM ores with a top size of +/- 450 mm, and a relative Mohs hardness 6 to 7 (Junge, et al., 2023), which meet the very severe criteria mentioned above based on both the size and hardness which was outlined in Section 2.3. Thus, the performance of this silo can be used as a benchmark for future research.

It is important to note that even though the values provided in Table 5.1 and 5.2 are based on approximations established from the analysis of the results in Chapter 4 and the details presented in Chapter 2 on the exposure environment. In addition, they also offer a useful starting point. Further research development can be undertaken to evaluate the suitability of the acceptance criteria in various practical applications. This will also help refine the parameters for more reliable predictions of abrasion resistance.

The required service life of the structure (row f)

The required service life of the structure is an important consideration with respect to the design process. The importance of establishing a service life specification lies in the understanding that the degree of abrasive wear experienced by the silo concrete is directly influenced by the abrasive and impact load cycles the concrete is exposed to throughout the service life of the structure (Scott and Safiuddin, 2015). Thus, the required concrete abrasion resistance increases with the increase in service life.

This research did not examine the service life of silos used in mineral processing, but understanding this is essential for the development of comprehensive design considerations regarding concrete abrasion resistance. Nevertheless, it is expected that the service life of the structures in the mineral processing plant will be the same as the life of the mine. Typically, this service life, often set at around 50 years, should be determined by the mine owner. Guidance on typical values can be found in design codes such as SANS 10160 and EN 1990.

5.2 Deemed to satisfy design: concrete composition considerations

The following specifications integrate aspects of both prescriptive and performance-based approaches. Furthermore, they also provide a more comprehensive understanding of the factors that influence the abrasion resistance of concrete, and thus assist to refine the abrasion resistance parameters more accurately. They can also be used in conjunction with the test acceptance criteria given in Table 5.1 above.

The results presented in Chapter 4 clearly support that the abrasion resistance of concrete is mostly influenced by a combination of the strength and hardness of the aggregate, the strength of the aggregate -paste bond, and the strength of the paste (which is indirectly measured using compressive strength) (Beushausen, et al., 2021b). It should therefore follow that improving the above-mentioned properties should result in the overall improvement of the concretes' abrasion resistance.

5.2.1 Specification of compressive strength for abrasion resistance performance

A moderately positive correlation between concrete compressive strength and abrasion resistance was observed in the study. Correlation coefficients of 0.84 and 0.6 for the mixes cast with the 19 mm and 13,2 mm aggregate sizes respectively, were obtained in relation to the concrete compressive strength and abrasion resistance. However, the structural analysis and design should dictate the compressive strength required. Only after the structural design specified compressive strength, should the compressive strength required for abrasion resistance be factored in. The compressive strength required for abrasion resistance should therefore always be greater or equal to the concrete compressive strength specified in the structural analysis and design. It should be noted that to obtain values that lie within the ranges in Table 5.1 for the various exposure conditions, other factors other than strength can be varied as well, which will be discussed below.

Furthermore, above a compressive strength of 70 MPa (mixes with a mass loss < 1.0 g), there is very minimal improvement in abrasion resistance over time. This was observed to be the case as the various mixes had similar performance, and minimal mass loss differences throughout the 7,14 and 28 days. This, however, is the case given that the influence of the aggregate type is considered. Thus, it could be extracted from the analysis that the benefits of high strength, and strength gain development on the abrasion resistance of concrete are limited above a compressive strength of 70 MPa.

For very severe to extreme cases, concrete compressive strength > 50 MPa should be specified, this is based on the abrasion mass loss ranges in Table 5.1. At 28 days, the abrasion mass loss for all 50 MPa mixes was lower than 2.5 g, and in some cases lower than 2 g, thus indicating its suitability for application for the above-mentioned cases. See Table E 1 for more information.

When considering extremely abrasive environments, the abrasion resistance of concrete can be improved by paring a high concrete compressive strength (f_{cu} > 80 MPa) with high performance aggregates as expressed in Section 5.2.3. Furthermore, the abrasion resistance of concrete was shown to be influenced mostly by the aggregate properties rather than the compressive strength, therefore the aggregate selection should take preference over the specification of compressive strength.

5.2.2 Specification of concrete density for abrasion resistance

Two distinct data point groups of abrasion mass loss with respect to concrete density were obtained from this study as shown in Figure 4.5. Concrete density data groups, specifically within the ranges of 2200 kg/m³ to 2500 kg/m³ and 2500 kg/m³ to 2800 kg/m³, were obtained in this research. The concrete mixes corresponding to the higher density range (2500 kg/m³ to 2800 kg/m³) demonstrated lower abrasion mass loss recorded throughout the research, which is supported by a strong correlation of 0.88 and 0.94 respectively, where the increase in density resulted in the decrease in abrasion mass loss observed. Consequently, it is recommended that concrete densities be maintained within the 2500 kg/m³ to 2800 kg/m³ range, or above, as a notable correlation was identified between increasing concrete density and enhanced abrasion resistance.

This recommendation above is suitable for both severe and extreme cases, however, this alone was not seen to benefit abrasion resistance when considered separately. Concrete density should rather be considered together with the compressive strength, and aggregate properties. When assessing the influence of compressive strength on abrasion resistance, it is crucial to concurrently evaluate concrete density in conjunction with other pertinent factors, including aggregate size, type, and density. A comprehensive analysis of these variables is necessary to accurately determine their collective impact on the abrasion resistance of concrete. This consideration increases

the probability of meeting the exposure condition related acceptable mass loss ranges in Table 5.1 above.

5.2.3 Aggregate properties and characteristics influencing abrasion resistance performance.

The selection of aggregates for the production of abrasion resistant concrete should be based on the properties, and performance of the aggregate as outlined below. However, it is important to note that the aggregate selection would be limited by the geographical availability of the aggregate for a particular construction site.

The results obtained in this research show that there is a very strong correlation between the aggregate type, size, density, and abrasion resistance. Figure 4.8 shows a correlation of 0.97, between the aggregate density, and the abrasion mass loss at 28 days, where the increase in aggregate density resulted in the decrease in the abrasion mass loss observed. Furthermore, the aggregates with a density ranging between 2850 kg/m^3 to 3000 kg/m^3 showed relatively similar abrasion resistance. Thus, the aggregate density selection criteria for abrasion resistant concrete should preferably range between the above-mentioned densities, or greater where possible.

The ACV values and LA abrasion tests were used as a means of selecting aggregates in this study. These values are useful indices of overall quality, but the usefulness of the aggregate is still confined to the acceptance limits in SANS 1083 (2018). Lower ACV and LA abrasion values were observed to produce concrete with significantly high abrasion resistance. Therefore, aggregates with lower ACV and LA abrasion values are preferred. ACV values between 5.9 – 12% and LA abrasion values < 9 % are preferred for more severe and extreme cases as they had the highest abrasion resistance. Furthermore, the aggregate 10% FACT values should also be considered, aggregates with a 10% FACT in excess of about 170kN are recommended for concrete with a compressive strength more than 60MPa (Davis and Alexander, 1994).

Lastly, the aggregate size was also established to have an influence on the abrasion resistance of concrete. The results on Figure 4.10 show that the abrasion mass loss observed increased with the decrease in aggregate size for all the 18 mixes. Thus, indicating the positive influence of increasing aggregate size. Larger aggregates, where practically possible, are preferred, as they are shown to improve abrasion resistance. However, care should be taken to minimize effects of larger aggregates on the salient constructability requirements, concrete compressive strength and other durability performance requirements.

5.2.4 The influence of construction quality on the abrasion resistance of concrete

Even though the experimental work in this research was not focused on the workmanship, it is important to note that it is as important as the considerations mentioned above. The overall performance of the structure, relative to the design,

relies heavily on the quality of construction. These construction quality considerations discussed below, are based on the literature reviewed in Section 2.8 of the Literature Review.

The fresh concrete properties such as setting times and workability discussed in 3.4.3 and 3.4.4 affect the quality of the concrete, which could be detrimental to the abrasion resistance performance of the concrete. The setting times influence the formation of cold joints from two successive silo slipform lifts, which could later develop into cracks as discussed in the findings from the SIMM inspection. These cracks promote prying action that forms between the concrete counterface and the stored material. This would therefore result in the rapid increase in concrete deterioration. Additional information on the influence of cracks on silo concrete deterioration can be obtained in Appendix C.

Similarly, the setting times affect the concrete's ability to be placed and compacted also affects the quality, as poorly compacted concrete will significantly affect both the mechanical properties, and overall durability of concrete (Razak, et al., 2004). This results in the increase in concrete porosity, and promotes the formation of microcracks in the concrete (ASTM, 2018). These would therefore result in the impairment of abrasion resistance performance of the counterface. The initial setting times obtained in this research did not vary significantly from the times expressed in the ACI recommendations. However, care should be taken as these times are influenced by site specific ambient temperature, wind, humidity and transportation requirements.

5.3 Practical implications of under-designing for abrasion resistance

Section 3.5 above outlines the risks related to under designed concrete for severe to extreme impact and abrasion. Within the first 2 years of operation, a liner had to be installed on the internal surface of the silo to counteract the concrete material loss on the internal surface due to impact and abrasion. However, 17 years later the liner had been abraded off and has resulted in the exposure of reinforcement as seen in Figure 3.9. Research has shown that the exposure of reinforcement increases the rate of deterioration, specifically the corrosion of reinforcement. This can result in further, and increased rate of deterioration of the concrete, due to a synergy of the deterioration mechanisms.

Furthermore, structural engineers rely on the bond between the reinforcement and the concrete for the tensile capacity of the concrete. Concrete silos experience relatively high radial stresses as discussed in Section 2.5.1 in the Literature Review. The abrasion of concrete reduces the concrete and reinforcement bond strength, thus compromising the structural integrity of the silo. This therefore causes material related risks, and the risk of sudden collapse which could lead to materials processing production stoppages and safety concerns. Therefore, the selection of concrete for used for silos and bins in mineral processing should be reliable and durable enough to withstand the service life environment, with minimal rehabilitation required.

5.4 Comparison between ACI concrete design recommendations and experiment results

This subsection seeks to draw comparisons between the *Commentary on Standard Practice for Design and Construction of Silos and Stacking Cubes for Storing Granular Materials* (ACI 313R-97, 1997), and the results obtained from this research. References will be drawn from the arguments put forth in the Research Methodology section of this research report.

ACI recommendation - R2.2-Cements

"In general, the types of cement permitted by ACI 318 are permitted under the recommended practice, except as noted. Experience has shown that there can be some variation in the physical properties of each type of cement. Type I cement that is very finely ground (a fineness modulus greater than 2000 on the Wagner scale) can act in the same manner as Type III and cause difficulties by accelerating the initial set during a slipform operation." (ACI 313R-97, 1997:2).

The above statement indicates that Type I cement causes constructability related issues (linked to accelerated initial set), thus is not suitable for the construction of silos. These effects have been well established to be adequately counteracted by the introduction of a retarder. Additionally, very significant benefits were obtained from the use of Type I cements on the abrasion resistance when compared to the ACI 313 recommendations. The initial setting times of the CEM I mixes can be made more favourable with the introduction of retarders where required. Thus, this alone cannot be used as a sole reason to oppose the use of Type 1 cement.

ACI recommendation - R2.3 Aggregates

"Aggregates for the exposed parts of the silo or bunker should be the same type and source if it is desired to avoid variations in appearance of the complete work." (ACI 313R-97, 1997:2).

The above quoted commentary does not make mention of the other aggregate requirements established in the results section above, e.g. the influence of aggregate type, size and density on abrasion resistance. Therefore, further considerations are required to be addressed with respect to the abrasion resistance performance of the silo internal wall concrete. These considerations are as outlined in 5.2.3 above.

ACI recommendation - R2.5 Admixtures

"The use of admixtures in concrete silo walls is a common construction method of controlling the initial set of concrete, and therefore the rate at which the slipform… may be raised." (ACI 313R-97, 1997:2-3).

The use of chemical admixtures in silo construction should be predominantly aimed at optimizing the w/c ratio. By effectively reducing the water content, these admixtures

enhance the desired mechanical properties of the concrete as mentioned above. A lower w/c ratio is instrumental in improving the compressive strength and minimizing pore volume, thereby increasing the overall density of the hardened concrete. As established above, concrete density has a significant influence on abrasion resistance, therefore, the use of a superplasticizer would yield greater benefits to the abrasion resistance of concrete, than the use of retarders on influencing setting times.

With respect to fresh concrete, the enhanced density positively affects the concrete stiffness, enabling the formwork to be stripped (lifting of the sliding formwork) with minimal risk of collapse. The use of a retarder would, however, be essential where site conditions require longer setting times.

5.5 Performance-based design summary

The performance-based design considerations outlined in this chapter offer quantifiable parameters which can be used to characterize the performance of concrete exposed to impact and abrasion. As mentioned in the Literature Review, further development into the design of abrasion resistant concrete for severe and extreme cases is required, specifically for mineral processing operations. The design, analysis and specification of concrete constituents should not only consider the ability of the structure to resist structural loads, but also environmental loads affecting the durability of the concrete.

The approach outlined in this section is based on the quantification of the exposure environment, which is dependent on the tribological contact type, abrasive particle size, and hardness. These parameters are then used to indicate the severity of exposure, and thus the acceptance criteria, based on the acceptable mass loss observed at 28 days, using the SANS1048 tumbling test and test procedure.

The performance of the constituents of concrete can also be curated to fit within a particular performance criterion, to ensure that the overall concrete performs within the exposure condition abrasion mass loss ranges specified in Table 5.1. Even though further development of the above testing and acceptance criteria is required. The approach offers a starting point into the performance-based design considerations, allowing ongoing improvement and adaptation as additional data becomes available.

Lastly, a comparison between the performance of the ACI recommendations and the other mixes cast in this study is conducted in Section 5.4. This is done to evaluate the abrasion resistance performance limitations of the ACI recommendations, and the suitability of the proposed mixes with a 0.4 w/c ratio on silo constructability.

CHAPTER 6

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The main aim of this study was to investigate RC silo concrete deterioration due to impact and abrasion wear resulting from the stored bulk solids, and to use a tribosimulative test to provide a comprehensive understanding of the influence different concrete constituents have on improving the durability of concrete. The experimental outcomes are outlined in this section, and the conclusions made are based on the analysis of the results, and discussions in this research.

The findings from the literature review indicate a significant gap in the understanding of the mechanisms and factors contributing to silo deterioration in mineral processing, particularly concerning the effects of impact and abrasion wear. Current research addressing these phenomena remains limited, resulting in an inadequate understanding of tribological interactions between bulk solids and silo RC. This underscores the necessity for further investigation into the wear mechanisms and material behaviours under silo operational conditions.

The silo inspection conducted in the study revealed that these structures are subjected to extremely abrasive environmental exposure conditions. From the inspection, it was observed that the abrasive characteristics of RoM platinum ore have led to significant deterioration of the sacrificial shotcrete liner on the internal face of the silo wall, with complete wear observed in certain areas. The primary factors contributing to the deterioration of the silo's structural condition were identified as the abrasion and impact from bulk solids interacting with the internal wall surfaces, which correlates with observations from literature. This deterioration has resulted in the exposure of structural reinforcement elements at the lower segment of the western wall. At the time of the investigation, the silo was not completely empty, but it was noted that one horizontal hoop reinforcement bar was damaged and lost its design strength. The current condition of this area poses a vulnerability that could possibly lead to a local or global failure of the structure.

The above-mentioned findings from the inspection therefore underscore the critical importance of the development of performance-based designs and construction considerations for, silo slip form construction, and the overall concrete durability performance throughout the design life of the structure. By comparing the recommendations established by the ACI with the mixes with a 0.4 w/c ratio, this research highlights the potential for enhancing the concrete's durability performance, particularly in terms of its abrasion resistance and compressive strength, without affecting the salient construction requirements.

Additionally, the second comparison drawn on the influence of the concrete constituents on abrasion resistance reveals that changes in the constituents, such as aggregate type, size, and binder variations, play a significant role in improving the overall durability of the concrete. These will be discussed in more detail in sub-Section 6.1.1. Generally, all 18 concrete mixes met their specified characteristic compressive strengths at 28 days, with considerable margins above the required strengths. Therefore, the compressive strength of the silo concrete was not a concern for any of the mixes.

Lastly, it is acknowledged that additional benefits of SCMs can be viewed later than 28 days, and that the 28-day compressive strength and abrasion resistance performance of the mixes with SCMs can be slightly lower than the ones with PC. However, for concrete mixes with small SCM replacement quantities (< 20 %) the 28-day results provide a sufficient and reliable indication of performance. Thus, the credibility and usefulness of the 28-day results cannot be ignored. These results serve as a reliable benchmark for evaluating the initial behaviour of concrete, especially when the SCM replacement percentage and quantities are relatively low.

6.1.1 Conclusions from the concrete abrasion resistance test and the influence of concrete constituents on abrasion resistance

To adequately design for the aggressive exposure conditions outlined above, the SANS 1058:2012 tumbling test was identified to be a suitable tribosimulative test and was thus adopted in this study. This abrasion test was then used to study the influence of concrete constituents on abrasion resistance. 18 different andesite, dolerite and granite mixes were cast and tested at 3, 7, 28 and 7, 14 and 28 days for concrete compressive strength and abrasion resistance respectively. The conclusions drawn from the experiment are detailed below.

The abrasion resistance of the concrete is inherently linked to the age of concrete, revealing a direct relationship whereby the increase in age correlates with improvement in abrasion resistance. The increase in age of concrete results in the increase in the abrasion resistance of the concrete at a decreasing rate. This phenomenon was evident for all 18 mixes.

Moreover, the abrasion resistance of concrete was found to be strongly associated with the concrete compressive strength, with correlation coefficients of 0.84 and 0.6 observed for the 19 mm and the 13,2 mm aggregate mixes respectively. The increase in concrete strength results in the increase in the overall abrasion resistance of the concrete. This was evident throughout the abrasion mass loss observed from the mixes cast in this research. The rate of abrasion resistance gain is also a function of the compressive strength gain, where higher strength concrete had a relatively small difference in abrasion resistance between 7 to 14 and 14 to 28 days when compared to the relatively lower strength concrete.

Furthermore, the increase in concrete density showed an increase in the abrasion resistance of the concrete. High correlation coefficients of 0.94 and 0.88 for the 13,2 and 19 mm aggregate mixes, respectively, were observed between concrete density and abrasion mass loss were. Indicating a relatively high reliability of the trend from the data points. It could therefore be argued that the abrasion resistance of concrete is also influenced by the density of the concrete. In this case, the concrete density was largely influenced by the density of the aggregate.

The performance of the granite aggregates with respect to abrasion resistance was different from what was established in literature. Granite aggregates were established to have a relatively high abrasion resistance from the investigations discussed in the literature review. However, the investigations conducted in this research show that they had the least abrasion resistance when compared to andesite and dolerite aggregates. This consequently leads to a disparity in alignment with existing literature, resulting in a misalignment of interpretations. The solution proposed in Section 5.2.3 therefore requires that the specification of aggregate should not be by aggregate name, but rather by the aggregate properties such as the FACT 10%, ACV% and LA Abrasion %. This allows for more accurate performance-based design specification of aggregates.

The degree of influence of the aggregate on concrete abrasion resistance depends also on the strength of the concrete. The findings indicate that the enhancement of concrete's abrasion resistance is significantly correlated with both the compressive strength of the concrete and the quality of the aggregate. This was evident as the mixes comprised of harder aggregates and higher concrete compressive strengths had the highest abrasion resistance when compared to those cast with poor aggregate quality.

The aggregate size also plays an important role in the abrasion resistance of concrete. Similar concrete mix types with only the aggregate size as a differentiator (e.g. APC 19 and APC13) had different abrasion resistance mass loss observed, where the larger aggregates experienced the least amount of abrasion mass loss. Thus, together with the influence of concrete compressive strength, the specification of large, hard and dense aggregates for severe abrasion exposure should be a primary consideration.

Lastly, when analysing the mixes cast with a w/c ratio of 0.4 it becomes apparent that while compressive strength significantly contributes to the enhancement of abrasion resistance, it cannot be regarded as a sufficient sole indicator of the abrasion resistance properties. Notably, the mixes demonstrated a decrease in the abrasion mass loss with age, when the results were normalized with concrete compressive strength. This suggests that other than concrete compressive strength, other factors play a more critical role in influencing the abrasion resistance of concrete. This therefore means that when taking into consideration silo concrete mix design, more

emphasis should be placed on the concrete constituents other than the compressive strength.

6.1.2 Conclusions on the performance-based design considerations, for abrasion resistant concrete, for mineral processing operations.

The proposed acceptance criteria for abrasion mass loss as outlined in Table 5.1 provides a framework for evaluating the performance of the concrete under specific environmental exposure conditions (i.e., silos used in mineral processing). The alignment of these findings with the exposure conditions of PGM ores, characterized by significant size and hardness, validates the applicability of the established criteria. This approach not only serves as a foundation for benchmarking but also highlights the need for continued research.

The deemed-to-satisfy design approach for assessing the abrasion resistance of concrete represents a practical and effective way of ensuring that structures maintain their durability in exposure environments characterised by extreme impact and abrasion wear. By following these performance-based guidelines, designers can mitigate the risk of premature deterioration or failure of concrete structures due to the physical factors mentioned above. However, despite the simplification offered by this approach, it is important to acknowledge that it may not always serve as the most cost-effective or efficient solution for all projects, necessitating careful consideration of context-specific factors.

The findings indicate that adherence to ACI recommendations provides a solid foundation for structural integrity, while innovative adjustments to mix design can lead to advancements in concrete's mechanical properties without compromising construction requirements. This dual approach not only contributes to a deeper understanding of concrete performance but also serves as a valuable resource for industry practitioners seeking to implement optimized mix designs in silo slipform applications, and overall durability performance.

Overall, the insights gained from this investigation emphasize the importance of continuously exploring and refining concrete compositions to meet evolving construction demands, ultimately fostering more durable structures. Future research should further explore the long-term performance implications of these findings in real-world applications to validate and extend the applicability of the proposed considerations.

6.2 Future research recommendations

- Future studies will be essential for refining the performance-based design and acceptance criteria outlined in Table 5.1, thus enhancing our understanding of abrasion resistance and ensuring that materials can withstand the depth of their intended applications.

- Refining parameters for evaluating abrasion resistance in silos, including the development of predictive models that can cater for a wider array of abrasive materials other than those outlined in this study.

- A study on the influence of the variation in strength on abrasion resistance. This can also be used to identify when the aggregate size and type become more influential in the development of abrasion resistance.

- Further studies on the influence of the binder type on abrasion resistance further than 28 days to allow for the pozzolanic reactions to occur. This will allow for a far more accurate understanding of the performance of pozzolanic materials on abrasion resistance, as this was not found to be significant in this study. This will assist in defining the silo concrete constituents' performance criteria and requirements.

- Further investigations into the effects of various supplementary cementitious materials (SCMs) and their respective percentage replacements on abrasion.

- Further studies into the influence of various surface treatment methods and techniques on impact, abrasion and the resulting synergic actions. This will allow for a better understanding of the applicability and efficacy of surface treatment options on abrasion resistance.

- Further studies into the performance of different aggregate types on abrasion resistance. A bigger pool of aggregates allows for more data to be extracted and analyzed to assess what other trends can be observed. Use an image analysis tool to evaluate the relationship between aggregate: paste surface area ratio and abrasion resistance.

- Conduct comparisons between the SANS tumbling test and other abrasion resistance test methods to identify which test method can better simulate the aggressiveness of the environment these silos are exposed to.

- The development of more abrasion resistance test apparatus using tribosimulative test methods. This will allow for the development of wear-life prediction models that can be used to simulate the abrasive wear experienced in real-life applications.

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APPENDIX A TRIAL MIXES AS PER THE ACI RECOMMENDATION

In addition to the 18 mixes referenced in the research report. Three norite 19 mm trial mixes with 100% CEMII, 85/15 CEMII/FA, 92.5/7.5 CEMII/CSF binders, and w/c ratios of 0.46, 0.45, and 0.48 respectively were based on concrete mix design selections for construction of a silo, informed by the ACI 313R-97 recommendations. These mixes were designed based on the ACI recommendations and industry standards as discussed in Section 2.9.2 and are used as a benchmark for salient construction requirements and the relative abrasion resistance performance.

Table A 1 provides mix proportions for concrete cubes cast with a 50 MPa characteristic strength based on the ACI recommendations given above. The primary objective of these mixes was to analyze the variation between ACI, and industry-standard recommendations mentioned above. Even though ACV, LA abrasion, and 10% FACT information could not be obtained for the Norite aggregate, they are known to behave similarly to dolerite aggregates and have a relatively high particle density (Bonser and Alexander, 2021a).

Table A 1: Mix Proportions for norite aggregates cast with respect to the ACI recommendations.

Material	**CEM II 42,5R 100%**	**CEM II 42,5R /FA 75/15**	**CEM II 42,5R / CSF 92.5/7.5**
Aggregate Type	Norite	Norite	Norite
Aggregate size	19,0mm	19,0mm	19,0mm
Mix Identifier	NPC19	NFA19	NSF19
Water (kg/m^3)	180	180	180
CEM II 42,5N (kg/m^3)	385	339	344
FA (kg/m^3)	0	60	0
CSF (kg/m^3)	0	0	30
Superplasticizer (%)	0.7	0.6	0.6
19 mm Stone (kg/m^3)	1280	1280	1280
Fine Aggregate (kg/m^3)	1055	1010	1055
w/c ratio (kg/m^3)	0.46	0.45	0.48
Approximate ratio	1:2:13	1:2:13	1:2:13
Mix label	NPC19	NFA19	NSF19

The mixes were tested as per the test methodology outline in Chapter 3, and the results are shown in Appendix B and the raw data in Appendix E.

APPENDIX B ADDITIONAL EXPERIMENT ANALYSIS AND RESULTS

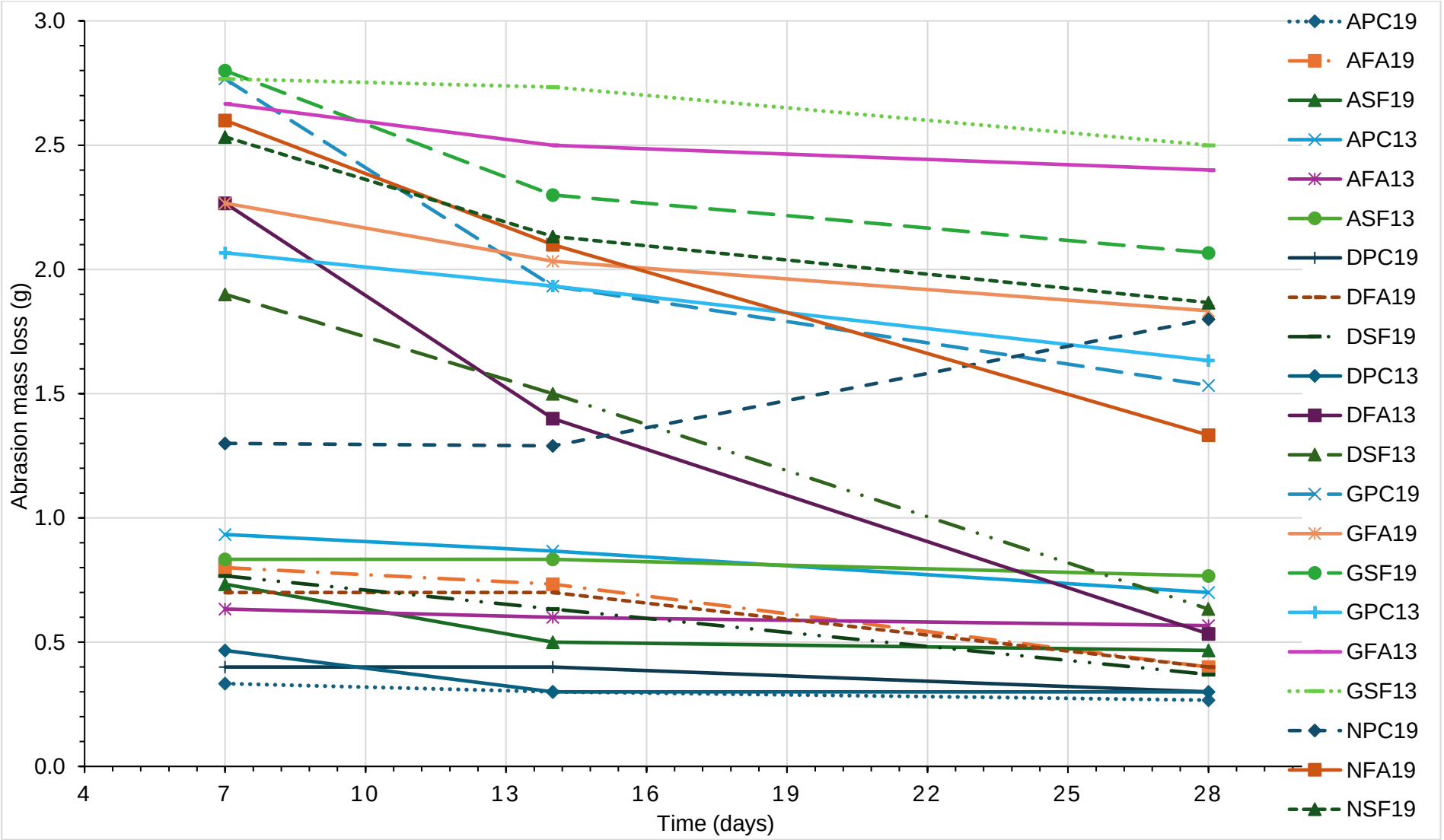
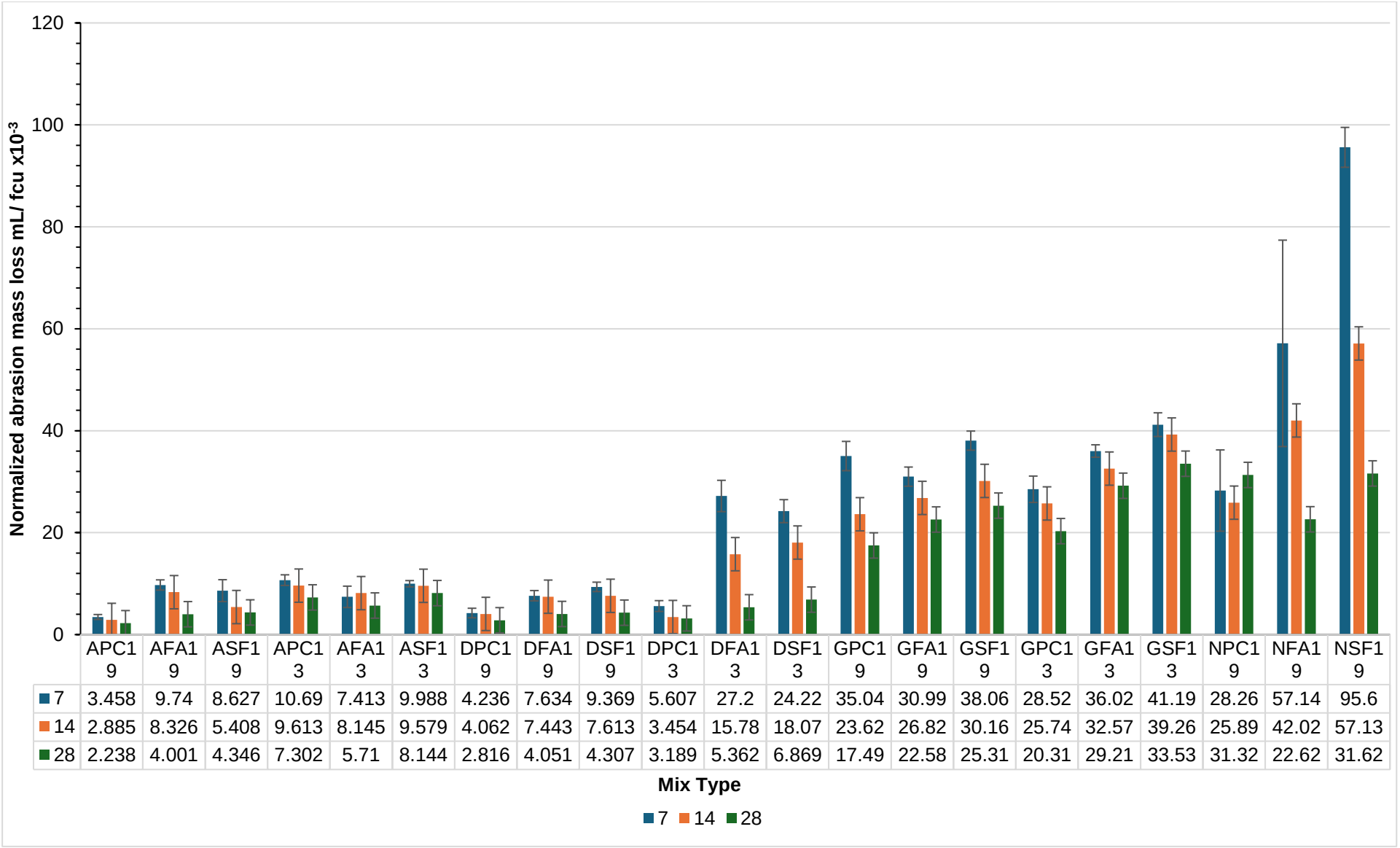


Figure B 1: 28-day time development of abrasion mass loss for the various mixes



	APC1 9	AFA1 9	ASF1 9	APC1 3	AFA1 3	ASF1 3	DPC1 9	DFA1 9	DSF1 9	DPC1 3	DFA1 3	DSF1 3	GPC1 9	GFA1 9	GSF1 9	GPC1 3	GFA1 3	GSF1 3	NPC1 9	NFA1 9	NSF1 9
7	3.458	9.74	8.627	10.69	7.413	9.988	4.236	7.634	9.369	5.607	27.2	24.22	35.04	30.99	38.06	28.52	36.02	41.19	28.26	57.14	95.6
14	2.885	8.326	5.408	9.613	8.145	9.579	4.062	7.443	7.613	3.454	15.78	18.07	23.62	26.82	30.16	25.74	32.57	39.26	25.89	42.02	57.13
28	2.238	4.001	4.346	7.302	5.71	8.144	2.816	4.051	4.307	3.189	5.362	6.869	17.49	22.58	25.31	20.31	29.21	33.53	31.32	22.62	31.62

Figure B 2: Normalized graph of abrasion mass loss observed at 7,14, and 28 days for the various 21 mixes.

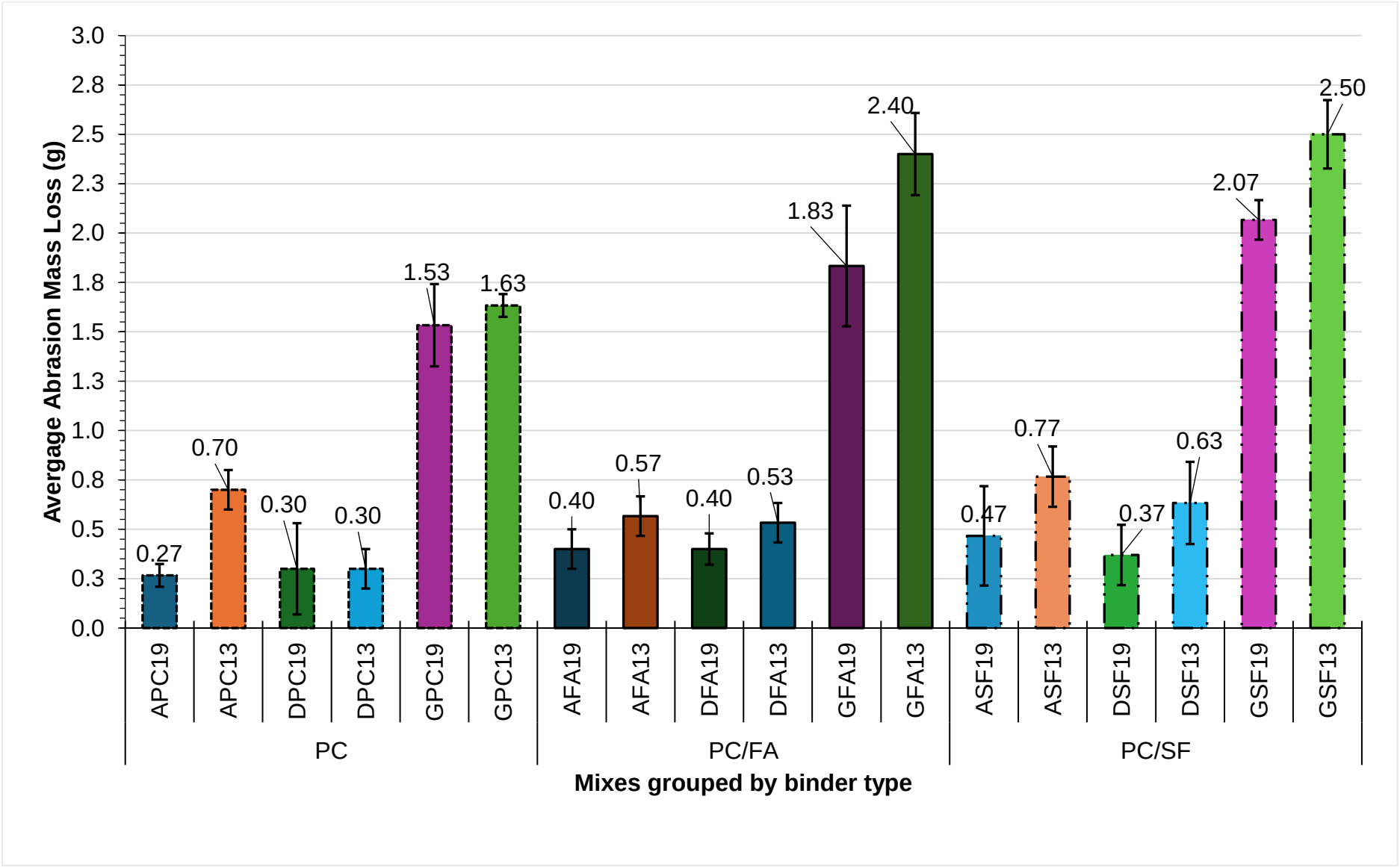


Figure B 3: 28-day comparison of the abrasion mass loss values for the various mixes grouped by binder type.

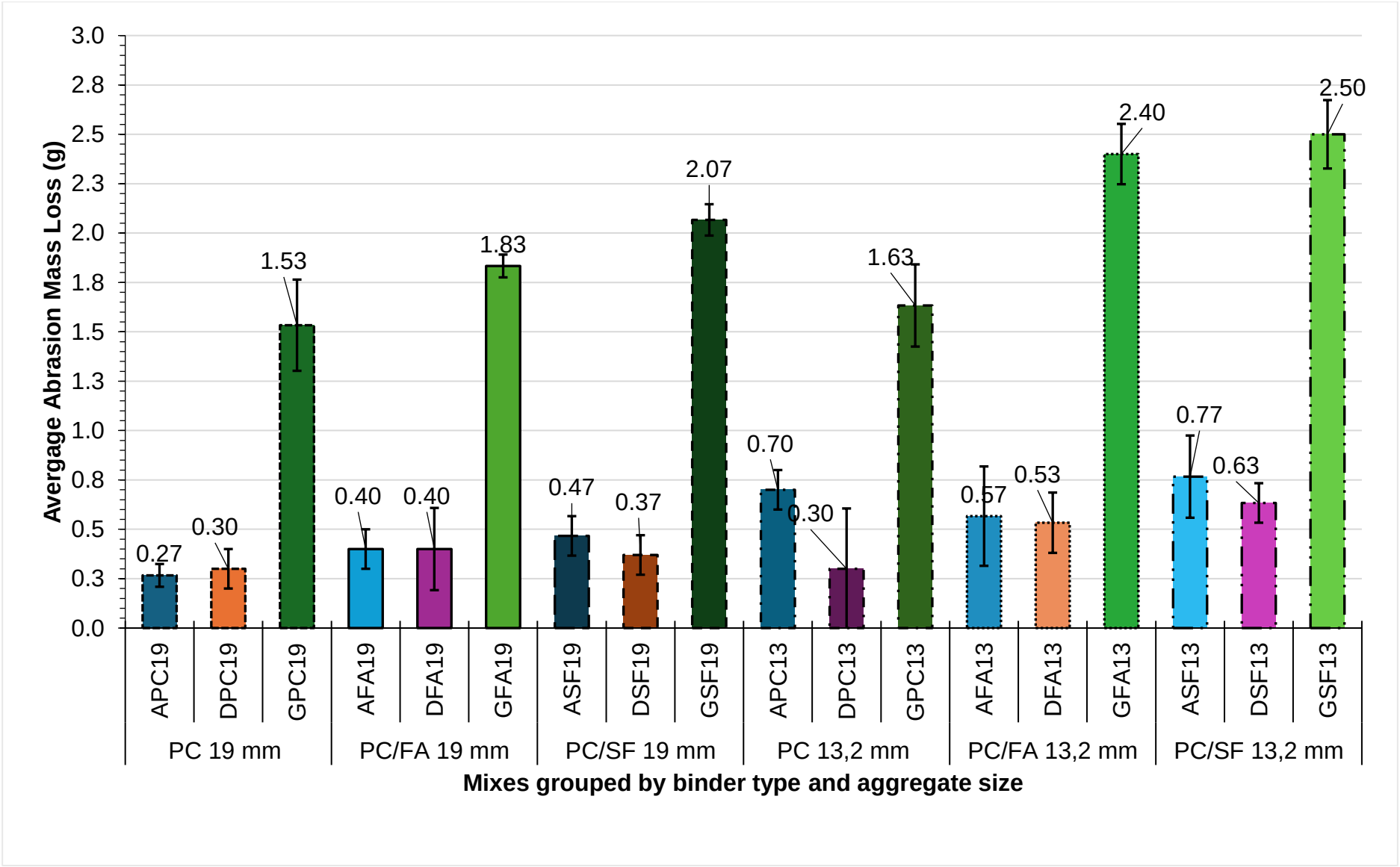


Figure B 4: 28-day comparison of the abrasion mass loss values for the various mixes grouped by binder type and aggregate size.

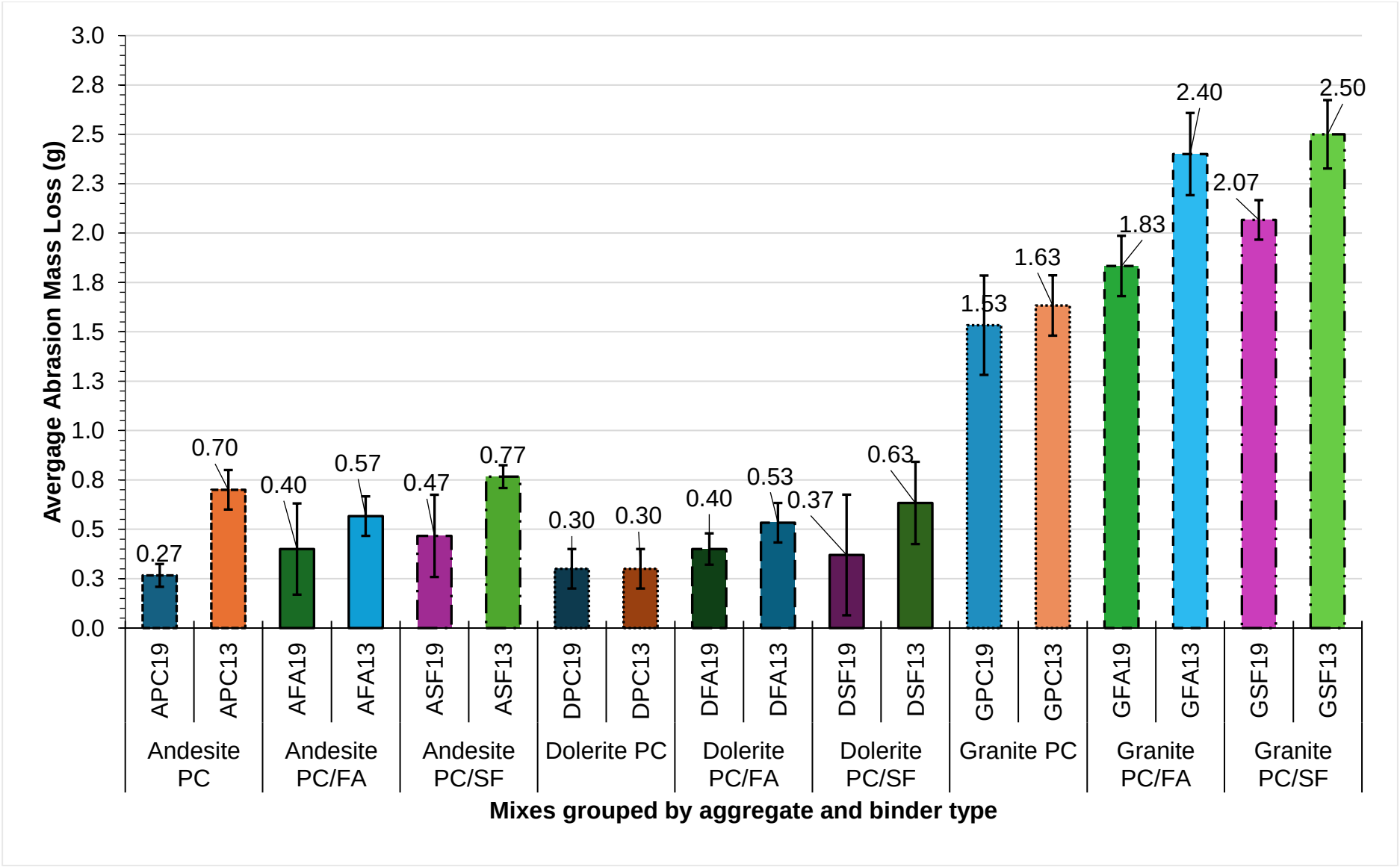


Figure B 5: 28-day comparison of the abrasion mass loss values for the various mixes grouped by aggregate and binder type.

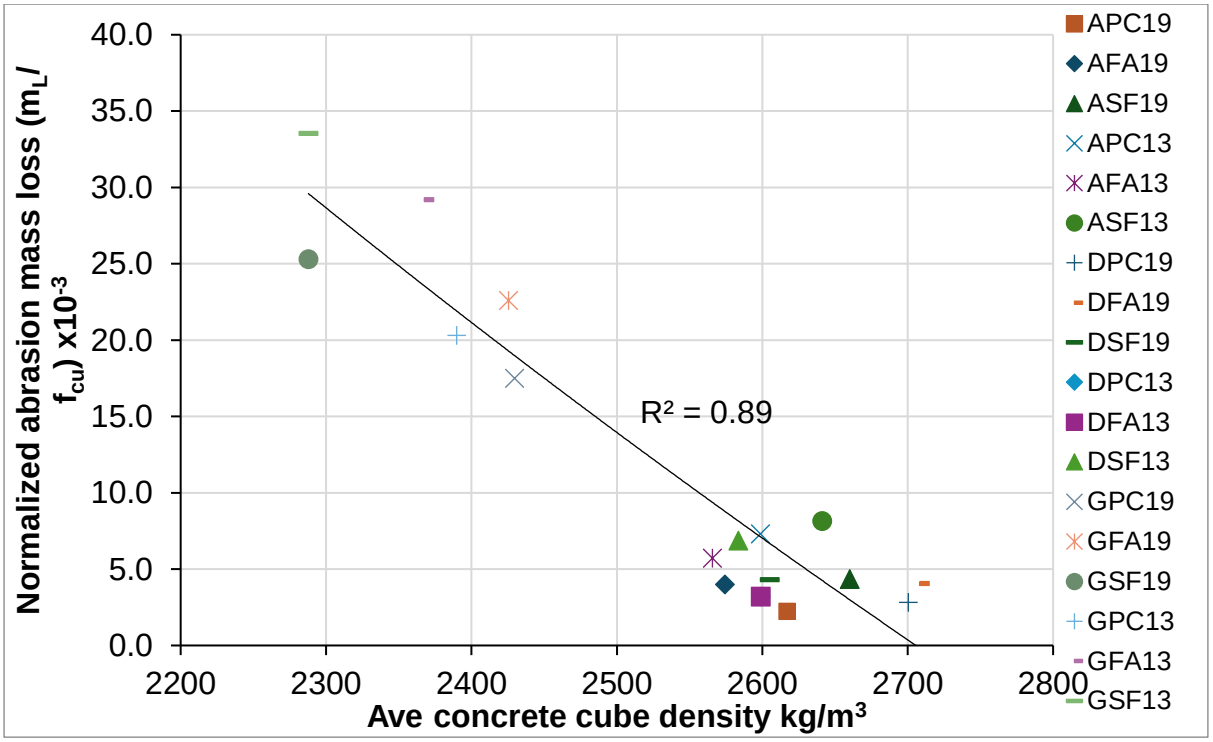


Figure B 6: Relationship between abrasion mass loss observed and 28-day average concrete cube density kg/m^3.

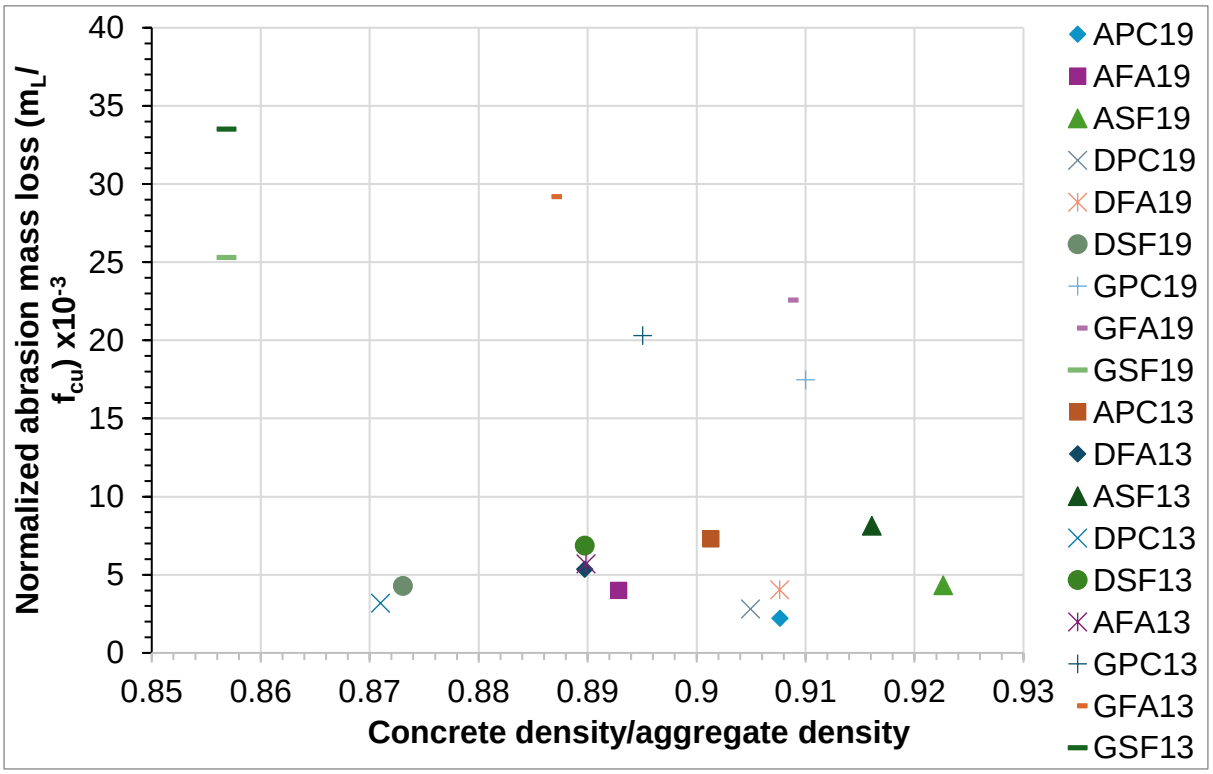


Figure B 7: Graph showing relationship between abrasion mass loss and concrete density, normalized with both compressive strength and concrete density respectively.

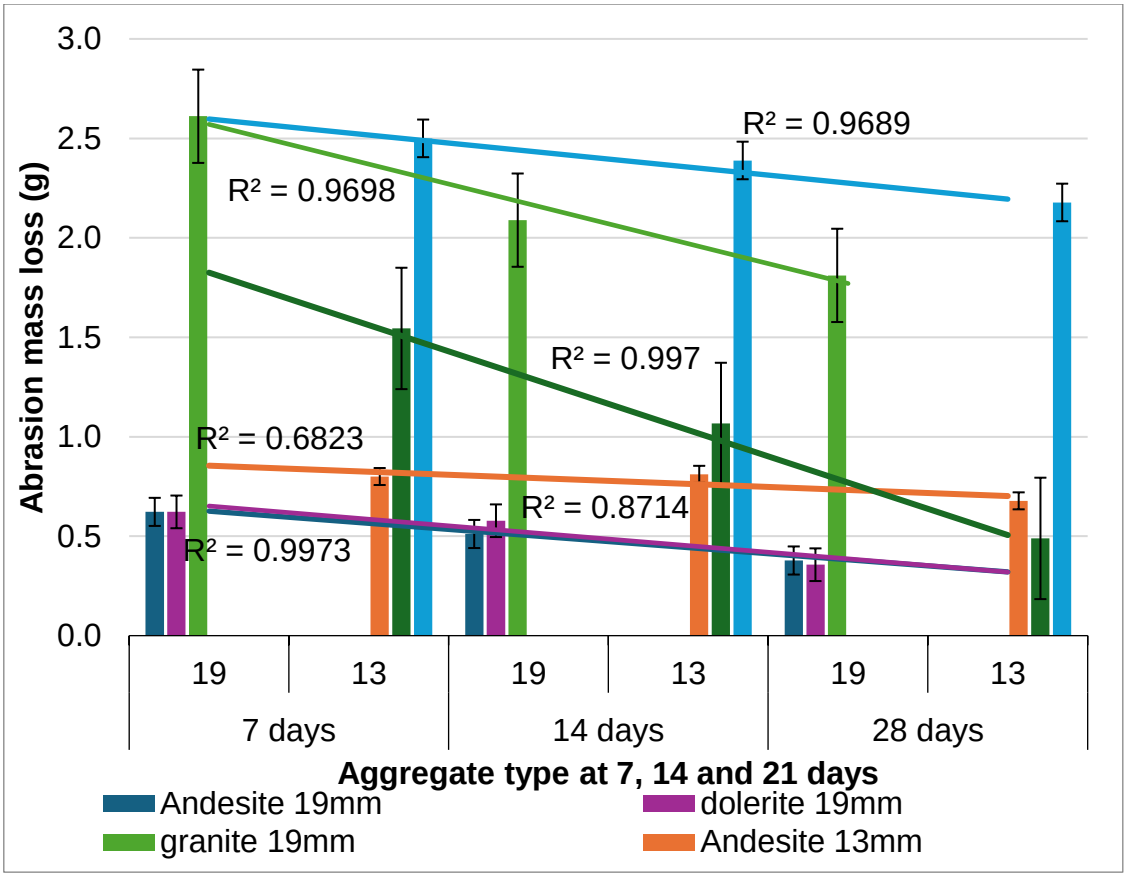


Figure B 8: Time development of abrasion mass loss with respect to aggregate type at 7, 14, and 28 days.

Table B 1: Slump records for all the 21 mixes

	Andesite			Dolerite			Granite			Norite		
Slump	PC	PC/FA	PC/CSF	PC	PC/FA	PC/CSF	PC	PC/FA	PC/CSF	PC	PC/FA	PC/CSF
13,2 mm (mm)	155	160	150	150	165	155	160	150	140	-	-	-
19 mm (mm)	150	160	145	160	165	160	150	160	150	95	135	140

Table B 2: Visual comparison of the 19 mm abrasion test results at 28 days

Mix type	NPC19	NFA19	NSF19
Norite	 m_L: 1.80g	 m_L: 1.33g	 m_L: 1.87g

APPENDIX C PLATINUM RoM SILO INSPECTION

Report Title	:	Platinum: RoM Silo Inspection
Mine	:	Platinum
Author	:	Afikile Hintsa
Location	:	Burgersfort Latitude: -24.9333839° Longitude: 30.0947752° Altitude (ASL): 949.56 m

Executive Summary

A SIMM inspection of the RoM silo at a Platinum Crusher Plant was carried out on the 9th of November 2023 During a short Maintenance shutdown. The inspection was carried out in general compliance with the Anglo-American best practice guidelines AA-BPG-S03.

The RoM silo was commissioned in 2006 and has a live material capacity of 5000 tons. At the time of inspection, the silo had a total throughput of approximately 34 926 073 tons of ore with a maximum feed material size of 420mm. The RoM silo was in 2005 and commissioned in 2006 mentioned above.

The findings for the silo are included together in this report and can be summarized as follows:

a. Due to the abrasive nature of RoM platinum ore material, the sacrificial shotcrete liner to the inside face of the wall is completely worn away in some areas. Structural reinforcement is subsequently exposed at the lower portion of the western wall. The silo was not completely empty at the time of the investigation, but it was noted that one horizontal hoop reinforcement bar was damaged and lost.

b. Diagonal cracks at the top of the silo wall are located below the main steel girder supports. These cracks are deemed to be serviceability cracks due to point loads at the cast-in plates. Visible efflorescence at some of the cracks indicate that these are old cracks. Considering that the silo was commissioned over 17 years ago and the cracks in their current condition are all less than 0,2 mm wide with no visible signs of delamination or spalling. These cracks are considered not to significantly affect the integrity of the wall.

c. Horizontal cracks were also observed on the external wall of the silo. These cracks are typical of lifting cracks during the slipform operation or from cold joints where the slide may have been stopped. No moisture was shown to have penetrated

through these cracks at the time of the inspection, therefore indicating that these cracks do not penetrate through to the internal face of the silo.

d. General housekeeping was not satisfactory, which could obscure any visible signs of structural defects. From the inspection findings, the structure is safe to operate, given that the exposed rebar is repaired and the cover-crete is reinstated.

Conditional Categories

All findings in this report are described using deterioration conditions listed in Table C 1 below.

Table C 1: Anglo SIMM inspection and deterioration conditional category table (Krige, 2006)

Category	Description	% Original Strength	Typical Remedial Action
0	The structure or structural component is in excellent condition, with no deterioration evident. Safe use of the structure is assured.	100	None required.
1	The structure or structural component has slight evidence of surface deterioration, but to an extent that there is no reduction in strength. Safe use of the structure is assured.	100	None required.
2	The structure or structural component has some deterioration, to an extent that there is slight reduction in strength. Safe use of the structure is assured.	95 – 100	Minor work, if stipulated in report.
`3	The structure or structural component shows deterioration, to an extent that there is some reduction in strength. There is some compromise to safe use of the structure. Repair should receive attention in maintenance scheduling.	75 – 95	Repair work to be done.
4	The structure or structural component shows severe deterioration, to an extent that there is a major reduction in strength. Safe use of the structure is severely compromised. Urgent attention should be given to repair.	50 – 75	Repair work or replacement of rebar and/or members.

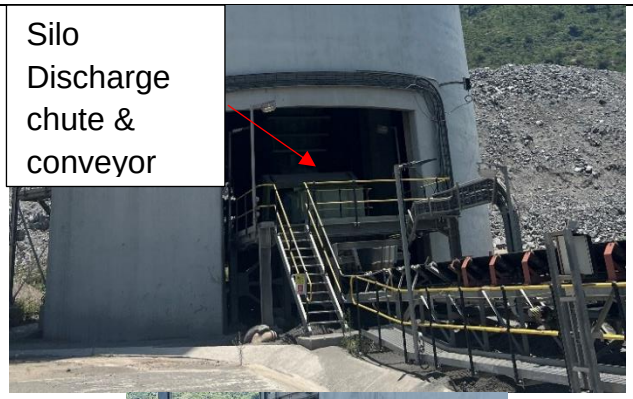
5	The structure or structural component shows severe deterioration, to an extent that there is little useful residual strength. Safe use of the structure is not possible. Urgent attention should be given to repair.	< 50	Urgent repair work or replacement of rebar and/or members.

This report reports findings related to structural deterioration; therefore, no additional comments were made where the structural components were found to be in good condition.

Table C 2: Silo SIMM inspection conditional report (Page: 138 to 145)

ITEM	PHOTO	DESCRIPTION
0		**CONSTRUCTION DATE:** The RoM Silo was constructed in 2005 and commissioned in July 2006. **DESCRIPTION:** The silo wall is 300 mm thick with an internal diameter of 15 000 mm. The overall height of the concrete silo is 31 340 mm above surface bed level. The depth of ore containment is 22 260 mm with two ore discharge openings in the 1 000 mm thick suspended slab. The wall was constructed of 40 MPa concrete with a 90 mm cover (40 mm cover + 50 mm sacrificial cover) to the internal wall reinforcement over the full material containment height. A sacrificial shotcrete liner was also installed over and above the 90 mm cover on the internal face of the silo wall, extending to the top of the wall. However, no details of the shotcrete were shown on the engineering drawings, as the shotcrete liner was installed after commissioning. **PREVIOUS REPAIRS:** In February 2007, cracks were identified on the internal and external surface of the Silo. The investigation performed in 2007 concluded that the cracks were construction related cracks and were of a non-structural nature. The horizontal cracks are typical of lifting cracks or cold joints where the slide may have been stopped.

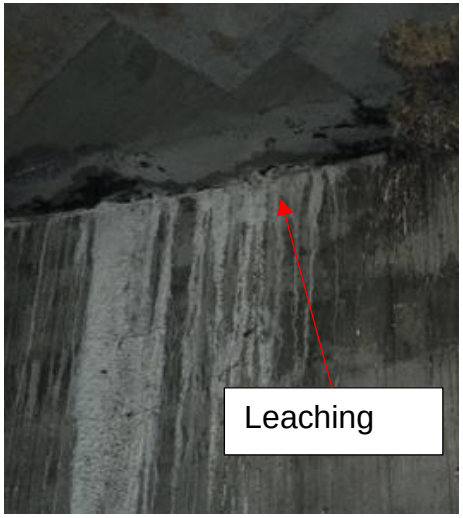
FOUNDATION AND SURROUNDING GROUND

ITEM	PHOTO	SCHEDULE OF FINDINGS	CONDITIONAL CATEGORY	
1	Silo Discharge chute & conveyor  Abrasion on surfacebed 	**DESCRIPTION:** View at ground level **FINDING/EXPLANATION:** Adequate storm water drainage to ensure no ponding or flooding occurs. Most forms of deterioration rely on water. In this case, external water could result in the deterioration of the concrete through ponding, which could result in the reduction in durability. Providing adequate drainage reduces the movement of water into the concrete thus improving its durability. Ponding can lead to the penetration of water into the concrete through permeation, absorption, or diffusion, which could subsequently result in the corrosion of the reinforcement. Minor abrasion on the surface bed due to pressure washing was also observed.	INDICATION OF SETTLEMENT	0
			CRACKS ON SURFACE BED	0
			WATER ACCUMULATION	1
			OTHER	1

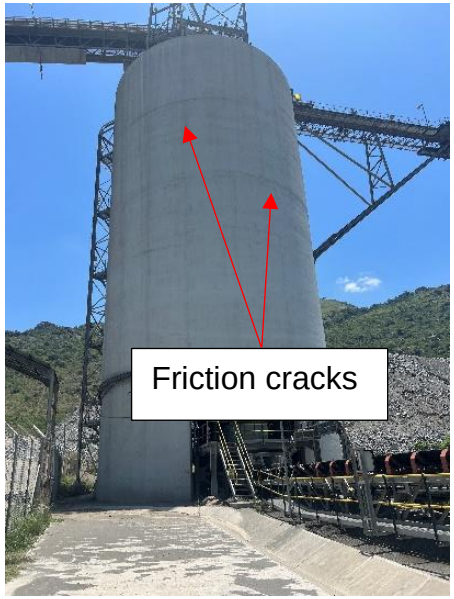
CONCRETE SURFACE BED

ITEM	PHOTO	SCHEDULE OF FINDINGS	CONDITIONAL CATEGORY	
2	 	**DESCRIPTION:** Surface bed below the suspended slab. **FINDING/EXPLANATION:** The surface bed is generally in good condition with minimal visible signs of deterioration. Insignificant abrasion-wear from foot traffic and equipment use is observed on the silo surface bed.	SPALLING	0
			REINFORCEMENT CORROSION	0
			CRACKING	0
			WATER LEAKS AND DAMPNESS	1
			MECHANICAL DAMAGE	0
			WEAR AND ABRASION	1
			CONCRETE BREAKDOWN	0

CONCRETE SUSPENDED SLAB SOFFIT

	PHOTO	SCHEDULE OF FINDINGS	CONDITIONAL CATEGORY	
3	 	**DESCRIPTION:** Leaching of moisture below suspended slab level with visible white stains encircled in red. These are caused by calcium hydroxide leaching through the concrete. **FINDING/EXPLANATION:** The silo is not covered at the top therefore it also retains an amount of rainwater together with the stored material. Pure or soft water is calcium hungry and has a low dissolved ion content, this results in the dissolution of the calcium hydroxide and the CSH (calcium silicate hydrate) from the hardened cement paste (Concrete Institute, 2013). Once the calcium hydroxide comes into contact with the air, it reacts with the carbon dioxide creating calcium carbonate which is the white substance seen in the image.	SPALLING	0
			REINFORCEMENT CORROSION	0
			CRACKING	0
			WATER LEAKS AND DAMPNESS	1
			MECHANICAL DAMAGE	0
			WEAR AND ABRASION	0
			CONCRETE BREAKDOWN	0

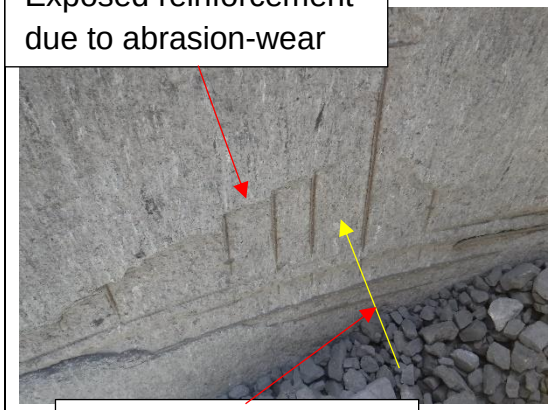
CONCRETE WALL - OUTSIDE FACE

ITEM	PHOTO	SCHEDULE OF FINDINGS	CONDITIONAL CATEGORY	
4	 	**DESCRIPTION:** The two pictures attached show a general view of the western elevation of the silo. **FINDING/EXPLANATION:** Minor horizontal cracks are visible along the circumference of the silo. The horizontal cracks typically form when the concrete sticks to the slipform during a lifting event, or from friction forces that develop between the shutter and the setting concrete. These horizontal cracks are also caused by joints or discontinuities are also as a result of delay in placement to allow for bonding of the material of the newly placed concrete with the set concrete from the previous slide event.	SPALLING	1
			REINFORCEMENT CORROSION	0
			CRACKING	2
			WATER LEAKS AND DAMPNESS	1
			MECHANICAL DAMAGE	0
			WEAR AND ABRASION	0
			CONCRETE BREAKDOWN	1

CONCRETE WALL INSIDE FACE - FACE OPPOSITE MATERIAL DISCHARGE

ITEM	PHOTO	SCHEDULE OF FINDINGS	CONDITIONAL CATEGORY	
5	 	**DESCRIPTION:** View on sacrificial shotcrete liner on internal face of Eastern silo wall. **FINDING/EXPLANATION:** No visible signs of exposed structural reinforcement. Considering that the silo was not completely empty at the time of the investigation, this must be confirmed.	SPALLING	0
			REINFORCEMENT CORROSION	0
			CRACKING	1
			WATER LEAKS AND DAMPNESS	0
			MECHANICAL DAMAGE	0
			WEAR AND ABRASION	1
			CONCRETE BREAKDOWN	1

CONCRETE WALL INSIDE FACE -CONTINUED - FACE DIRECTLY IN LINE WITH MATERIAL DISHARGE

ITEM	PHOTO	SCHEDULE OF FINDINGS	CONDITIONAL CATEGORY	
6	Exposed reinforcement due to abrasion-wear  Direction of discharge  Mild abrasion-wear marks on interna wall	**DESCRIPTION:** View of the internal wall of the silo showing the internal silo wall on the Western eastern side. **FINDING/EXPLANATION:** Due to the abrasive nature of RoM platinum ore material, the concrete on the inside face of the wall is in some areas completely worn away. The structural reinforcement is exposed at the lower portion of the western wall. The depth of concrete cover provided to the reinforcement in a structure plays a crucial role in determining the overall strength and durability of the structure. A lack of sufficient concrete cover can have significant adverse effects on the bond strength that develops between the reinforcement and the concrete as there would not be sufficient concrete for the bond stresses to develop. This, in turn, can lead to a reduction in the hoop strength of silos, which are particularly vulnerable to such issues due to their cylindrical shape. White abrasion marks are also observed on the walls in both images. These are due to the material scratching the concrete surface	SPALLING	2
			REINFORCEMENT CORROSION	2
			CRACKING	2
			WATER LEAKS AND DAMPNESS	2
			MECHANICAL DAMAGE	0
			WEAR AND ABRASION	3
			CONCRETE BREAKDOWN	3

ITEM	SCHEDULE OF FINDINGS CONTINUED
6	The loss of hoop strength in silos can have far-reaching consequences, including a reduction in the overall strength of the structure and an increase in the risk of failure. The reduction in concrete cover can also be attributed to the progressive corrosion of the reinforcement due to its exposure to environmental factors, such as moisture and chemical agents. The corrosion process weakens the bond between the reinforcement and the surrounding concrete, while also exerting stresses to the surrounding concrete, leading to a loss of strength and durability over time. The surface roughness also contributes significantly to the increased rate of deterioration as the rate of abrasion is also influenced by the countersurface roughness, therefore the rate of deterioration will rapidly increase as more cracks develop. At the time of the investigation, the silo was not completely empty, but it was noted that one horizontal hoop reinforcement bar was damaged and effectively lost its strength. Therefore, it is critical to ensure that the appropriate level of concrete cover is provided to the reinforcement in silos and other structures to prevent such issues from arising.

Schedule of Findings

Table C 3 lists all findings from the inspection.

Table C 3: Summary of findings

Finding	Deterioration Condition Category
Silo General	
Poor drainage around silo.	1
Silo Concrete	
Severed abrasion wear of sacrificial shotcrete liner to inside of bin wall. Exposed and damaged wall reinforcement on lower section of western wall.	3
Diagonal hairline cracks below the main steel girder supports are deemed to be serviceability cracks	1
Horizontal cold joints or lifting cracks. Not of structural nature.	1 to 2
Minor horizontal and vertical hairline cracks on the external face of the silo wall.	1
Mechanical damage at soffit and side of wall opening.	1
Damaged joint sealant	1
Moisture seepage at soffit of suspended slab.	1 to 2

Conclusions

- Horizontal cracks observed on the outside face of the silo wall are not of a structural nature and are construction related. These cracks are typical of cold joints where the slide may have been stopped, or of lifting cracks. Lifting cracks are caused by friction forces from the sliding shutter lifting the setting concrete. Minor horizontal and vertical hairline plastic settlement cracks were also observed but none of these are of a structural nature.

- Due to the abrasive nature of RoM platinum ore material, the sacrificial shotcrete liner to the inside face of the wall is completely worn away in some areas. Structural reinforcement is subsequently exposed at the lower portion of the western wall. Structural reinforcement is subsequently exposed at the lower portion of the western wall. At the time of the investigation, the silo was not completely empty, but it was noted that one horizontal hoop reinforcement bar was damaged and lost its design strength. This area of the silo is vulnerable in its current condition and could result in possible accelerated deterioration.

- The influence of abrasion and impact of particles on the internal wall of the silo has been found to be the most significant factor when considering the deterioration condition of the structure. Therefore, further research is necessary to ensure the robustness of concrete to withstand both the impact and abrasion on the internal wall of the silo. This study underscores the importance of understanding the impact of abrasion on the structural integrity of silos, which can lead to better design and maintenance practices for long-term sustainability.

APPENDIX D AGGREGATE GRADING RESULTS

D1: Coarse Aggregates

1. Andesite 19mm

Table D 1: 19 mm andesite aggregate properties

AGGREGATE PROPERTIES			
Item	**Test Specification**	**Unit**	**Value**
Loose Bulk Density	SANS 5845:1994	kg/m³	1570
Compacted Bulk Density (CBD)	SANS 5845:1994	kg/m³	1760
Relative Density	SANS 8544:1994	ratio	2.90
Aggregate Crushing Value	SANS 5841:1994	ratio	6
10% FACT	SANS 5842:1994	kN	564
Dust Content	SANS 201:2008	%	
True Density	Gas Pycnometer	kg/m³	2883.2

Table D 2:19 mm andesite aggregate sieve analysis

SIEVE ANALYSIS as per SANS 201:2002					
Sieve size (mm)	**7.1**	**10.0**	**14.0**	**20.0**	**26,5**
Cumulative % passing	0.1	0.1	6.3	70.8	100.0
Recommended envelope	0-5	0-25	0-50	85-100	100

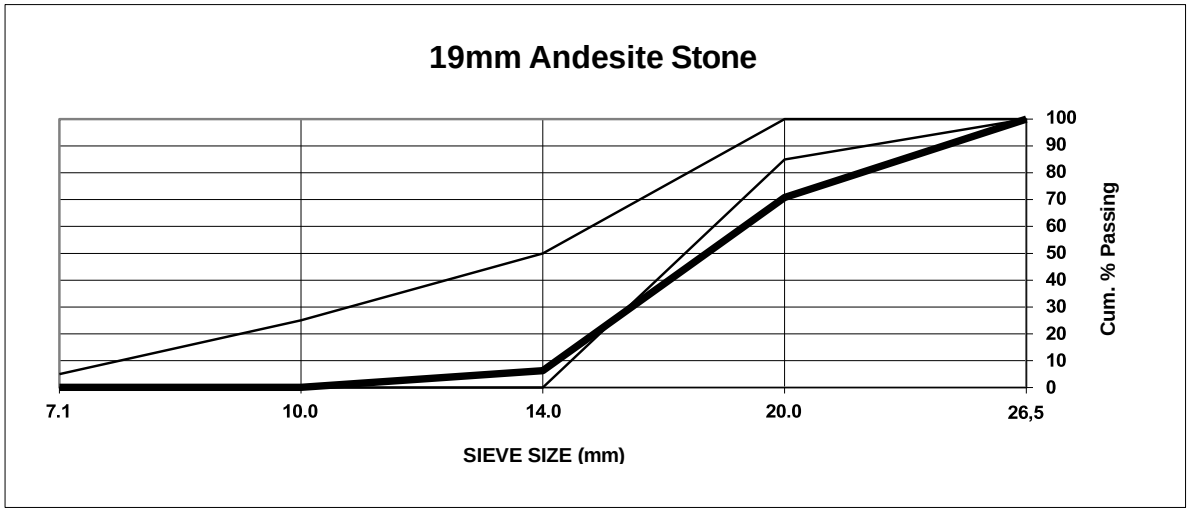


Figure D 1: 19 mm andesite envelope range as per Specification: SANS 1083:2002

2. Dolerite 19mm

Table D 3: 19 mm dolerite aggregate properties

AGGREGATE PROPERTIES			
Item	**Test Specification**	**Unit**	**Value**
Loose Bulk Density	SANS 5845:1994	kg/m³	1590
Compacted Bulk Density (CBD)	SANS 5845:1994	kg/m³	1750
Relative Density	SANS 8544:1994	ratio	2.97
Aggregate Crushing Value	SANS 5841:1994	%	12
10% FACT	SANS 5842:1994	kN	344
Dust Content	SANS 201:2008	%	0.6
True Density	Gas Pycnometer	kg/m³	2984

Table D 4: 19 mm dolerite aggregate sieve analysis

SIEVE ANALYSIS as per SANS 201:2002					
Sieve size (mm)	**7.1**	**10.0**	**14.0**	**20.0**	**26.5**
Cumulative % passing	0.6	1.5	14.1	77.0	100.0
Recommended envelope	0-5	0-25	0-50	85-100	100

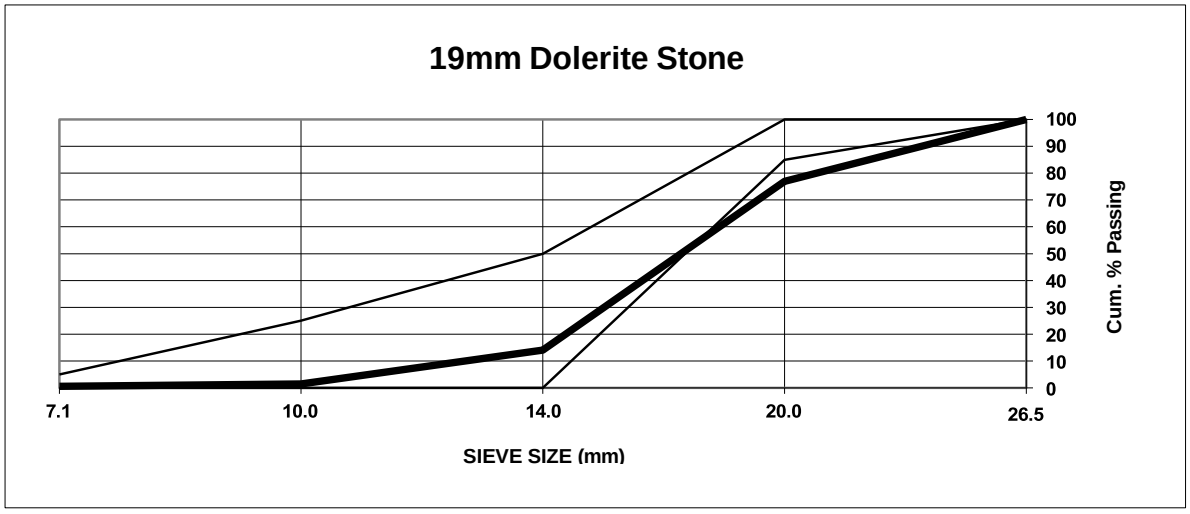


Figure D 2: 19 mm dolerite envelope range as per Specification: SANS 1083:2002

3. Granite 19mm

Table D 5: 19 mm granite aggregate properties

AGGREGATE PROPERTIES			
Item	**Test Specification**	**Unit**	**Value**
Loose Bulk Density	SANS 5845:1994	kg/m³	1420
Compacted Bulk Density (CBD)	SANS 5845:1994	kg/m³	1580
Relative Density	SANS 8544:1994	ratio	2.63
Aggregate Crushing Value	SANS 5841:1994	%	20
10% FACT	SANS 5842:1994	kN	162
Dust Content	SANS 201:2008	%	0.2
True Density	Gas Pycnometer	kg/m³	2670

Table D 6: 19 mm granite aggregate sieve analysis

SIEVE ANALYSIS as per SANS 201:2002					
Sieve size (mm)	**7.1**	**10.0**	**14.0**	**20.0**	**26.5**
Cumulative % passing	0.2	1.3	11.0	79.8	100.0
Recommended envelope	0-5	0-25	0-50	85-100	100

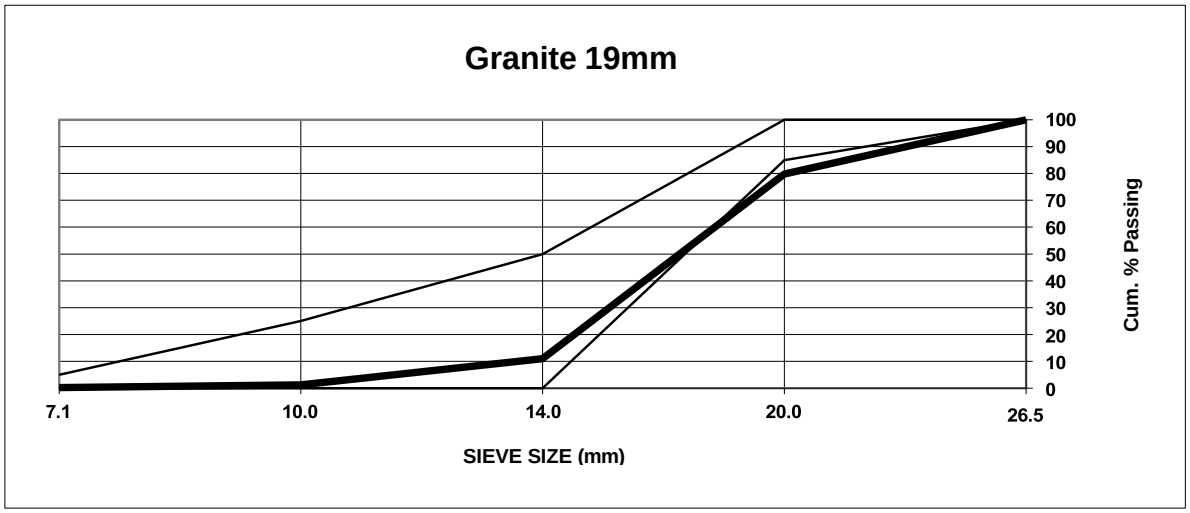


Figure D 3: 19 mm granite envelope range as per Specification: SANS 1083:2002

4. Andesite 13,2mm

Table D 7: 13,2 mm andesite aggregate properties

AGGREGATE PROPERTIES			
Item	**Test Specification**	**Unit**	**Value**
Loose Bulk Density	SANS 5845:1994	kg/m³	1530
Compacted Bulk Density (CBD)	SANS 5845:1994	kg/m³	1670
Relative Density	SANS 8544:1994	ratio	2.85
Aggregate Crushing Value	SANS 5841:1994	%	6
10% FACT	SANS 5842:1994	kN	564
Dust Content	SANS 201:2008	%	0.4

Table D 8: 13,2 mm andesite sieve analysis

SIEVE ANALYSIS as per SANS 201:2002					
Sieve size (mm)	**5.00**	**7.1**	**10.0**	**14.0**	**20.0**
Cumulative % passing	0.1	0.2	6.6	84.2	100.0
Recommended envelope	0-5	0-25	0-55	85-100	100

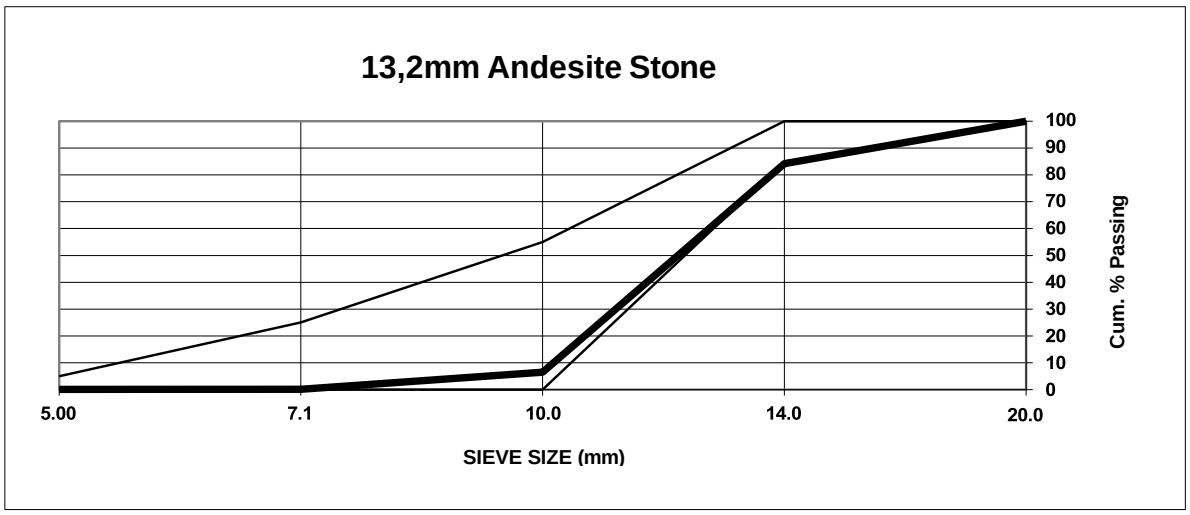


Figure D 4: 13,2 mm andesite envelope range as per Specification: SANS 1083:2002

5. Dolerite 13,2mm

Table D 9: 13,2 mm andesite aggregate properties

AGGREGATE PROPERTIES			
Item	**Test Specification**	**Unit**	**Value**
Loose Bulk Density	SANS 5845:1994	kg/m³	1650
Compacted Bulk Density (CBD)	SANS 5845:1994	kg/m³	1920
Relative Density	SANS 8544:1994	ratio	2.96
Aggregate Crushing Value	SANS 5841:1994	%	12
10% FACT	SANS 5842:1994	kN	344
Dust Content	SANS 201:2008	%	0.1

Table D 10: 13,2 mm dolerite sieve analysis

SIEVE ANALYSIS as per SANS 201:2002					
Sieve size (mm)	**5.00**	**7.1**	**10.0**	**14.0**	**20.0**
Cumulative % passing	0.6	0.9	13.0	91.4	100.0
Recommended envelope	0-5	0-25	0-55	85-100	100

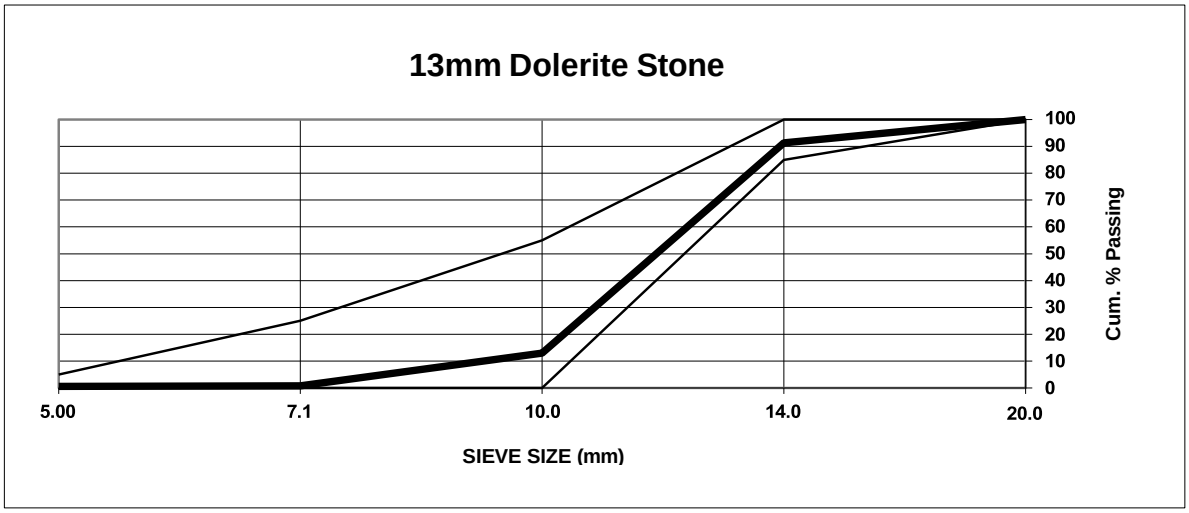


Figure D 5: 13,2 mm dolerite envelope range as per Specification: SANS 1083:2002

6. Granite 13,2mm

Table D 11: 13,2 mm granite aggregate properties

AGGREGATE PROPERTIES			
Item	**Test Specification**	**Unit**	**Value**
Loose Bulk Density	SANS 5845:1994	kg/m³	1410
Compacted Bulk Density (CBD)	SANS 5845:1994	kg/m³	1540
Relative Density	SANS 8544:1994	ratio	2.61
Aggregate Crushing Value	SANS 5841:1994	%	20
10% FACT	SANS 5842:1994	kN	162
Dust Content	SANS 201:2008	%	0.3

Table D 12: 13,2 mm granite sieve analysis

SIEVE ANALYSIS as per SANS 201:2002					
Sieve size (mm)	**5.00**	**7.1**	**10.0**	**14.0**	**20.0**
Cumulative % passing	0.5	3.5	29.4	94.3	100.0
Recommended envelope	0-5	0-25	0-55	85-100	100

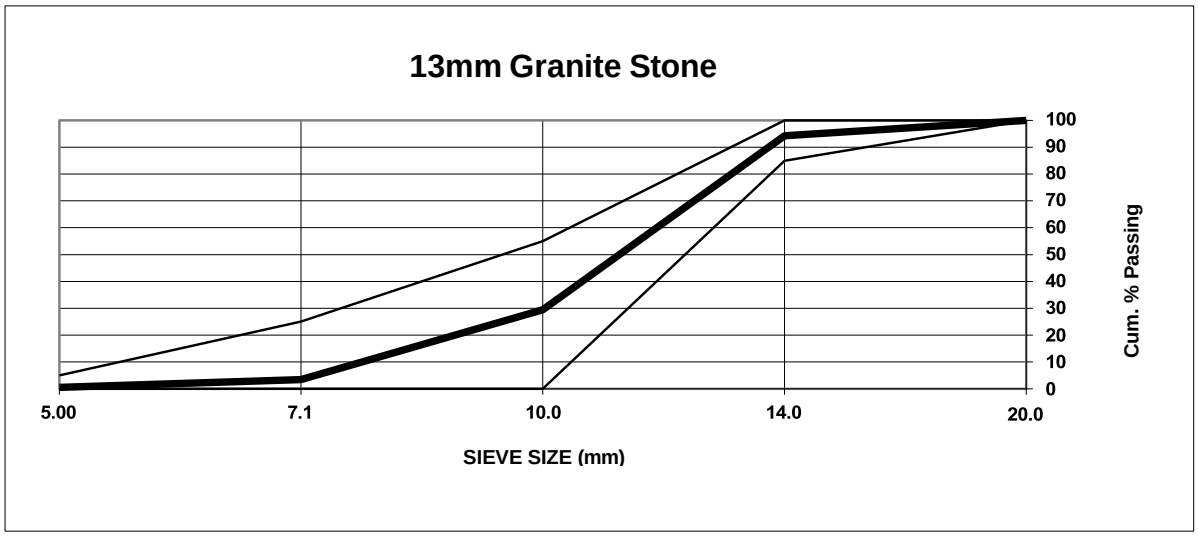


Figure D 6:13,2 mm granite envelope range as per Specification: SANS 1083:2002

7. Norite 19mm

Table D 13: 19mm norites aggregate properties

AGGREGATE PROPERTIES			
Item	**Test Specification**	**Unit**	**Value**
Loose Bulk Density	SANS 5845:2006	kg/m³	1820
Compacted Bulk Density (CBD)	SANS 5845:2006	kg/m³	2010
Relative Density	SANS 8544:2006	%	3.40
Flakiness Index	SANS 5847:2002	%	-
Aggregate Crushing Value	SANS 5841:2008	ratio	-
10% FACT	SANS 5842:2006	kN	-
Dust Content	SANS 0201:2008	%	0.9
Water absorption	SANS 5843:2002	%	-

Table D 14: 19mm norite aggregate sieve analysis

SIEVE ANALYSIS as per SANS 0201:2008					
Sieve size (mm)	**7.1**	**10.0**	**14.0**	**20.0**	**26,5**
Cumulative % passing	0.9	4.0	46.6	100.0	100.0
Recommended envelope	0-5	0-25	0-50	85-100	100

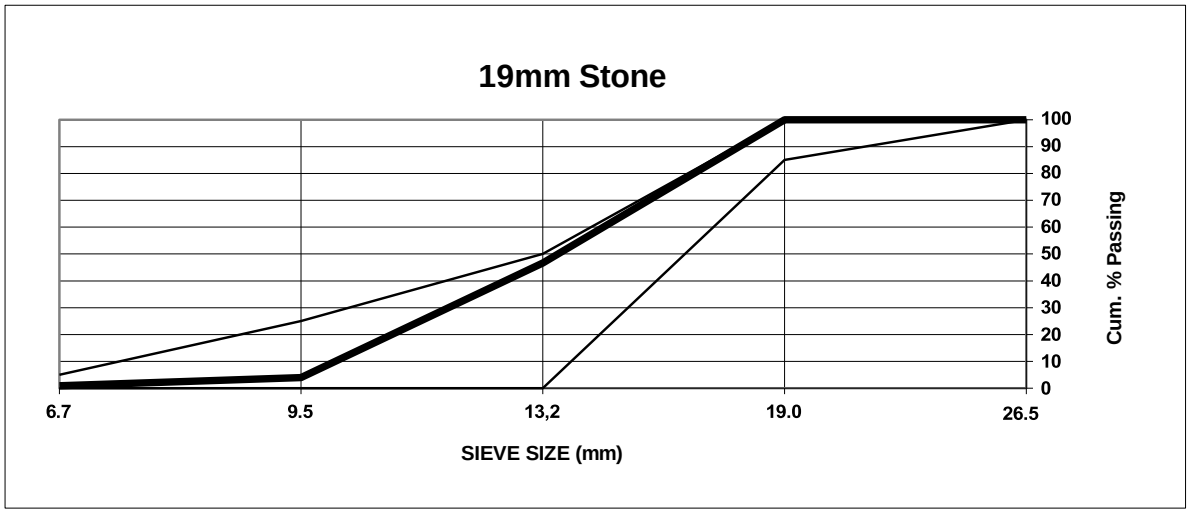


Figure D 7:19 mm norite envelope range as per Specification: SANS 1083:2002

D2: Fine Aggregates

1. Andesite

Table D 15: Andesite sand properties

AGGREGATE PROPERTIES			
Item	**Test Specification**	**Unit**	**Value**
Silt content	SANS 5838:1976	ratio	6.0
Fineness Modulus	SANS 0201:2002	ratio	3.50
Loose Bulk Density	SANS 5845:1994	kg/m³	1880
Compacted Bulk Density	SANS 5845:1994	kg/m³	2120
Relative Density	SANS 8544:1994	ratio	2.86
Dust Content	SANS 201:2008	%	10.4

Table D 16: Andesite sand sieve analysis

SIEVE ANALYSIS as per SANS 201:2002							
Sieve size (mm)	**0.075**	**0.15**	**0.30**	**0.60**	**1.00**	**2.00**	**5.00**
Cumulative % passing	10.4	13.6	19.0	27.7	36.8	56.7	96.0
Recommended envelope	0-10	5-25	20-40	40-60	60-90	75-100	90-100

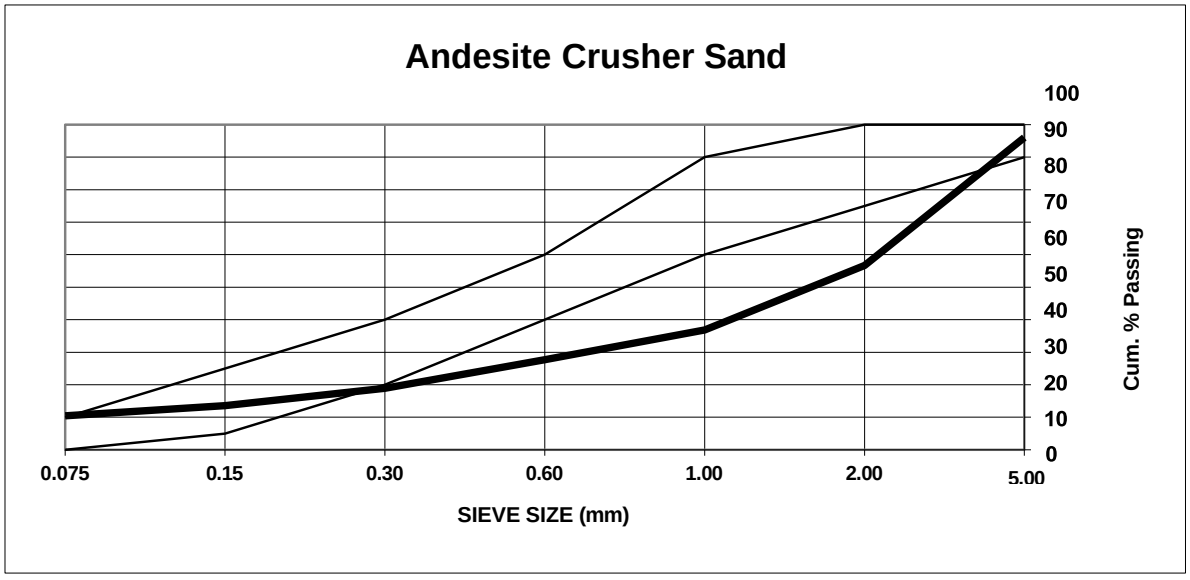


Figure D 8: Andesite sand envelope range as per Specification: SANS 1083:2002

2. Dolerite

Table D 17: Dolerite sand properties

AGGREGATE PROPERTIES			
Item	**Test Specification**	**Unit**	**Value**
Silt content	SANS 5838:1976	ratio	-
Fineness Modulus	SANS 0201:2002	ratio	4.07
Loose Bulk Density	SANS 5845:1994	kg/m³	1840
Compacted Bulk Density	SANS 5845:1994	kg/m³	2000
Relative Density	SANS 8544:1994	ratio	2.95
Dust Content	SANS 201:2008	%	1.6

Table D 18: Dolerite sand sieve analysis

SIEVE ANALYSIS as per SANS 201:2002							
Sieve size (mm)	**0.075**	**0.15**	**0.30**	**0.60**	**1.00**	**2.00**	**5.00**
Cumulative % passing	1.6	4.4	9.1	17.3	26.3	38.9	97.9
Recommended envelope	0-10	5-25	20-40	40-60	60-90	75-100	90-100

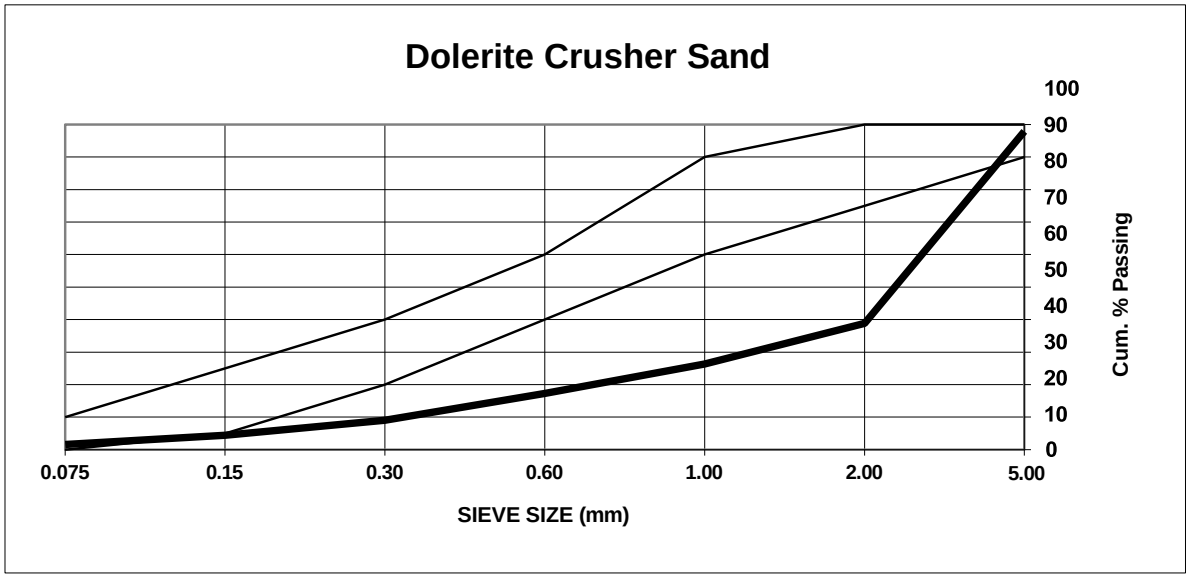


Figure D 9: Dolerite sand envelope range as per Specification: SANS 1083:2002

3. Granite

Table D 19: Granite sand properties

AGGREGATE PROPERTIES			
Item	**Test Specification**	**Unit**	**Value**
Silt content	SANS 5838:1976	ratio	2.4
Fineness Modulus	SANS 0201:2002	ratio	3.17
Loose Bulk Density	SANS 5845:1994	kg/m³	1770
Compacted Bulk Density	SANS 5845:1994	kg/m³	2050
Relative Density	SANS 8544:1994	ratio	2.62
Dust Content	SANS 201:2008	%	8.7

Table D 20: Granite sand sieve analysis

SIEVE ANALYSIS as per SANS 201:2002							
Sieve size (mm)	**0.075**	**0.15**	**0.30**	**0.60**	**1.00**	**2.00**	**5.00**
Cumulative % passing	8.7	15.2	24.8	38.0	48.5	65.0	91.8
Recommended envelope	0-10	5-25	20-40	40-60	60-90	75-100	90-100

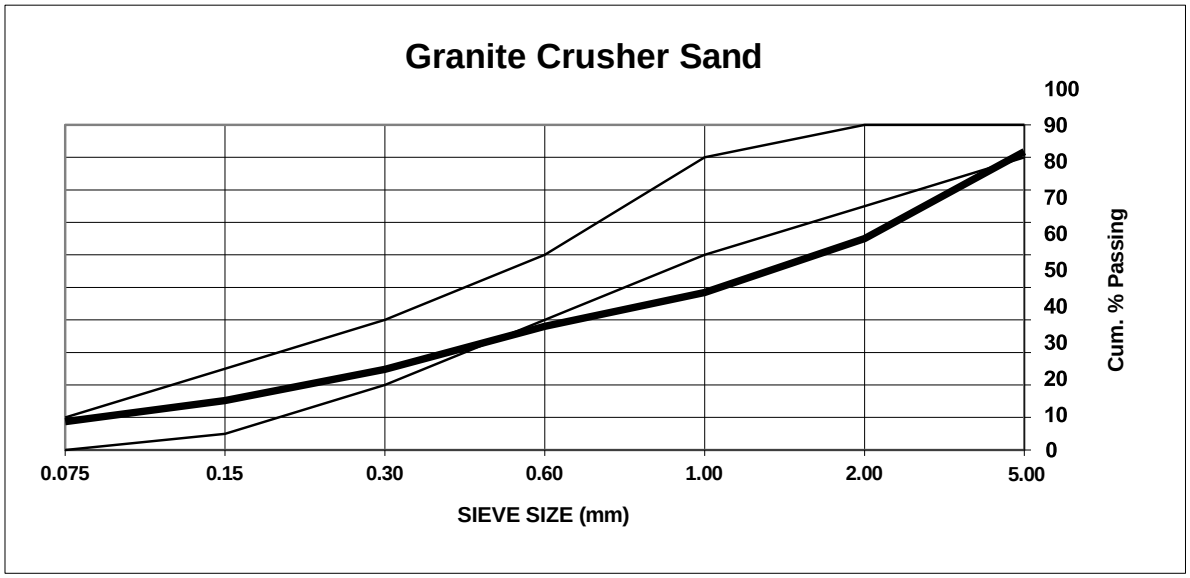


Figure D 10: Granite sand envelope range as per Specification: SANS 1083:2002

4. Norite

Table D 21: Norite sand properties

AGGREGATE PROPERTIES			
Item	**Test Specification**	**Unit**	**Value**
Silt content	SANS 5838:2006	ratio	2.4
Fineness Modulus	SANS 0201:2008	ratio	2.56
Loose Bulk Density	SANS 5845:2006	kg/m³	2270
Compacted Bulk Density	SANS 5845:2006	kg/m³	2540
Relative Density	SANS 8544:2006	%	3.45
Dust Content	SANS 0201:2008	%	8.9

Table D 22: Norite sieve analysis

SIEVE ANALYSIS as per SANS 201:2008							
Sieve size (mm)	**0.075**	**0.15**	**0.30**	**0.60**	**1.00**	**2.00**	**5.00**
Cumulative % passing	8.9	19.7	36.9	51.7	66.9	78.9	91.4
Recommended envelope	0-10	5-25	20-40	40-60	60-90	75-100	90-100

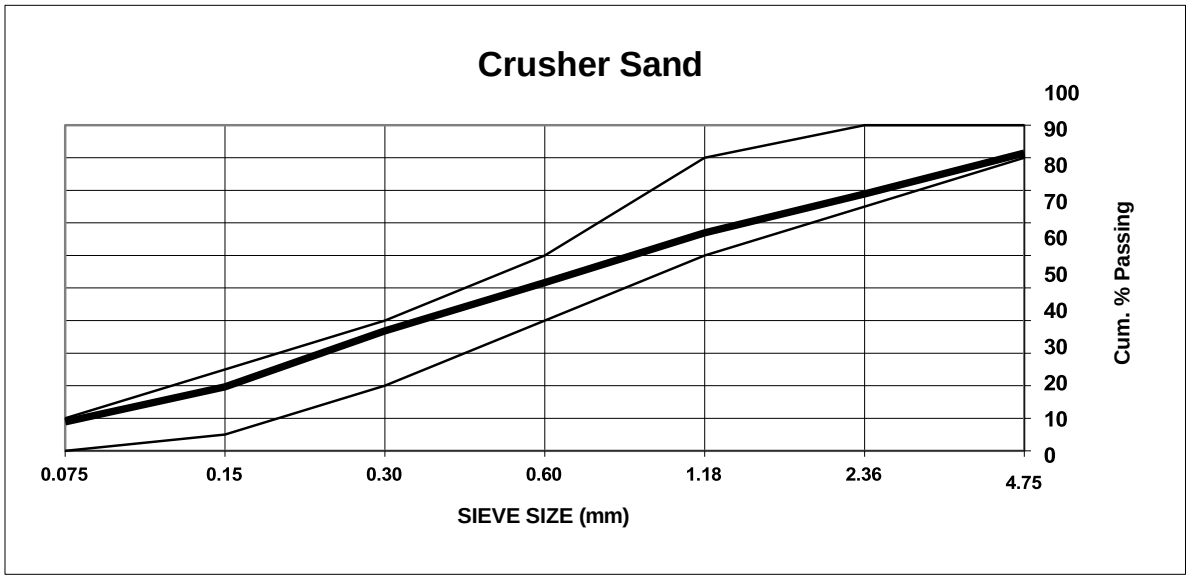


Figure D 11: Norite sand envelope range as per Specification: SANS 1083:2002

APPENDIX E COMPRESSION AND ABRASION TEST RESULTS

Table E 1: Compression and abrasion mass loss results (Pages 159 to 168)

RESULTS																	
	Compression test								Abrasion test								
Mix Identifier	Test Date	Day No.	Weight (g)	Force (kN)	f_{cu} (MPa)	Average f_{cu} (MPa)	STDev	Coefficient of variation (%)	Test Date	Day No.	mass before (g)	Mass after (g)	Mass loss (g)	Average mass loss (g)	STDev	Coefficient of variation (%)
APC19	24/2/15	3	2706	791	79.1				24/2/15	7	2620.1	2620	0.1			
	24/2/15	3	2666	782	78.2				24/2/15	7	2676.7	2676.5	0.2			
	24/2/15	3	2678	786	78.6	78.63	0.45	0.47	24/2/15	7	2553.5	2552.8	0.7	0.33	0.32	78.7
	24/2/19	7	2660	970	97				24/2/23	14	2628.1	2627.7	0.4			
	24/2/19	7	2634	954	95.4				24/2/23	14	2667.5	2667.2	0.3			
	24/2/19	7	2665	968	96.8	96.40	0.87	0.74	24/2/23	14	2620	2619.8	0.2	0.30	0.10	27.2
	24/3/11	28	2660	1184.1	118.41				24/3/11	28	2587.4	2587.2	0.2			
	24/3/11	28	634	1200.6	120.06				24/3/11	28	2617.5	2617.2	0.3			
	24/3/11	28	2651	1190.2	119.02	119.16	0.83	0.57	24/3/11	28	2646.6	2646.3	0.3	0.27	0.06	17.7
AFA19	24/2/15	3	2635	682	68.2				24/2/15	7	2654.8	2653.7	1.1			
	24/2/15	3	2642	735	73.5				24/2/15	7	2686.3	2685.8	0.5			
	24/2/15	3	2638	695	69.5	70.40	2.76	3.20	24/2/15	7	2707.8	2707	0.8	0.80	0.30	30.6
	24/2/19	7	2668	810	81				24/2/23	14	2429.9	2428.8	1.1			
	24/2/19	7	2713	830	83				24/2/23	14	2642.4	2641.7	0.7			
	24/2/19	7	2705	824	82.4	82.13	1.03	1.02	24/2/23	14	2705	2704.6	0.4	0.73	0.35	39.1
	24/3/11	28	2634	986	98.6				24/3/11	28	2521	2520.7	0.3			
	24/3/11	28	2697	1016	101.6	99.97	1.52	1.24	24/3/11	28	2628.5	2628.1	0.4	0.40	0.10	20.4

RESULTS																
Mix Identifier	Compression test								Abrasion test							
	Test Date	Day No.	Weight (g)	Force (kN)	f_{cu} (MPa)	Average f_{cu} (MPa)	STDev	Coefficient of variation (%)	Test Date	Day No.	mass before (g)	Mass after (g)	Mass loss (g)	Average mass loss (g)	STDev	Coefficient of variation (%)
	24/3/11	28	2688	997	99.7				24/3/11	28	2574.5	2574	0.5			
ASF19	24/2/15	3	2660	754	75.4				24/2/15	7	2664.1	2663.5	0.6			
	24/2/15	3	2670	751	75.1				24/2/15	7	2560.5	2559.6	0.9			
	24/2/15	3	2673	752	75.2	75.23	0.15	0.17	24/2/15	7	2633.3	2632.6	0.7	0.73	0.15	17.0
	24/2/19	7	2690	844	84.4				24/2/23	14	2626.4	2625.9	0.5			
	24/2/19	7	2689	855	85.5				24/2/23	14	2576	2575.4	0.6			
	24/2/19	7	2688	851	85.1	85.00	0.56	0.53	24/2/23	14	2632.2	2631.8	0.4	0.50	0.10	16.3
	24/3/11	28	2694	1113	111.3				24/3/11	28	2662.6	2662	0.6			
	24/3/11	28	2764	1098	109.8				24/3/11	28	2673	2672.4	0.6			
	24/3/11	28	2732	1010	101	107.37	5.56	4.23	24/3/11	28	2646.1	2645.9	0.2	0.47	0.23	40.4
APC13	24/2/16	3	2676	769	76.9				24/2/15	7	2562.8	2561.6	1.2			
	24/2/16	3	2673	778	77.8				24/2/15	7	2616.4	2615.3	1.1			
	24/2/16	3	2670	774	77.4	77.37	0.45	0.48	24/2/15	7	2609	2608.5	0.5	0.93	0.38	33.1
	24/2/20	7	2677	865	86.5				24/2/23	14	2590.4	2589.3	1.1			
	24/2/20	7	2658	880	88				24/2/23	14	2580.8	2579.6	1.2			
	24/2/20	7	2609	874	87.4	87.30	0.75	0.71	24/2/23	14	2588.4	2588.1	0.3	0.87	0.49	46.5
	24/3/12	28	2683	962	96.2				24/3/11	28	2580	2579.3	0.7			
	24/3/12	28	2655	956	95.6				24/3/11	28	2609	2608.2	0.8			
	24/3/12	28	2672	958	95.8	95.87	0.31	0.26	24/3/11	28	2609	2608.4	0.6	0.70	0.10	11.7
AFA13	24/2/16	3	2695	749	74.9				24/2/15	7	2575.2	2574.7	0.5			
	24/2/16	3	2658	735	73.5	74.53	0.91	0.99	24/2/15	7	2579	2578.4	0.6	0.63	0.15	19.7

RESULTS																
Mix Identifier	Compression test								Abrasion test							
	Test Date	Day No.	Weight (g)	Force (kN)	f_{cu} (MPa)	Average f_{cu} (MPa)	STDev	Coefficient of variation (%)	Test Date	Day No.	mass before (g)	Mass after (g)	Mass loss (g)	Average mass loss (g)	STDev	Coefficient of variation (%)
	24/2/16	3	2697	752	75.2				24/2/15	7	2597.4	2596.6	0.8			
	24/2/20	7	2666	884	88.4				24/2/23	14	2594.7	2593.9	0.8			
	24/2/20	7	2647	838	83.8				24/2/23	14	2598.6	2598	0.6			
	24/2/20	7	2654	841	84.1	85.43	2.57	2.46	24/2/23	14	2595.1	2594.7	0.4	0.60	0.20	27.2
	24/3/12	28	2671	986	98.6				24/3/11	28	2565.2	2564.4	0.8			
	24/3/12	28	2634	1004	100.4				24/3/11	28	2566.7	2566.2	0.5			
	24/3/12	28	2666	987	98.7	99.23	1.01	0.83	24/3/11	28	2566.7	2566.3	0.4	0.57	0.21	30.0
ASF13	24/2/16	3	2631	728	72.8				24/2/15	7	2588.8	2588.1	0.7			
	24/2/16	3	2618	718	71.8				24/2/15	7	2565.2	2564.7	0.5			
	24/2/16	3	2623	723	72.3	72.30	0.50	0.56	24/2/15	7	2547	2545.7	1.3	0.83	0.42	40.8
	24/2/20	7	2648	840	84				24/2/23	14	2573.9	2573.2	0.7			
	24/2/20	7	2641	830	83				24/2/23	14	2587.1	2586.2	0.9			
	24/2/20	7	2644	833	83.3	83.43	0.51	0.50	24/2/23	14	2574.3	2573.4	0.9	0.83	0.12	11.3
	24/3/12	28	2658	947	94.7				24/3/11	28	2641	2640.2	0.8			
	24/3/12	28	2629	940	94				24/3/11	28	2641	2640.3	0.7			
	24/3/12	28	2634	937	93.7	94.13	0.51	0.45	24/3/11	28	2644	2643.2	0.8	0.77	0.06	6.1
DPC19	24/2/19	3	2706	791	79.1				24/2/19	7	2697.4	2696.9	0.5			
	24/2/19	3	2666	782	78.2				24/2/19	7	2713.2	2712.8	0.4			
	24/2/19	3	2678	786	78.6	78.63	0.45	0.47	24/2/19	7	2711.2	2710.9	0.3	0.40	0.10	20.4
	24/2/23	7	2744	926	92.6				24/2/26	14	2706.9	2706.4	0.5			
	24/2/23	7	2769	972	97.2	94.43	2.44	2.11	24/2/26	14	2735.1	2734.7	0.4	0.40	0.10	20.4

RESULTS																	
Mix Identifier	Compression test								Abrasion test								
	Test Date	Day No.	Weight (g)	Force (kN)	f_{cu} (MPa)	Average f_{cu} (MPa)	STDev	Coefficient of variation (%)	Test Date	Day No.	mass before (g)	Mass after (g)	Mass loss (g)	Average mass loss (g)	STDev	Coefficient of variation (%)
	24/2/23	7	2754	935	93.5				24/2/26	14	2722.1	2721.8	0.3			
	24/3/15	28	2753	1052	105.2				24/3/15	28	2697	2696.7	0.3			
	24/3/15	28	2740	1073	107.3				24/3/15	28	2710	2709.6	0.4			
	24/3/15	28	2741	1071	107.1	106.53	1.16	0.89	24/3/15	28	2695	2694.8	0.2	0.30	0.10	27.2
DFA19	24/2/19	3	2635	682	68.2				24/2/19	7	2702.4	2701.6	0.8			
	24/2/19	3	2642	735	73.5				24/2/19	7	2686.3	2685.8	0.5			
	24/2/19	3	2638	695	69.5	70.40	2.76	3.20	24/2/19	7	2707.8	2707	0.8	0.70	0.17	20.2
	24/2/23	7	2744	921	92.1				24/2/26	14	2654.8	2653.8	1			
	24/2/23	7	2760	917	91.7				24/2/26	14	2698.1	2697.2	0.9			
	24/2/23	7	2753	913	91.3	91.70	0.40	0.36	24/2/26	14	2678.1	2677.9	0.2	0.70	0.44	50.8
	24/3/15	28	2730	979	97.9				24/3/15	28	2701.4	2700.9	0.5			
	24/3/15	28	2773	998	99.8				24/3/15	28	2711.1	2710.8	0.3			
	24/3/15	28	2771	985	98.5	98.73	0.97	0.80	24/3/15	28	2713.6	2713.2	0.4	0.40	0.10	20.4
DSF19	24/2/19	3	2660	682	68.2				24/2/19	7	2664.1	2663.5	0.6			
	24/2/19	3	2670	735	73.5				24/2/19	7	2560.5	2559.6	0.9			
	24/2/19	3	2673	737	73.7	71.80	3.12	3.55	24/2/19	7	2633.3	2632.5	0.8	0.77	0.15	16.3
	24/2/23	7	2597	816	81.6				24/2/26	14	2626.4	2625.7	0.7			
	24/2/23	7	2606	821	82.1				24/2/26	14	2576	2575.4	0.6			
	24/2/23	7	2601	818	81.8	81.83	0.25	0.25	24/2/26	14	2565	2564.4	0.6	0.63	0.06	7.4
	24/3/15	28	2667	863	86.3				24/3/15	28	2610.1	2609.7	0.43			
	24/3/15	28	2662	856	85.6	85.90	0.36	0.34	24/3/15	28	2608.1	2607.8	0.28	0.37	0.08	17.5

RESULTS																	
Mix Identifier	Compression test								Abrasion test								
	Test Date	Day No.	Weight (g)	Force (kN)	f_{cu} (MPa)	Average f_{cu} (MPa)	STDev	Coefficient of variation (%)	Test Date	Day No.	mass before (g)	Mass after (g)	Mass loss (g)	Average mass loss (g)	STDev	Coefficient of variation (%)
	24/3/15	28	2664	858	85.8				24/3/15	28	2598.5	2598.1	0.4			
DPC13	24/2/19	3	2676	791	79.1				24/2/15	7	2648.2	2647.9	0.3			
	24/2/19	3	2673	782	78.2				24/2/15	7	2670.4	2669.8	0.6			
	24/2/19	3	2670	779	77.9	78.40	0.62	0.65	24/2/15	7	2617.9	2617.4	0.5	0.47	0.15	26.7
	24/2/23	7	2754	834	83.4				24/2/23	14	2677	2676.6	0.4			
	24/2/23	7	2744	831	83.1				24/2/23	14	2658	2657.7	0.3			
	24/2/23	7	2753	832	83.2	83.23	0.15	0.15	24/2/23	14	2659.8	2659.6	0.2	0.30	0.10	27.2
	24/3/15	28	2742	834	93.5				24/3/11	28	2580	2579.8	0.2			
	24/3/15	28	2753	954	95.4				24/3/11	28	2609	2608.6	0.4			
	24/3/15	28	2755	933	93.3	94.07	1.16	1.01	24/3/11	28	2609	2608.7	0.3	0.30	0.10	27.2
DFA13	24/2/19	3	2695	749	74.9				24/2/19	7	2644	2641.6	2.4			
	24/2/19	3	2658	735	73.5				24/2/19	7	2632.7	2629.7	3			
	24/2/19	3	2697	752	75.2	74.53	0.91	0.99	24/2/19	7	2638	2636.6	1.4	2.27	0.81	29.1
	24/2/23	7	2736	839	83.9				24/2/26	14	2632.3	2631.1	1.2			
	24/2/23	7	2733	830	83				24/2/26	14	2650.9	2649.7	1.2			
	24/2/23	7	2731	831	83.1	83.33	0.49	0.48	24/2/26	14	2670.7	2668.9	1.8	1.40	0.35	20.2
	24/3/15	28	2742	1011	101.1				24/3/15	28	2659	2658.2	0.8			
	24/3/15	28	2753	985	98.5				24/3/15	28	2658.2	2658	0.2			
	24/3/15	28	2751	988	98.8	99.47	1.42	1.17	24/3/15	28	2648.9	2648.3	0.6	0.53	0.31	46.8
DSF13	24/2/19	3	2631	728	72.8				24/2/19	7	2527.1	2525.4	1.7			
	24/2/19	3	2618	718	71.8	72.30	0.50	0.56	24/2/19	7	2527.1	2525.4	1.7	1.90	0.35	14.9

RESULTS																
Mix Identifier	Compression test								Abrasion test							
	Test Date	Day No.	Weight (g)	Force (kN)	f_{cu} (MPa)	Average f_{cu} (MPa)	STDev	Coefficient of variation (%)	Test Date	Day No.	mass before (g)	Mass after (g)	Mass loss (g)	Average mass loss (g)	STDev	Coefficient of variation (%)
	24/2/19	3	2623	723	72.3				24/2/19	7	2622.2	2619.9	2.3			
	24/2/23	7	2736	839	83.9				24/2/26	14	2481.3	2479.9	1.4			
	24/2/23	7	2709	759	75.9				24/2/26	14	2508	2506.5	1.5			
	24/2/23	7	2703	755	75.5	78.43	4.74	4.93	24/2/26	14	2520.1	2518.5	1.6	1.50	0.10	5.4
	24/3/15	28	2671	759	75.9				24/3/15	28	2624.1	2623.4	0.7			
	24/3/15	28	2669	998	99.8				24/3/15	28	2508.3	2507.9	0.4			
	24/3/15	28	2685	1009	100.9	92.20	14.13	12.51	24/3/15	28	2620.1	2619.3	0.8	0.63	0.21	26.8
GPC19	24/2/20	3	2462	729	72.9				24/2/20	7	2423	2420.8	2.2			
	24/2/20	3	2489	739	73.9				24/2/20	7	2424.6	2421	3.6			
	24/2/20	3	2455	726	72.6	73.13	0.68	0.76	24/2/20	7	2429.6	2427.1	2.5	2.77	0.74	21.8
	24/2/23	7	2475	783	78.3				24/2/27	14	2462.3	2460.4	1.9			
	24/2/23	7	2507	790	79				24/2/27	14	2489.2	2487.1	2.1			
	24/2/23	7	2498	796	79.6	78.97	0.65	0.67	24/2/27	14	2455	2453.2	1.8	1.93	0.15	6.5
	24/3/16	28	2517	869.13	86.913				24/3/16	28	2420	2418.7	1.3			
	24/3/16	28	2533	876.9	87.69				24/3/16	28	2433.2	2431.7	1.5			
	24/3/16	28	2507	883.56	88.356	87.65	0.72	0.67	24/3/16	28	2440.5	2438.7	1.8	1.53	0.25	13.4
GFA19	24/2/20	3	2477	678	67.8				24/2/20	7	2414.8	2412.6	2.2			
	24/2/20	3	2465	689	68.9				24/2/20	7	2435.2	2433.1	2.1			
	24/2/20	3	2467	685	68.5	68.40	0.56	0.66	24/2/20	7	2436.5	2434	2.5	2.27	0.21	7.5
	24/2/23	7	2534	729	72.9				24/2/27	14	2481.3	2479.1	2.2			
	24/2/23	7	2514	734	73.4	73.13	0.25	0.28	24/2/27	14	2476.5	2474.4	2.1	2.03	0.21	8.4

RESULTS																	
Mix Identifier	Compression test								Abrasion test								
	Test Date	Day No.	Weight (g)	Force (kN)	f_{cu} (MPa)	Average f_{cu} (MPa)	STDev	Coefficient of variation (%)	Test Date	Day No.	mass before (g)	Mass after (g)	Mass loss (g)	Average mass loss (g)	STDev	Coefficient of variation (%)
	24/2/23	7	2522	731	73.1				24/2/27	14	2477.2	2475.4	1.8			
	24/3/16	28	2532	809.19	80.919				24/3/16	28	2425.2	2423.5	1.7			
	24/3/16	28	2514	814.74	81.474				24/3/16	28	2436.6	2434.6	2			
	24/3/16	28	2513	811.41	81.141	81.18	0.28	0.28	24/3/16	28	2420.3	2418.5	1.8	1.83	0.15	6.8
GSF19	24/2/20	3	2405	643	64.3				24/2/20	7	2365.2	2362.4	2.8			
	24/2/20	3	2433	647	64.7				24/2/20	7	2388.4	2385.7	2.7			
	24/2/20	3	2430	644	64.4	64.47	0.21	0.26	24/2/20	7	2387.4	2384.5	2.9	2.80	0.10	2.9
	24/2/23	7	2481	739	73.9				24/2/27	14	2365	2362.5	2.5			
	24/2/23	7	2476	735	73.5				24/2/27	14	2363	2361	2			
	24/2/23	7	2477	733	73.3	73.57	0.31	0.34	24/2/27	14	2400	2397.6	2.4	2.30	0.26	9.4
	24/3/16	28	2458	820.29	82.029				24/3/16	28	2396	2394.1	1.9			
	24/3/16	28	2475	815.85	81.585				24/3/16	28	2391	2388.9	2.1			
	24/3/16	28	2417	813.63	81.363	81.66	0.34	0.34	24/3/16	28	2408.5	2406.3	2.2	2.07	0.15	6.0
GPC13	24/2/20	3	2469	697	69.7				24/2/20	7	2423.6	2421.3	2.3			
	24/2/20	3	2478	702	70.2				24/2/20	7	2401.3	2399.3	2			
	24/2/20	3	2466	704	70.4	70.10	0.36	0.42	24/2/20	7	2404.1	2402.2	1.9	2.07	0.21	8.2
	24/2/23	7	2509	731	73.1				24/2/27	14	2411.5	2409.6	1.9			
	24/2/23	7	2507	723	72.3				24/2/27	14	2405.1	2403	2.1			
	24/2/23	7	2503	720	72	72.47	0.57	0.64	24/2/27	14	2394.5	2392.7	1.8	1.93	0.15	6.5
	24/3/16	28	5207	811.41	81.141				24/3/16	28	2387.5	2386.1	1.4			
	24/3/16	28	2507	802.53	80.253	80.44	0.63	0.64	24/3/16	28	2399.2	2397.5	1.7	1.63	0.21	10.4

RESULTS																	
Mix Identifier	Compression test								Abrasion test								
	Test Date	Day No.	Weight (g)	Force (kN)	f_{cu} (MPa)	Average f_{cu} (MPa)	STDev	Coefficient of variation (%)	Test Date	Day No.	mass before (g)	Mass after (g)	Mass loss (g)	Average mass loss (g)	STDev	Coefficient of variation (%)
	24/3/16	28	2512	799.2	79.92				24/3/16	28	2387.5	2385.7	1.8			
GFA13	24/2/20	3	2502	680	68				24/2/20	7	2364.6	2361.5	3.1			
	24/2/20	3	2475	685	68.5				24/2/20	7	2412.7	2409.9	2.8			
	24/2/20	3	2470	682	68.2	68.23	0.25	0.30	24/2/20	7	2429.3	2427.2	2.1	2.67	0.51	15.7
	24/2/23	7	2447	739	73.9				24/2/27	14	2420.3	2418.1	2.2			
	24/2/23	7	2452	742	74.2				24/2/27	14	2418.6	2415.9	2.7			
	24/2/23	7	2450	740	74	74.03	0.15	0.17	24/2/27	14	2430.5	2427.9	2.6	2.50	0.26	8.6
	24/3/16	28	2469	820.29	82.029				24/3/16	28	2397.2	2394.9	2.3			
	24/3/16	28	2449	823.62	82.362				24/3/16	28	2357.2	2354.8	2.4			
	24/3/16	28	2445	821.4	82.14	82.18	0.17	0.17	24/3/16	28	2355.6	2353.1	2.5	2.40	0.10	3.4
GSF13	24/2/20	3	2356	621	62.1				24/2/20	7	2358.3	2356.2	2.1			
	24/2/20	3	2365	618	61.8				24/2/20	7	2261.8	2259.4	2.4			
	24/2/20	3	2363	622	62.2	62.03	0.21	0.27	24/2/20	7	2308.2	2304.4	3.8	2.77	0.91	26.8
	24/2/23	7	2400	670	67				24/2/27	14	2400.1	2397.2	2.9			
	24/2/23	7	2396	674	67.4				24/2/27	14	2396.8	2394.1	2.7			
	24/2/23	7	2391	671	67.1	67.17	0.21	0.25	24/2/27	14	2391.6	2389	2.6	2.73	0.15	4.6
	24/3/16	28	2500	743.7	74.37				24/3/16	28	2297	2294.4	2.6			
	24/3/16	28	2487	748.14	74.814				24/3/16	28	2268.6	2266.3	2.3			
	24/3/16	28	2506	744.81	74.481	74.56	0.23	0.25	24/3/16	28	2305.4	2302.8	2.6	2.50	0.17	5.7
NPC19	24/2/16	3	2889.4	302	30.2				24/2/20	7	2907.7	2906.1	1.6			
	24/2/16	3	2901.1	301	30.1	30.03	0.21	0.57	24/2/20	7	2889.4	2888.6	0.8	1.30	0.44	27.4

RESULTS																
Mix Identifier	Compression test								Abrasion test							
	Test Date	Day No.	Weight (g)	Force (kN)	f_{cu} (MPa)	Average f_{cu} (MPa)	STDev	Coefficient of variation (%)	Test Date	Day No.	mass before (g)	Mass after (g)	Mass loss (g)	Average mass loss (g)	STDev	Coefficient of variation (%)
	24/2/16	3	2906.1	298	29.8				24/2/20	7	2901.1	2899.6	1.5			
	24/2/20	7	2909.4	460	46				24/2/27	14	2908.3	2907.2	1.07			
	24/2/20	7	2894.2	457	45.7				24/2/27	14	2893.5	2892.4	1.1			
	24/2/20	7	2911.7	463	46.3	46.00	0.30	0.53	24/2/27	14	2918.2	2916.5	1.7	1.29	0.36	22.5
	24/3/12	28	2912	575	57.5				24/3/16	28	2911.7	2909.4	2.3			
	24/3/12	28	2911.9	573	57.3				24/3/16	28	2895.6	2894.2	1.4			
	24/3/12	28	2911.5	576	57.6	57.47	0.15	0.22	24/3/16	28	2908	2906.3	1.7	1.80	0.46	20.8
NFA19	24/2/16	3	2856.4	264	26.4				24/2/16	7	2856.4	2854.2	2.2			
	24/2/16	3	2949.2	263	26.3				24/2/16	7	2949.2	2946.7	2.5			
	24/2/16	3	2907.7	267	26.7	26.47	0.21	0.64	24/2/16	7	2907.7	2904.6	3.1	2.60	0.46	14.4
	24/2/20	7	2884.5	459	45.9				24/2/23	14	2931	2928.9	2.1			
	24/2/20	7	2966.7	454	45.4				24/2/23	14	2897.2	2895	2.2			
	24/2/20	7	2927	452	45.2	45.50	0.36	0.65	24/2/23	14	2911.3	2909.3	2	2.10	0.10	3.9
	24/3/12	28	2891	589	58.9				24/3/12	28	2885.1	2884.6	0.5			
	24/3/12	28	2874	588	58.8				24/3/12	28	2967.1	2966.3	0.8			
	24/3/12	28	2903	591	59.1	58.93	0.15	0.21	24/3/12	28	2929.6	2926.9	2.7	1.33	1.19	73.1
NSF19	24/2/16	3	2911.5	143	14.3				24/2/16	7	2911.4	2909.1	2.3			
	24/2/16	3	2872.4	152	15.2				24/2/16	7	2872.5	2868.9	3.6			
	24/2/16	3	2901.9	156	15.6	15.03	0.67	3.62	24/2/16	7	2901.4	2899.7	1.7	2.53	0.97	31.3
	24/2/20	7	2922.3	264	26.4				24/2/23	14	2904.5	2902.1	2.4			
	24/2/20	7	2873.3	266	26.6	26.50	0.10	0.31	24/2/23	14	2896.2	2894.4	1.8	2.13	0.31	11.7

RESULTS																	
Mix Identifier	Compression test								Abrasion test								
	Test Date	Day No.	Weight (g)	Force (kN)	f_{cu} (MPa)	Average f_{cu} (MPa)	STDev	Coefficient of variation (%)	Test Date	Day No.	mass before (g)	Mass after (g)	Mass loss (g)	Average mass loss (g)	STDev	Coefficient of variation (%)
	24/2/20	7	2915.7	265	26.5				24/2/23	14	2876.9	2874.7	2.2			
	24/3/12	28	2919.8	588	58.8				24/3/12	28	2921.8	2919.8	2			
	24/3/12	28	2872.3	591	59.1				24/3/12	28	2874.3	2872.3	2			
	24/3/12	28	2913.1	592	59.2	59.03	0.21	0.29	24/3/12	28	2914.7	2913.1	1.6	1.87	0.23	10.1

APPENDIX F: ETHICS WAIVER

UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG

HUMAN RESEARCH ETHICS COMMITTEE (NON-MEDICAL)

Registration number: REC-101114-044

SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING ETHICS COMMITTEE

Ethics clearance / waiver number: CEECC-1716238-2024

08 March 2024

Re: Afikile Hintsa (1716238)

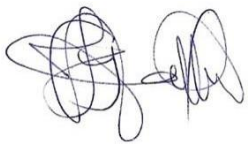
To whom it may concern,

Afikile Hintsa (1716238) is currently registered as an MSc student at the School of Civil and Environmental Engineering, University of the Witwatersrand, Johannesburg. This letter is to confirm that, at the time of writing, Afikile Hintsa does not need ethical clearance for his study entitled "PERFORMANCE-BASED DESIGN CONSIDERATIONS FOR ABRASION-RESISTANT CONCRETE FOR STRUCTURES IN MINERAL PROCESSING PLANTS". This decision has been reached based upon a description of the project supplied by Afikile Hintsa to the School of Civil and Environmental Engineering Ethics Committee, constituted as a subcommittee of the University Human Research Ethics Committee (Non-Medical), which has been evaluated by the subcommittee chair. This decision has then been ratified by the University Human Research Ethics Committee (Non-Medical). If, however, Afikile Hintsa changes the methods of data collection and analysis for this project, this decision may no longer be valid. If such changes take place, this should be communicated to the School of Civil and Environmental Engineering Ethics Committee.

Please feel free to contact me should you require any further information.

Thank you.

Yours sincerely,



Prof John Ndiritu

Shaun Schoeman (Senior Administrative Officer)
Solomon Mahlangu House, 10th Floor, Room 10004, Jorissen Street, Braamfontein, Johannesburg Private Bag 3, Wits 2050
T + 27(0)11 717 1408 | **E** Shaun.Schoeman@wits.ac.za | hrecnon-medical@wits.ac.za
www.wits.ac.za/research/about-our-research/ethics-and-research-integrity/