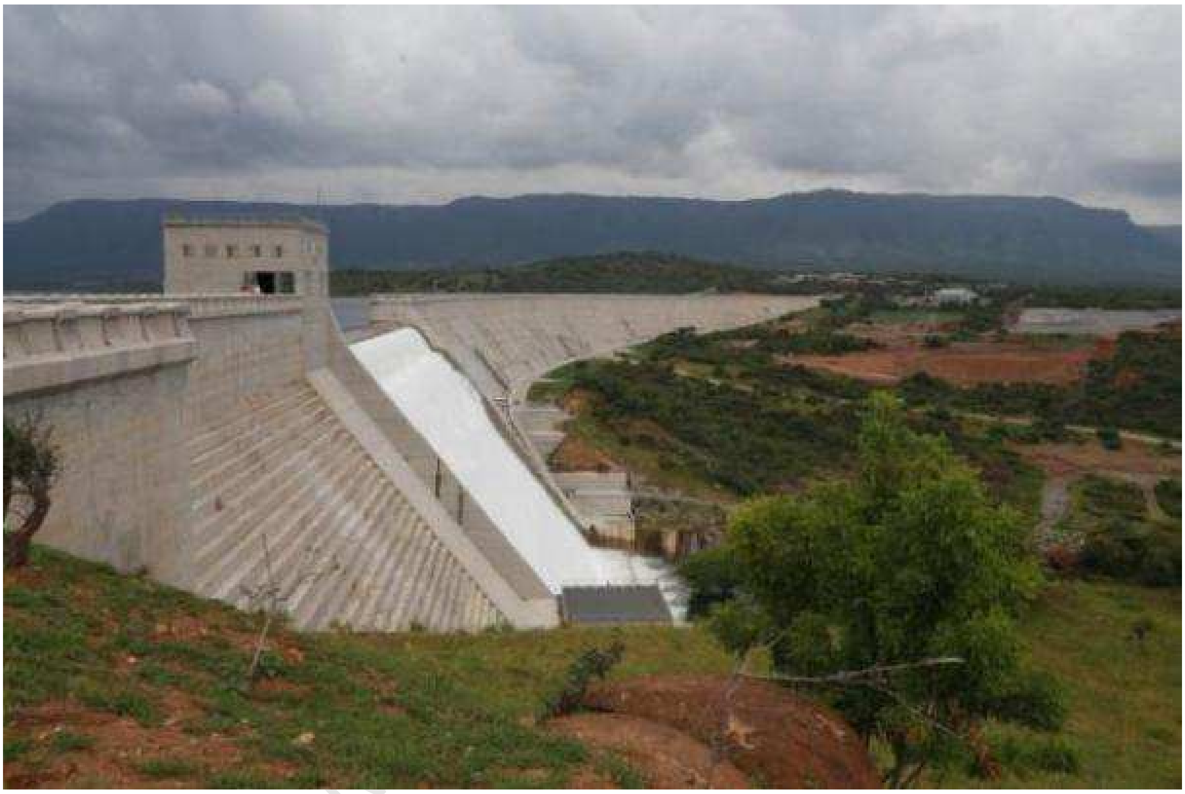
ABRASION RESISTANCE OF IV-RCC USED TO CONSTRUCT SPILLWAY CONCRETE STEPS OF SOUTH AFRICAN DAMS



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Terms of Reference

The Department of Water and Sanitation (DWS) had previously used conventional vibrated concrete (CVC), also called skin concrete, grade 20/38, on the downstream steps of spillways, over which the flood water is discharged down to the stilling basin (apron) of a dam.

During the construction of De Hoop Dam in Limpopo 2008, DWS has developed a high paste, high fly ash (FA) content, cohesive roller compacted concrete (RCC) mix, grade 15/38 for placement at De Hoop Dam (DHD). The Contractor then further developed and succeeded in the use of Immersion-Vibrated RCC (IV-RCC) in place of the CVC. Due to the high FA content and the resultant long-term strength increase, the IV-RCC was used to form the spillway steps, which simplified placement of concrete.

The development and use of IV-RCC has raised the question of a performance-based specification for future projects with regard to the abrasion resistance and durability of the spillway steps. DWS then realised the need for academic research that will lead to setting of such standards and/or performance specifications for the spillway steps of future dams.

Executive Summary

This dissertation outlines the investigation on abrasion resistance of roller compacted concrete designed for spillway steps of dams in South Africa. Literature on abrasion resistance of concrete has been reviewed and factors affecting abrasion resistance are discussed. These factors include hardness of concrete, aggregate/paste bond, type of aggregates, concrete compressive strength, curing, surface treatment and the quality of the concrete surface which is influenced by the finishing method. Available test methods as outlined by ASTM International Standards are also discussed in the literature review but only two methods (sandblasting method and wire brush method) were used in this research. These have been chosen because of their availability (at the UCT Civil Engineering Laboratory) and relevancy to this research. The sandblasting method was the most relevant in this research because it stimulates similar abrasion action as waterborne action on the concrete surface. The other method has been chosen for its availability in the UCT lab, to compare its results with the sandblasting results, and to evaluate whether if it can be used to assess abrasion resistance of hydraulic structures.

A two-way experimental approach was adopted to achieve results for this research. The first approach was a laboratory investigation, where concrete cubes were produced under controlled conditions and tested for abrasion resistance, compressive strength, oxygen permeability index (OPI) and Sorptivity test. The durability index tests were conducted to get a general evaluation of the concrete's microstructure. If the OPI values are acceptable (more than 9) then the concrete's general microstructure would be accepted to be durable. Materials (aggregates) from De Hoop Dam and those readily available at the UCT laboratory were used to cast different types of concrete to be investigated and compared. The types of concrete included conventional concrete, fly ash concrete and slag (GGBS) concrete. Fly ash is used in most concrete dam construction due to its pozzolanic properties which help slowing down the heat of hydration. The slag was included in these mixes in order to have available results when it is used in future projects as it is highly likely to be used for areas in the KwaZulu-Natal province which have a less reactive type of slag in terms of heat of hydration. The raising of the Hazelmere Dam, close to Durban, is currently using GGBS as an extender. The second approach of this research was based on abrasion testing of cores drilled from the stepped wall of De Hoop Dam. These cores were drilled and taken to UCT laboratory for investigations with the same test methods used for laboratory cubes. A comparison was drawn between the test results of the laboratory made cubes and those drilled from the dam spillway, and a correlation was investigated between these two. Furthermore, the sandblast test method was compared with the wire brush method to assess which one produces more reliable results.

The abrasion results showed approximately 30% difference in abrasion resistance performance between the conventional concrete and the roller compacted concrete mixes, with the former being more abrasion resistant. When the percentage of the extender for the RCC mix was adjusted from 70% to 65% these two concrete mixes almost performed equally with a 9% difference in abrasion results. It was confirmed that beyond 45% replacement of Portland cement with fly ash, there is no improvement in abrasion resistance of concrete. However, there were no significant differences (only 9%) between abrasion resistant values of concrete with 45% or 65% fly ash replacements. Therefore it was observed that abrasion resistance of concrete was compromised beyond 65% fly ash replacement. Aggregates with sub-angular shape and rough texture have proven to yield high abrasion resistant concrete. The concrete made with blends of GGBS and Portland cement showed slightly improvement in abrasion resistance of concrete when compared to fly ash concrete.

The cores drilled from the structure had abrasion resistance values 3 times more than the laboratory produced cubes and this was consistent with both the sandblasting and wire brush method, indicating that the actual structure has adequate abrasion resistance. The sandblasting method has proven to be reliable and more sensitive and it is recommended for assessment of abrasion resistance of hydraulic structures, while the wire brush method can be used for general quality control.

Recommendations based on the results and literature study will be made available to the Department of Water and Sanitation to update their specifications, which was one of the key goals of this research.

Contents page

Definitions of technical terms, acronyms and symbols.

Technical terms

Abrasion - process of wearing away of a surface by friction. In this context Abrasion means wearing away of the concrete surface due to water and silt flowing over it.

Curing – process of maintaining moisture content and temperature of concrete to permit complete hydration of cementitious products after concrete has been placed and compacted.

Extender–cementitious materials added to the concrete mixture as a replacement material for a portion of Portland cement present, e.g. fly ash (FA), lime, silica fume, ground granulated blast furnace slag (GGBS) etc.

Paste -a mixture composed of cementitious material and water that binds aggregates together to make concrete.

Spillway-a structure designed to provide the flood releases from a dam.

Sandblasting- an abrasive process whereby sand is blasted to a surface under high pressure to wear down the surface or expose the aggregates.

Grade 20/38- The first number indicates the strength of concrete of 20 MPa in this case and the second number indicates the nominal maximum size of the coarse aggregate used in the concrete mix which is 38 mm in this case.

Acronyms used

ASTM- American Society for Testing and Materials

C&CI- Cement and Concrete Institute

CVC-Conventional Vibrated Concrete also referred to as skin concrete

DWS-Department of Water and Sanitation

DHD-De Hoop Dam

FA - Fly Ash

GGBS - Ground Granulated Blast furnace Slag

IV-RCC – Immersion-Vibrated Roller Compacted Concrete

NOC- Non Overspill Crest

OPI- Oxygen Permeability Index test

POC- Ordinary Portland cement

RCC - Roller Compacted Concrete

UCT- University of Cape Town

1. Introduction

1.1. Roller compacted concrete and abrasion resistance

Concrete material is widely used in the construction of dams for its durability and low maintenance during service, if designed and placed properly. Roller compacted concrete is a type of concrete with similar ingredients as conventional mass concrete but in different proportions. It contains much less water (<130 liters per m^3) and has high replacement (up to 70%) of Portland cement with a pozzolan (fly ash) or slag. The less water content and high stone content in the mix make it drier with a zero slump. However, the high percentage of pozzolan, especial fly ash (FA), improves the workability of the concrete mix drastically such that it is possible to compact the concrete with either poker vibrators or roller vibrators. Such a concrete mix, with high paste content, is referred to as Immersion-Vibrated Roller Compacted Concrete (IV-RCC).

Initially in 1961, during the construction of Alpe Gera Dam in North Italy, RCC was used for backfill and in the construction of concrete pavements. Since the 1970s it has been used to construct concrete gravity dams with the benefit of accelerated construction, low cement content and cheaper construction materials. In South Africa conventional vibrated concrete (CVC), also called skin concrete, has been used on the downstream steps of RCC spillways, over which the flood water is discharged down to the stilling basin (apron) of a dam. The class of this conventional skin concrete was usually specified as grade 20/53 and later revised to grade 20/38 at De Hoop Dam (DHD) in 2009.

During the construction of De Hoop Dam (2007-2013), DWS had developed a high paste, high FA content, cohesive roller compacted concrete (RCC) mix grade 15/38 for placement. The Contractor at DHD then further developed and succeeded in the use of Immersion-Vibrated RCC (IV-RCC) in lieu of the CVC. Due to the high FA content and the long-term strength increase, it has been used successfully for forming the spillway steps of DHD, which simplified and accelerated RCC placement.

While concrete is designed to withstand structural loads, it must also stand the test of time to environmental attacks, and abrasion is one of such forms of natural attacks to concrete. Abrasion resistance of concrete is a measure of concrete durability and abrasion is a physical attack of the concrete surface from abrasive forces. The concrete surface is considered durable if its level of abrasion resistance is such that the depth of abrasion induced wear does not exceed the allowable depth for the intended service period of the structure (Papenfus, 2002).

1.2. Problem Statement

The development and use of IV-RCC has raised questions with regards to the abrasion resistance and durability of the spillway steps. There is little information available on the quantification or measure as an indication of the abrasion resistance of the IV-RCC in comparison to CVC in the spillway steps. It is important that these characteristics be investigated, as the flowing water over the spillway steps will abrade the concrete surface and cause deterioration over time.

The commonly adopted procedure for assessing abrasion resistance of concrete surfaces in South Africa is the ASTM C418: Standard Test Method for Abrasion Resistance of Concrete by Sandblasting. During the construction of De Hoop Dam the acceptability of the test results for IV-RCC could not concluded, and that lead to a need for academic research to compare the IV-RCC abrasion resistance results to those of conventional concrete. These results are discussed in Section 2.

1.3. Research Justification

Durability is one of the most important material performance concepts when it comes to expected service life of a structure. Abrasion, which is a physical attack, is one of the factors influencing durability of concrete. It is crucial that durability is achieved to avoid deterioration and unplanned expensive rehabilitation of a structure during its service life.

The research aims at developing performance specifications which will help ensuring that abrasion of spillway steps is avoided therefore enhancing durability. This will avoid associated high costs of early and unnecessary repair and rehabilitation.

This research also aims at establishing performance specifications and associated test methods for the concrete to be used to construct future spillway steps in South Africa. The purpose of this research is to enable the development of a standard or a performance specification for concrete to be used in the spillway steps of future dams, and also to establish criteria which the new concrete spillway steps can be monitored against.

1.4. Development Plan

The following actions were taken to complete this research:

- Literature on abrasion resistance of concrete was reviewed and is discussed in Section 2 of this report.
- A formative academic proposal was submitted to the department of Civil Engineering at UCT and to DWS for approval and the summary is outlined in Section 3.
- Materials (aggregates and sand) to be used for laboratory work were transported from De Hoop Dam to UCT laboratory in Cape Town.
- Cores were drilled from De Hoop Dam which has a stepped RCC spillway constructed by DWS, and tested at the UCT laboratory.
- Laboratory investigations were conducted as detailed in Section 3.
- The results from the laboratory investigations were analysed and discussed in Sections 4 and 5.
- Conclusions were drawn from these results and the supporting literature, and then recommendations are made to the Department of Water and Sanitation to update the specifications for the durability of the spillway steps.

2. Literature review and project experience

In this chapter abrasion resistance of concrete is defined, and factors affecting abrasion resistance are discussed. Also measurement procedures for abrasion resistance are summarised. The results of the abrasion testing conducted during the construction of De Hoop Dam are also discussed in this chapter.

2.1. Abrasion Resistance

Abrasion resistance is a property of hardened concrete giving an indication of its durability. Abrasion is one of the factors influencing (by physical attack) the durability of concrete. A more durable concrete will abrade less compared to a less durable concrete. Abrasion means wearing away of concrete surface, exposing the concrete aggregates due to physical attacks such as water, silt and other abrasive materials that induce friction when transported across the concrete surface. The first sign of abrasion damage is a slight roughening of the surface due to the loss of the exposed surface layer of the concrete.

Abrasion, as defined by ASTM (2005), is the physical wear due to hard particles or protuberances forced against and moving along a solid interface. Ballim et al (2009) refers to concrete abrasion as "wearing of the surface of concrete caused by repeated rubbing or frictional action". Abrasion resistance of concrete then is the ability of concrete to resist scratching and/or wearing.

2.2. Factors influencing abrasion resistance of concrete

Hardness of the concrete and aggregate/paste bond are the two major factors influencing abrasion resistance of concrete (Papenfus, 2003), and are discussed below among other factors. These factors, which give a good theoretical base, were considered when this research was conducted. Figure 1 shows how some of the various factors affecting abrasion resistance relate to concrete hardness and aggregate/paste bond.

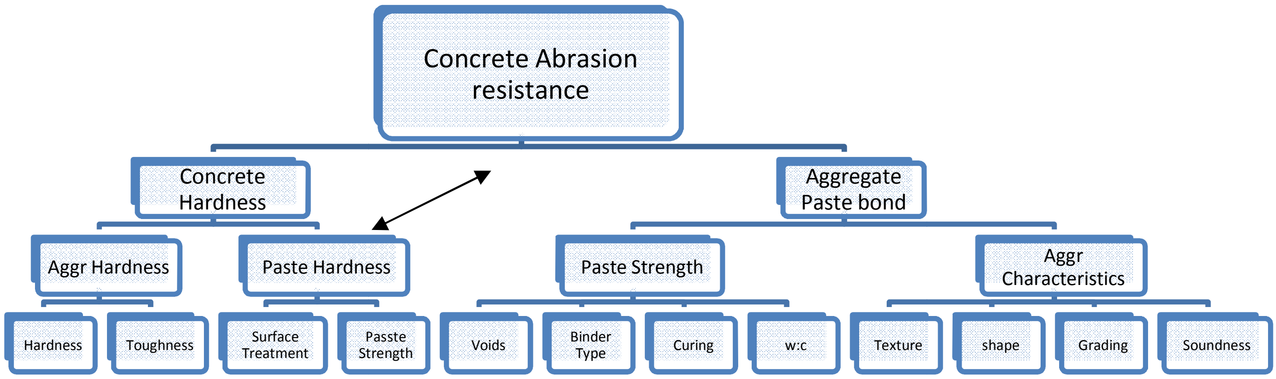

Figure 1: Various factors affecting abrasion resistance of concrete (Papenfus, 2003).

2.2.1. Hardness of concrete

Hardness in concrete is a function of the hardness of the two major constituents of the concrete mix, these are, the aggregate hardness and paste hardness (Papenfus, 2003). These two factors are also influenced by many other contributing factors as illustrated in Figure 1. In general aggregates are considerable stronger, stiffer and dimensionally stable than the paste (Perrie, 2009), therefore are more resistant to abrasion. The cement paste, especial for low strength concrete, is relatively weak in hardness and susceptible to abrasion, therefore is the weaker link of the two constituents. The abrasion resistance of concrete therefore, especial for low strength concrete, is largely determined by the properties of the cement paste.

The hardened cement paste is largely influenced by its porosity which is related to excess water required for workability of concrete in the fresh state but not used up during the hydration process. This excess water, which is lost over time due to evaporation, leaves flaws in the form of micro-cracks and discontinuities in the pore structure of the concrete (Perrie, 2009). These flaws influence many of the concrete properties (including strength and abrasion) because they are the weakest link where failure is initiated when concrete is under loading. The relationship between water:

cement ratio and compressive strength is also governed by these flaws within the pore structure of the concrete.

Papenfus (2003) argues that aggregates play a far more important role than the paste due to the high percentage of the total volume they contribute to the mass concrete. He further backed up this argument by stating that aggregates are much harder and more abrasion resistant than hardened binder paste. However, his argument reveals that the paste is the weakest link, therefore making the paste properties more important than the aggregates when it comes to determining the abrasion resistance of concrete, especially for low strength concrete. Abrasion resistance is a property of the concrete surface which is largely made up of paste than the aggregates, the paste properties therefore are as important as the aggregates if not more. Papenfus' argument would be only true on high strength concrete or when measuring the abrasion resistance of the sub-surface concrete, where most of the paste has already worn out and the bulk of the concrete has aggregates exposed. In these cases the properties of the aggregates play an important role in abrasion resistance, as they also protect the paste that is not exposed.

2.2.2. Aggregate-paste bond

The bond between paste and aggregates is the weakest area in the concrete and it governs numerous intrinsic properties of concrete and abrasion resistance is one of them. This bond is influenced by the interfacial transition zone (ITZ) that exists between the cement paste and the aggregates, (Alexander, 2015). The stronger the bond is, the better the physical properties of the concrete and the more the concrete is resistant to abrasion. This interfacial bond increases with use of fine particles obtained from cement extenders (slag, fly ash, silica fume and limestone). These extenders bring a phenomenon known as "fine-filler effect" which improves the homogeneous microstructure of the paste which in turn improves the strength and impermeability and reduces the amount of bleeding of the concrete (Perrie, 2009). The interface bond also increases with decreasing water: cement ratio and improves with time given that there is sufficient water for the hydration process. These factors mentioned also affect the compressive strength of concrete, therefore correlating a relationship between compressive strength and abrasion resistance.

Physical characteristics of the aggregates such as surface texture, shape, grading and soundness play an important role in the quality of bond (Papenfus, 2003). The shear bond strength between the paste and the aggregates increases with increasing roughness of the surface texture of the aggregates. This interface strength also increases with use of absorbent aggregates and with use of ultrafines in the aggregates which also bring a fine-filler effect at the interface and also reduce bleeding (Perrie, 2009).

2.2.3. Aggregates

There are two special terms that are used in the following discussion, rock hardness and rock toughness, both these terms indicate physical properties of a rock and are important where abrasion resistance and concrete strength are concerned. Rock hardness is defined as the ability of a rock to resist scratching and is usually expressed as compressive fracture strength, while toughness is defined as the ability of a rock to absorb energy and plastically deform without fracturing (Sithole, 2017). Fine grained rocks, because of the ability of the fines to interlock and keep together, generally exhibit higher rock hardness compared to coarse grained rocks. Generally, igneous rocks have higher hardness and toughness because of the conditions under which they are formed.

As discussed previously, hardness of the aggregates plays an important role in concrete hardness. The harder the aggregates, the higher the concrete strength and abrasion resistance provided that the strength of the paste and the interfacial bond are equally good. The aggregate characteristics also play an important role in the abrasion resistance of concrete. While texture, shape, grading and soundness of the aggregates enhance the aggregate paste bond, the toughness of the aggregates in some cases (such as impact loading) plays a far more significant role than the hardness of the aggregates. This is due to better elastic nature from tougher aggregates (Papenfus, 2003).

The degree to which aggregates influence abrasion resistance of concrete depends on the strength of the concrete, the higher the strength the higher the influence of aggregates on abrasion resistance and strength (Perrie, 2009). Harder aggregates also help protect the softer paste component in the sub-surface of the concrete (Papenfus, 2003). Abrasion resistance of aggregates therefore plays a significant role in the abrasion resistance of high strength concrete.

Los Angeles abrasion test, in accordance with SANS 5846, is the most common test method used to measure abrasion resistance of aggregates. The Los Angeles test measures the degradation of mineral aggregates of standard gradings resulting from a combination of actions which include abrasion, impact and grinding in a rotating steel drum containing a specified number of steel spheres (Druyts, 2007). After the sample has been subjected to an impact crushing effect, it is removed from the drum and sieved to measure the degradation as a percentage loss. The specified maximum values expressed as percentage wear should not be exceeded for that sample to be considered adequate.

Kilic et al (2007) examined the influence of aggregate type on the strength characteristics and abrasion resistance of high strength silica fume concrete. Among these aggregates included gabbro, basalt, quartzite, limestone and sandstone. Concrete made with gabbro and basalt aggregates (igneous rocks) showed the highest abrasion resistance and compressive strength compared to the sandstone (sedimentary rock) which showed the lowest performance in these properties. The influence of the grain size of the parent rock was evident in this case. The aggregates (gabbro and basalt) derived from igneous rocks, with relatively fine grained minerals, yielded high abrasion resistant concrete compared to the coarse grained sandstone aggregates. This high performance of gabbro aggregates is expected in this research in comparison to the greywacke aggregates as the gabbro aggregates are stronger in hardness.

2.2.4. Concrete compressive strength

Abrasion resistance of concrete increases with increasing compressive strength but this does not necessarily mean that concrete with low compressive strength has low abrasion resistance. As discussed previously that abrasion influences the durability of concrete, therefore abrasion resistance of concrete is an indication of durability, and durability does not necessarily depend on the compressive strength of concrete (Beushausen, 2015). Although concrete with high compressive strength tends to give higher durability, this does not automatically mean that low compressive strength concrete is less durable. Factors like the type of binder used, compaction method applied, surface treatment/finishing and curing play a big role in durability of concrete.

Abrasion resistance of concrete pays more attention to the concrete surface while compressive strength is a measure of the core concrete's ability to resist compressive stresses. Alexander (1983) and Papenfus (2003) agree that any measure taken to improve concrete compressive strength also has a potential to improve abrasion resistance. Such measures include but are not limited to w/c ratio, cement content and type, mix design, compaction and curing.

Motsieloa (2009) showed in his thesis that the lower the water cement ratio the higher the abrasion resistance of concrete. In general, lower water cement ratio is linked to higher compressive strength; therefore abrasion resistance is also influenced by this. This was confirmed by his thesis, where concretes with higher compressive strength had higher values of abrasion resistance.

Papenfus (2003) argues that "*although abrasion resistance is related to compressive strength generally, by means of using special surface finishing processes or materials, it is possible to achieve a surface with a high abrasion resistance using a concrete that has a low compressive strength*". He further argues that, "*from poor construction practice, it is possible to produce a poor quality surface that has low abrasion resistance from high compressive strength concrete*". For example if a high compressive strength concrete was subjected to detrimental effects such as excessive bleeding or poor curing, the concrete surface would be compromised and have poor abrasion resistance but the compressive strength be still as good.

Papenfus (2003) investigated the relationship between abrasion resistance of concrete and compressive strength. There seems to be a trend of increase in abrasion resistance with increasing compressive strength as shown in Figure 2. Naik et al (2002) also identified a similar trend on their investigations on the effects of a source of fly ash on the abrasion resistance of concrete.

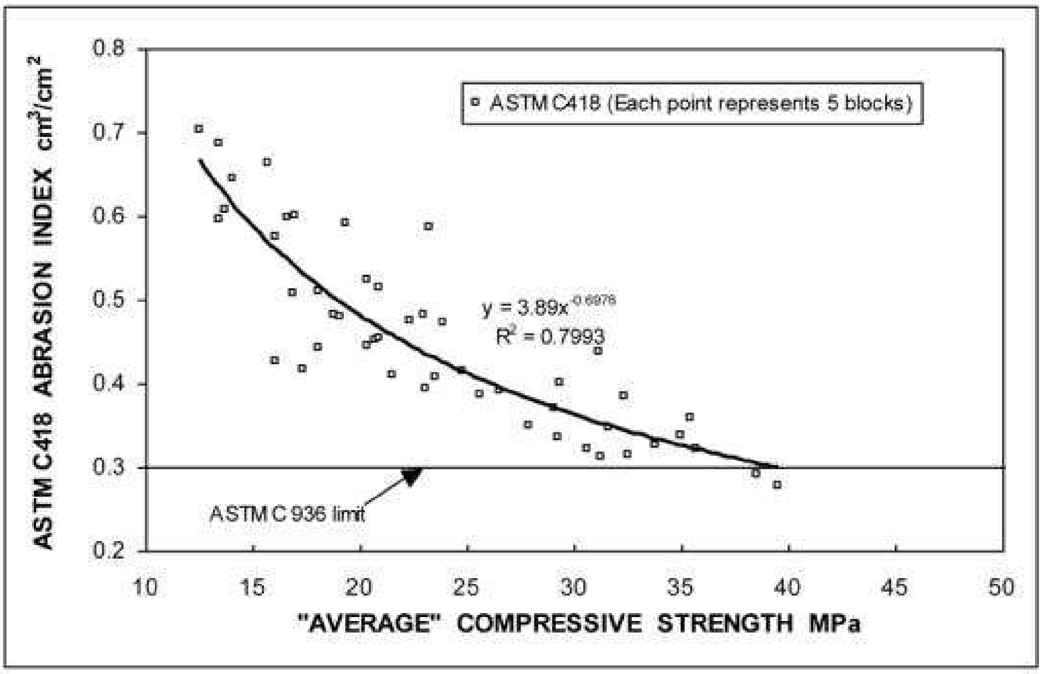

Figure 2: Relationship between compressive strength and abrasion resistance (Papenfus, 2003).

2.2.5. Surface quality of concrete

As defined earlier, abrasion resistance of concrete is more of a measure of surface quality than the concrete core microstructure. A good quality surface is crucial in improving the abrasion resistance of concrete (Ballim and Basson, 2001). Attention should be given to techniques used for surface finishing. Capillaries and voids near the surface should be collapsed after the bleeding stops. Papenfus (2003) argues that this void reduction increases the strength of the paste, hardness and aggregate bonding capabilities subsequently increasing the abrasion resistance of concrete.

2.2.6. Curing

It is generally known that adequate curing has a significant effect on the properties of concrete including strength and durability in general. Papenfus (2003) reveals that curing affects abrasion resistance far more than compressive strength because it affects the surface more. A poorly cured concrete surface will dry out quickly, prematurely stopping the hydration process. The curing method and time have significant influence on the physical properties of concrete. Adequate curing of concrete promotes the development of a good microstructure of the concrete. Curing therefore enhances durability of concrete by ensuring a good quality cover. Abrasion resistance of concrete is a measure of durability and therefore increases with increasing durability.

Moist curing of concrete at early ages, which is the preferred curing method for floors and spillway steps, plays an important role in enhancing abrasion resistance of concrete (Ballim and Basson, 2001). Curing enhances the paste strength and hardness. If the surface is not adequately cured it will dry out quickly, so will the surface that has to withstand the abrasion action.

2.2.7. Surface treatment

Abrasion resistance of concrete can be enhanced by application of surface treatments on the concrete. The various surface treatments that are used to increase abrasion resistance of concrete include dry shakes, fresh on fresh toppings, concrete overlays, coatings, polymer impregnation, liquid applied surface treatments and grinding (Papenfus, 2003). All these applications are discussed below.

2.2.7.1. Dry Shakes

Dry shakes have been used world-wide to enhance the surface of the concrete, with typical mixes consisting two parts fine aggregates and one part cement, applied on the surface of a freshly placed concrete either by hand or by automatic telescope. They work by absorbing the free bleed water on the surface of the concrete, therefore lowering the water cement ratio of the concrete mix near the surface subsequently improving the quality of the concrete surface. The timing of application of the dry shakes is very important in order to avoid delamination. After application, the surface is power trowelled or power floated to achieve a wearing surface of 2 mm to 4 mm thickness. The characteristics of the aggregates (as discussed earlier) used for dry shakes are very important for performance of the concrete surface finishing (Papenfus, 2003). The timing of the application is very important to achieve the desired results, it must be done while there is still some bleeding water on the surface of the concrete to get the shakes moisturised, but the bleeding water shouldn't be too much in order to avoid crazing cracks. On the contrary, too little water will compromise the bonding of the dry shakes leading to delamination (Papenfus, 2003).

2.2.7.2. Fresh on fresh toppings

Fresh on fresh toppings are cast monolithically with the base slab after a few hours delay (Papenfus, 2003). They usually have a higher cement content compared to the dry shakes and the thickness of the toppings can be up to 40 mm. These factors make these toppings to perform better than dry shakes in abrasion resistance, provided the topping has sufficient bond strength to the substrate concrete they are meant to protect.

2.2.7.3. Concrete Overlays

Concrete overlays have been used to resurface existing concrete or exposed surfaces of concrete and are mostly used in repairing concrete floors and pavements. With this method, attention needs to be paid to the bond strength between the concrete substrate and the overlay. This bond can be enhanced by surface preparation methods which includes roughening up and cleaning the receiving surface before the overlay is applied. Curing of the overlays is also important and the curing method is dependent on the type of material used.

2.2.7.4. Coatings

Surface coatings have been used world-wide to protect the surface of the concrete or concrete overlay and therefore improving its abrasion resistance as they are formulated to have a high abrasion resistance. Generally the coatings are made from epoxies, epoxy urethanes, polyurethanes, polyureas and acrylics.

2.2.8. Type of concrete

Different types of concrete have different characteristic properties depending on the type of binder, aggregates and admixtures used in the mix. There also exist different cement extenders, with different physical properties, that make up the binder, among these are silica fume, fly ash, slag and limestone. The binder type affects the microstructure of the concrete subsequently affecting properties of concrete including strength and the abrasion resistance.

2.2.8.1. Effects of Silica Fume

Silica fume particles are so fine that they are able to fill the voids between other binder particles and even penetrate the voids within floccs of these particles (Papenfus, 2003). Silica fume is good in filling the micro voids in the concrete matrix therefore improving the interface-transional zone between the aggregates and the paste. In the process it reduces the porosity of concrete subsequently increasing strength and abrasion resistance.

In their studies, Liu et al (2006) prepared concretes with 5% and 10% replacement of cement with silica fume and tested them for abrasion resistance. They concluded that silica fume decreases the abrasion rate of the concrete due to denser concrete and good interfacial bond between paste and aggregates. This was also confirmed by Cavdar (2009) in his studies where he concluded that "the increase of clinker, limestone and silica fume ratios increased the abrasion resistance when it was measured a year after casting of concrete".

2.2.8.2. Effects of GGBS

Slagment refines the pore structure of the concrete and makes concrete with reduced permeability, higher resistance to chemical attack. It has a potential to slightly improve workability and slows down development of strength but increases later age strength compared to plain Portland cement concrete. This makes it a desirable extender to improve strength and abrasion resistance of concrete. As it was discussed in Section 2.2.2, GGBS has the fine-filler effect which improves the microstructure of the concrete with subsequent improvement in other hardened properties of concrete such as strength and abrasion resistance.

Various authors confirm that replacement of cement with slag has a positive effect on abrasion resistance. Wu et al (2009) studied abrasion erosion resistance of concrete containing blast-furnace slag. They observed that the total abrasion volume of concrete decreased with increasing slag content but up to 45% content, and beyond 45% slag content the abrasion resistance was lower. Figure 3 shows the graphs of slag content in relation to total abrasion volume of concrete.

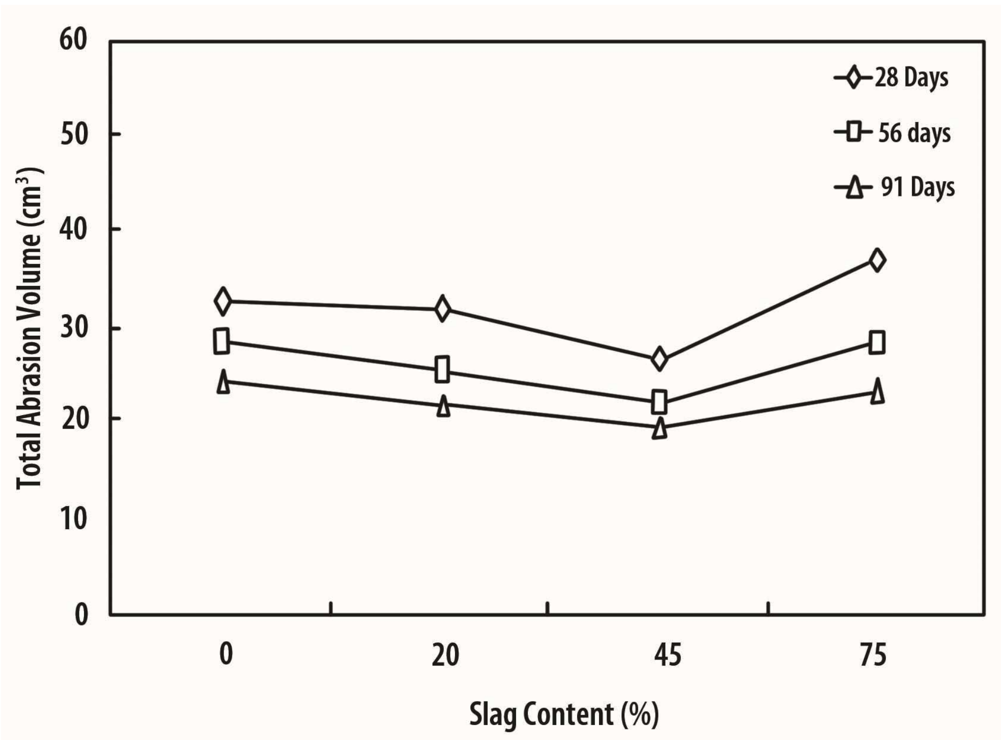

Figure 3: Effects of slag content on abrasion resistance of concrete (Wu et al, 2009).

2.2.8.3. Effects of Fly Ash

The rounded particle shape of fly ash results in improved concrete workability, reduced water content, more cohesion in the mix, better impermeability, improved long term strength development and higher resistance to chemical attack. All these factors have a beneficial effect on abrasion resistance of concrete. Because of its improved workability fly ash makes it possible to increase the stone content of the concrete mix, which also has a positive effect on abrasion resistance. Fly ash reacts with calcium hydroxide to form calcium silicate hydrate, thus converting a weak crystalline phase to a strong gel phase, this improves the microstructure of the concrete therefore enhancing abrasion resistance and other properties of concrete like strength and impermeability (Perrie, 2009).

Papenfus (1995) found that abrasion resistance of mixes incorporating 14%, 21% and 28% of fly ash was significantly more than the mixes of 50/50% blend of Portland cement and GGBS over long term basis (6 years after concrete placement). It was also noted that there was a significant improvement in abrasion resistance with finer gradings of fly ash and increasing replacement percentage with fly ash. However, this was tested with only up to 28% replacement of fly ash and it is not clear what happens beyond 30% replacements.

Various authors agree that replacement of Portland cement with fly ash improves the abrasion resistance of concrete but at levels beyond 50% replacement with fly ash, the abrasion resistance of concrete is compromised. This might be due to the reaction of fly ash with the available calcium hydroxide from the Portland cement to produce hardened concrete properties. At levels beyond 50% replacement, the fly ash must have consumed all the available calcium hydroxide and cannot make the reaction products anymore; therefore there is no more improvement beyond 50% replacement.

Papenfus (2003) concluded that the 28-day abrasion resistance of 28% fly ash replacement was very similar to the results of 100% OPC mix, and with replacements of up to 50% fly ash the abrasion resistance was relatively lower. All the fly ash mixes, up to 50% replacement, when measured after 90 or 365 days, showed improved results compared to OPC mix. Fly ash mixes therefore improve with age and since concrete abrasion is a slow process, it suits fly ash, given its superior long term strength development.

Atis (2002) investigated abrasion resistance of high volume fly ash concrete with replacements of 50% and 70%. His investigation results showed that, for high strength grades (>40 MPa), the abrasion resistance of high volume fly ash concrete (with 70% replacement with cement) was found to be higher than that of counterpart control (normal Portland cement concrete) and that of concrete made with 50% fly ash. This is the only study which has shown good abrasion resistance of concrete beyond 50% replacement with fly ash compared to conventional concrete.

Siddique and Khatib (2009) did a different approach where instead of cement replacement they replaced sand (fine aggregate) with different percentages of fly ash ranging from 35% to 55% and examined different properties of concrete including abrasion resistance. They found that the abrasion resistance of concrete was enhanced as the depth of wear decreased with increasing fly ash content. Even though the amount of Portland cement was not changed, and the total cementitious content was increased in the mix, but a very important trend of increase in abrasion resistance with increasing fly ash was identified.

2.3. Types of abrasion

There are various types of concrete abrasion that exist depending on the kind of loading the concrete is subjected to. These include ice abrasion, abrasion caused by cavitation, wear of hydraulic structures (waterborne abrasives), and wear on concrete floors and pavements.

Wear on concrete floors varies with the mechanism of loading action, being it rubbing action, hard impact or friction by traffic wheels. Moving objects on concrete floors cause one of the above mentioned abrasion actions.

The friction caused by traffic wheels on concrete roads and landing airplanes on airport aprons cuts off the surface of the concrete, abrading it in the longer run due to weak resistance from the concrete. The abrasion on roads can also be caused by floods and the abrasion action is similar to that of the hydraulic structures in this case.

2.3.1. Wear of hydraulic structures

Hydraulic structures and other water retaining structures such as dam spillways, weirs, stilling basins, bridge supports etc. experience wear from the passing of abrasive substances like rocks, sand, debris and other grinding substances which cause erosion of the concrete surface. Alexander (1983) emphasised that these structures can be used even after the surface layer has been removed, and thus the abrasion resistance of the sub-surface concrete is also important. He also revealed that the sandblasting test method, being able to simulate the same action of cutting away the weaker paste and exposing the aggregates, is a suitable test for hydraulic structures.

Another mechanism with this type of wearing is from the high velocities of flood water passed on the concrete surface of different elements; refer to Figure 4 for a spillway example. As the flood water is passing over the concrete surface with high velocities and negative pressures present, cavitation takes place mostly on the corners of the concrete elements. When cavitation bubbles explode near a concrete surface, the surface faces an extremely high pressure for a very short period of time on a very small area, and this kind of high energy impact is able to damage the concrete (Hasan, 2015).

Kryzanowski (2012) reveals that “waterborne particles act against the surface due to their characteristic movement: rotation, translational motions or a combination of these. Then the abrasive action of waterborne particles causes the development of fine cracks on the surface and within the concrete structure. These cracks develop due to the exceeded limited tensile stresses in concrete. Tensile and compressive forces accelerate the development of cracks, weaken the structure (material fatigue strength) and destroy the internal bonds in the structure, while the water flow starts to wash away the particles of cement binder and aggregates".

Figure 4: Flood water passing over the stepped spillway of De Hoop Dam.

Figure 5 shows a three stage process of abrasion action of a particle. The first stage reveals abrasion action due to the water molecules and is mainly influenced by the flow velocity and associated water pressures, (Liue et al, 2006). The abrasion in the second stage is caused by the impact of the solid particles on the surface of the concrete and this is influenced by the size and hardness of the particle. Then the last abrasion mechanism is due to the combination of the above actions and the weakening of interfacial bonds in the concrete.

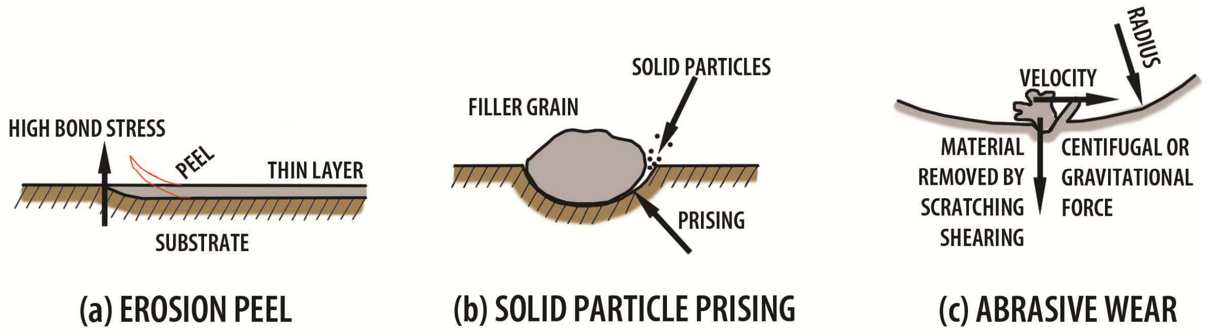

Figure 5: Abrasive action of water-borne particle on concrete surface (Liu et al., 2006).

Many examples exist of apron floors and/or splitters being abraded and damaged during a flood event. Figure 6 shows a damaged splitter at Driel Barrage Dam in the Drankensberg Mountains between KwaZulu-Natal and Free State due to abrasion of the concrete surface. The cavitation on the concrete exposed the reinforcement to water and in the long run it resulted in corrosion of the reinforcement bars and subsequently accelerating concrete deterioration.

Figure 6: Abrasion damaged on apron energy dissipating splitter at Driel Barrage Dam (DWS, 2015).

The stilling basin of Kouga Dam spillway near Port Elizabeth also experienced severe damage caused by high velocities of flood water passing over the spillway to the stilling basing. The combined waterborne abrasives and high flood velocities resulted in loss of fines to the concrete surface and left the concrete aggregates exposed, see Figure 7. This is where the sub-surface abrasion resistance is of importance because there is no planned repairing of concrete surface for these structures. It is also in such cases that the hardness and abrasion resistance of the aggregates is of importance because most of the left surface shows exposed aggregates and they must be able to protect the remaining paste.

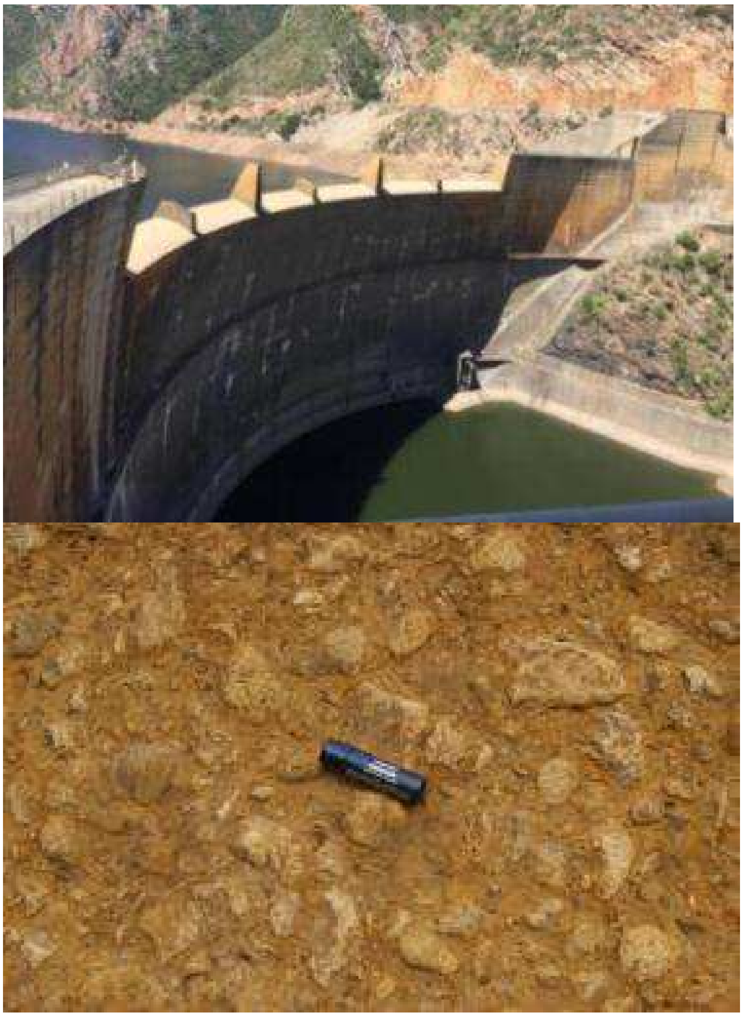

Figure 7: Loss of fines at the stilling basin of Kouga Dam Spillway (DWS, 2016).

The extremely large fluctuating loads acting on the floor blocks of Pit 6 Dam in the lateral direction were found to be the primary cause of the block failures as seen in Figure 8. This shows that one cannot ignore the force of water exerted on the concrete surface, its impact and ability to wear away the concrete surface and exposing the reinforcement bars.

Galvao et al (2012) published a study on abrasive effects observed in concrete hydraulic surfaces of dams. Figure 9 shows photos of visual inspection of the dam in south eastern Brazil. They noted in the inspections, that the state of degradation of the dam due to abrasion processes required additional repairs to the concrete hydraulic structure.

Figure 8: Pit 6 Dam located on the Pit River in northern California also experienced damage to floor blocks due to cavitations and fluctuation forces from the spillway (DWS, 2016).

Figure 9: Spillway dam in south eastern Brazil presented deterioration by abrasion, note the defects in the concrete structure caused by abrasive process (Galvao, 2012).

2.4. Test methods for abrasion resistance of concrete

There are various test methods available to measure the abrasion resistance of concrete. Some of these test methods are mentioned in the next chapter and their detailed descriptions can be obtained from ASTM standards.

2.4.1. Assessment of abrasion resistance of concrete using a wire brush

The wire-brush method was developed locally by the National Building Research Institute of the Council for Scientific and Industrial Research and does not form part of the ASTM test standards. The method measures the average depth to which a standard wire brush, under standard conditions, abrades the concrete surface (C&CI, 2001). The direction of the rotation of the brush must be reversible and it must be possible to lower the brush to a level below the base of the apparatus when conducting in-situ testing (see Figure 10). The method is preferred to be used where it is likely that wear will occur through abrasion of the relatively weaker cementing matrix. The test can be conducted in a laboratory or in the field where there is connection to electricity.

To carry out the test, the machine is positioned over the concrete specimen or test site, with all the brush wires in contact with the concrete surface, it then rotates the standard wire brush at 400 rpm under a normal force of 145 ± 5 N for 4 minutes, reversing the rotation direction every 30 seconds. Throughout the test the water must be kept flowing down the hollow drive shaft and through the brush to ensure cooling of the brush and removing some of the abraded material.

The wear is measured by taking between 20 to 40 depth gauge readings over the entire test area to establish the average depth of wear. Alternatively, the volume of the abraded material can be measured using modelling clay by filling the abraded portion and measuring the mass of the clay before and after filling the cavities, the difference will give the amount of clay used. In this investigation, this was simplified by measuring the mass of the specimen before and after the test to get mass loss due to abrasion.

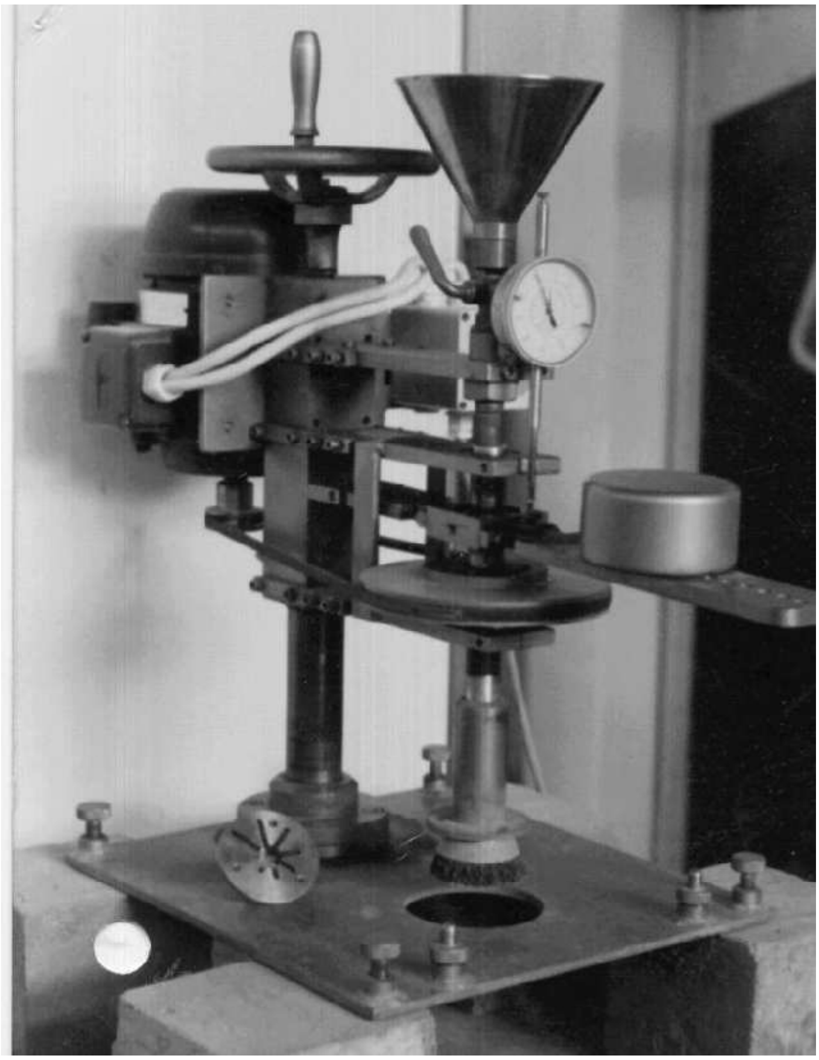

Figure 10: Wire brush test apparatus developed by the National Building Research Institute of the CSIR (Papenfus, 2003).

2.4.2. Standard test method for abrasion resistance of concrete by sandblasting: ASTM C418

This test method constitutes sandblasting a concrete surface area with silica sand graded to pass a 0, 850 mm sieve and be retained on a 0, 600 mm sieve. The significance and use of the test method covers the laboratory evaluation of the relative resistance of concrete surfaces to abrasion (ASTM C 418). The action of abrasives under traffic and water-transported abrasives on concrete surfaces is stimulated by this test method. This test method therefore is relevant to this research because it simulates the same action of waterborne abrasives.

The test apparatus consists of a measuring scale with a minimum capacity of 5 kg, an injector-type gun with a high velocity air jet, pressure control device equipped compressed air, a shield, an abrasive sand as described above and an oil base modeling clay, see Figure 11 (ASTM C 418).

The test procedure involves placing the test specimen with the surface to be tested perpendicular to the nozzle axis and at a distance of 75 ± 2, 5 mm from the end. The specimen is then clamped, with its shield attached firmly in place. The concrete surface is subjected to the blast for a period of 1 minute. This process is repeated 8 times on different spots on the exposed surface. The abraded volume is determined by measuring the mass difference of clay supply after filling the abrasion cavities. Again this was simplified by measuring the mass of the specimen before and after the test to get mass loss due to abrasion.

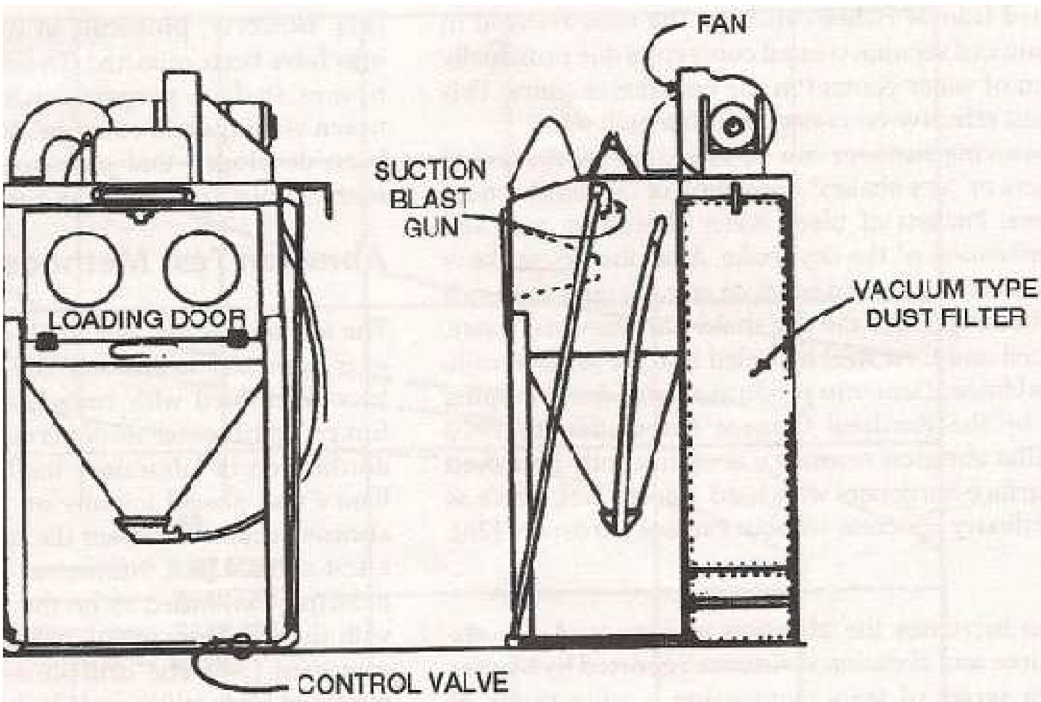

Figure 11: Sand blast cabinet (ASTM, 2005).

2.4.3. Standard test method for abrasion resistance of horizontal concrete surfaces: ASTM C779

There are three procedures covered by this method for determining the relative abrasion resistance of horizontal concrete surfaces, and the difference lies on the type and extent of the abrasive force imparted by each (ASTM C 779). All these test procedures are used to determine variations in surface properties of concrete and therefore do not give quantitative indication of the durability of a specific concrete surface. The significance and use of these tests therefore is limited to evaluating the effects of abrasion resistance of concrete. The effects of concrete materials, curing methods, surface treatment and surface finishing can be evaluated with these procedures. All three procedures use portable equipment, which is suitable for either laboratory or field testing. The three procedures are the revolving disk machine, the dressing wheel machine and the ball bearing machine and are briefly discussed below.

Kryzanowski (2012) revealed that the disadvantage of all these procedures is that they do not simulate the actual conditions of abrasion in hydraulic structures, thus representing a limitation to their application.

The revolving disk method

This test procedure slides and scuffs the steel disks in conjunction with abrasive grit to introduce frictional forces on the concrete specimen. This procedure simulates light to moderate foot traffic and light to medium tyre wheeled traffic (Scott and Afiuddin, 2015). Figure 12 shows the test equipment for this method.

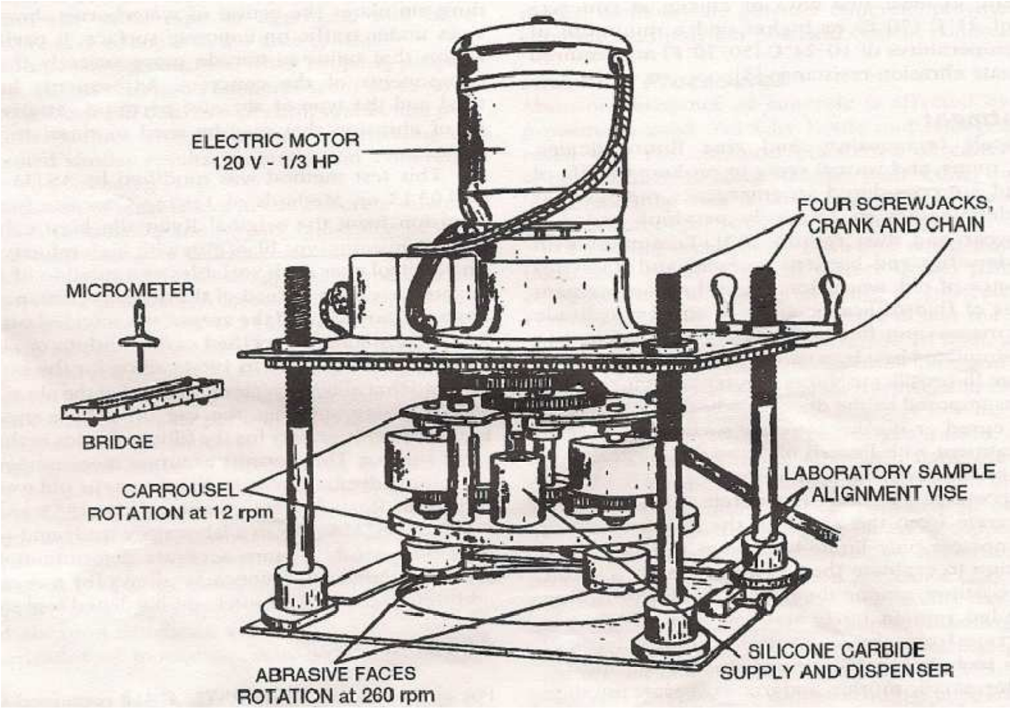

Figure 12: Revolving disks abrasion test machine (ASTM, 2005).

The dressing wheel method

This procedure uses impact and sliding friction of steel dressing wheel as shown in Figure 13, to abrade the horizontal surface of the test specimen. It imposes high compressive impact loads to simulate the rolling, pounding and cutting action of steel wheels or the effect of studded tyres (Scott and Afiuddin, 2015).

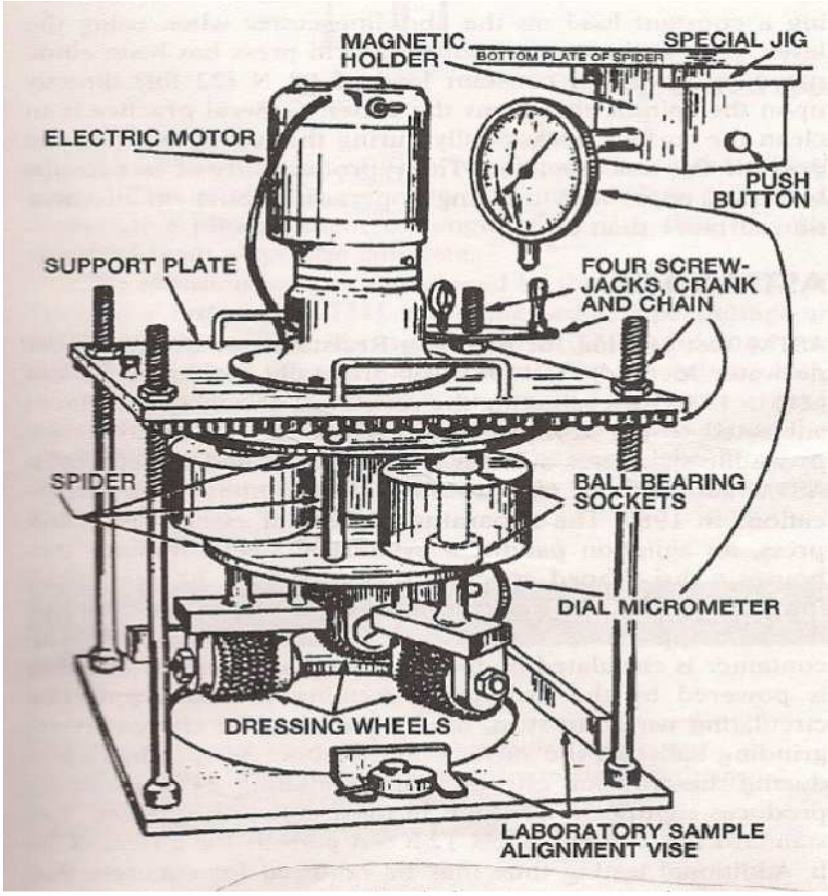

Figure 13: Dressing wheel abrasion test machine (ASTM, 2005).

The ball-bearing method

This procedure uses high contact stresses, impact and sliding friction from steel balls to wear the horizontal and wet concrete surface. This procedure simulates repeated dynamic loading through strong impacts, similar to that of rolling wheels (Scott and Afiuddin, 2015). Figure 14 shows the test equipment for this method.

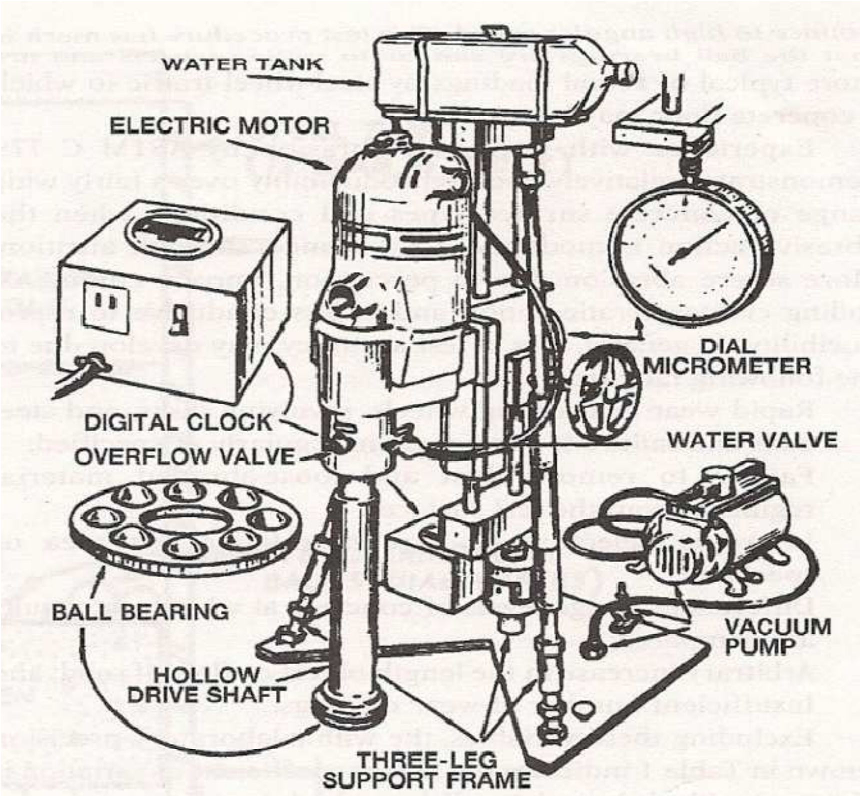

Figure 14: Ball bearing abrasion test machine (ASTM, 2005).

2.4.4. Standard test method for abrasion resistance of concrete or mortar surfaces by the rotating-cutter method: ASTM C 944

This test method is similar to the procedure using a dressing wheel (ASTM C 779) as discussed earlier on. The test gives an indication of the relative abrasion resistance of concrete or mortar based on cores or fabricated specimens. This method is best used for quality control of concrete and was primarily intended to be used on the top ends of concrete specimens with insufficient test area which cannot be tested with the previous discussed methods. The equipment for this test method is shown in Figure 15.

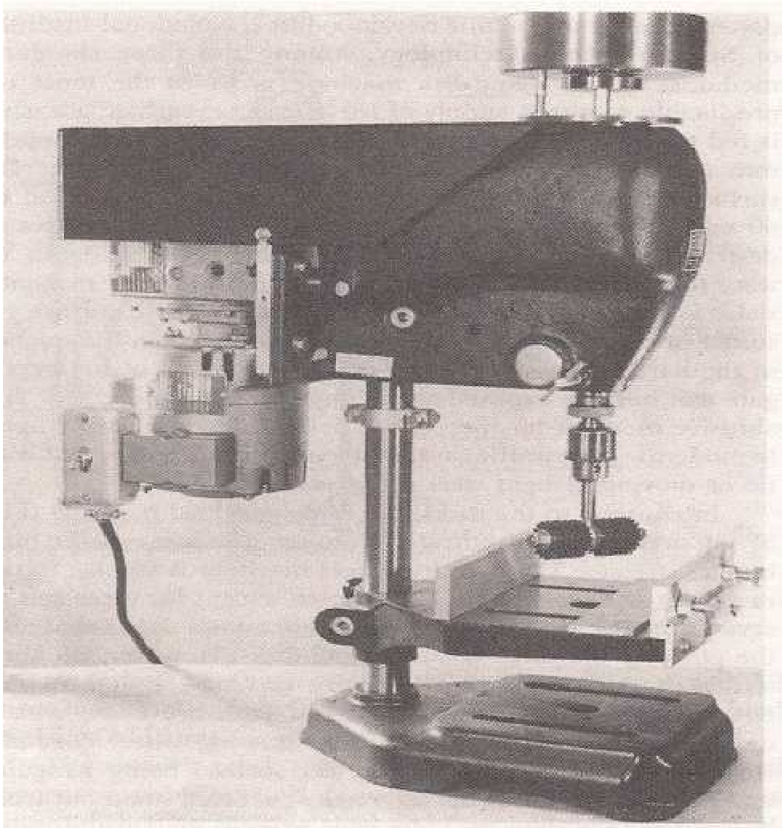

Figure 15: Rotating-cutter drill press (ASTM, 2005).

2.4.5. Standard test method for abrasion resistance of concrete (underwater method): ASTM C1138

This test method was developed to provide a relative evaluation of the abrasion resistance of hydraulic concrete structures such as dam spillways, stilling basins and weirs, which are subject to the waterborne abrasion. This method does not give indication of the expected service life of a specific concrete but it is useful in the selection of materials, mixtures and construction methods when waterborne action is expected. The nature of this method makes it very related to this research because the cause of the abrasion is the same and the purpose of the investigation is to compare different types of concrete (ASTM, 2005), however it was not used due to un-availability. Figure 16 shows the schematics of the underwater method.

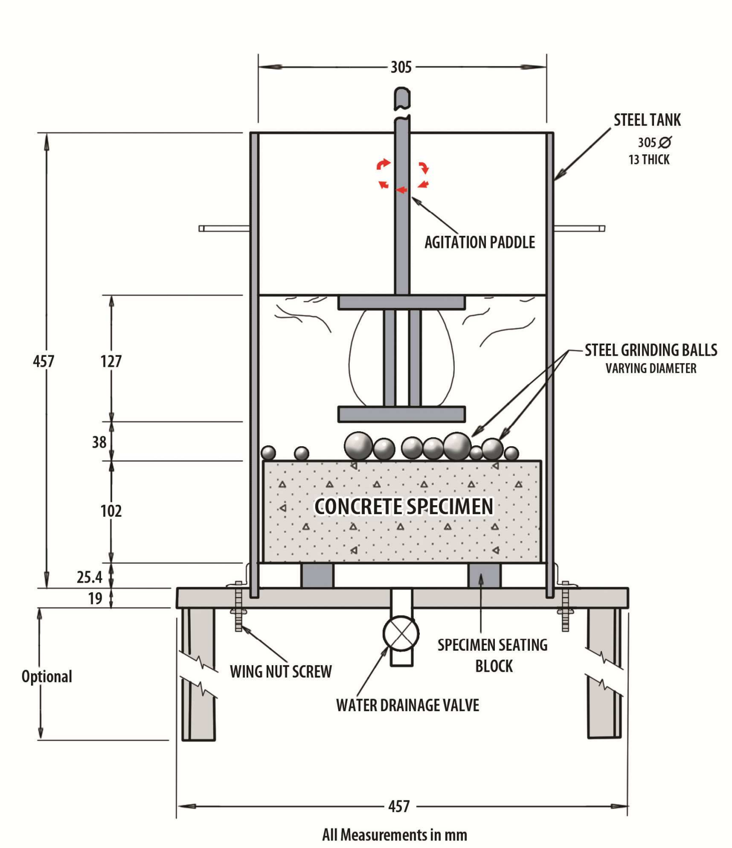

Figure 16: Test apparatus for underwater method (ASTM, 2005).

2.4.6. Rebound (Schmidt) hammer test

The rebound hammer test has been used in the industry to test the concrete surface hardness, as shown in Figure 17, and has been standardized in many countries. The test schematics use the rebound distance travelled by an inside elastic mass after an impact on the concrete surface and this rebound depends on the surface hardness against which the mass strikes. The rebound number is then correlated to the concrete surface hardness and therefore representing an indication of concrete strength and the test is only valid near the surface of the concrete.

Alexander (1983) reveals that the rebound hammer test has been found useful to give results for concrete surfaces which correlate reasonably well with wear resistance (Alexander, 1983). He recommended that this test might prove very useful in the future for evaluating abrasion properties of concrete, provided that sufficient correlation data can be collected and evaluated. Various authors have also done a similar research on this topic but there were no concrete conclusions made.

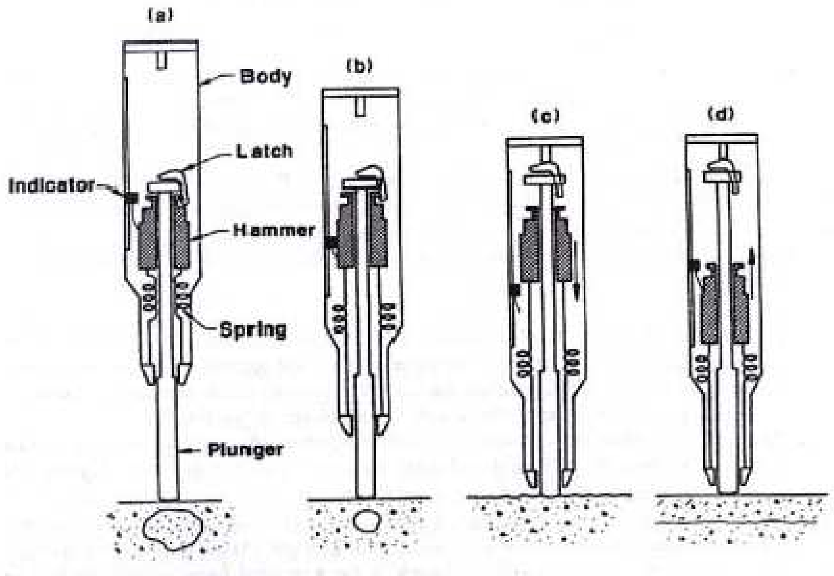

Figure 17: Schematics of the Schmidt rebound hammer test (Moyo, 2014).

2.5. Application of the different test methods

Scott and Afiuddin (2015) did a case study on abrasion resistance of concrete and they summarised which tests should be used to determine the abrasion resistance of concrete in different abrading conditions as shown in Table 1.

Table 1: Application of tests for abrasion resistance of concrete (Scott and Afiuddin, 2015).

	ASTM C418	ASTM C779			ASTM C944	ASTM C1138
		Method A	Method B	Method C		
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

2.6. Roller compacted concrete

Roller Compacted Concrete (RCC) is a mixture of fine and coarse size aggregates (up to 53 mm), Portland cement, pozzolan (fly ash) or slag which can be up to 70% of total cementitious material, and admixtures that are blended with water to a damp consistency that permits hauling and spreading with earth moving equipment and compaction with a vibratory roller (DWS, 2016). The difference between RCC and conventional concrete is that RCC has a high stone content, low cement content and low water content, making it a lesser cost option in comparison to conventional concrete. Mix proportions of these two mixes are given in Table 6 in Chapter 3, where mix A is of a conventional mix and mix B is RCC mix.

2.6.1. Properties of RCC

Roller Compacted Concrete exhibits, when set, the typical properties of conventional mass concrete, it only differs in the fresh state. RCC is a zero slump concrete due to lower water and cement contents and a higher aggregate content. Because of high pozzolan (fly ash) or slag content in the concrete mix, it has good impermeability microstructure, and strength development is gained over a long period of time (3 months and more) than the usually specified strength of conventional concrete at 28 days. Lastly, the issue of heat of hydration associated with mass concrete is also reduced by the high percentage of pozzolan or slag in the mix.

2.6.2. Immersion Vibrated RCC

IV-RCC is RCC with a consistency which also allows compaction by immersion vibrator also referred to as poker vibrator. No grout is added to enrich the mix, it is the type of RCC with a high paste for which the total cementitious material is approximately 200 kg/m^3, at De Hoop Dam the total cementitious content used was 210 kg/m^3.

2.6.3. Placement of the IV-RCC

Figure 18 shows the process of placing IV-RCC on the dam wall. As the picture is read from left to right, the IV-RCC is mixed at the batching plant and loaded to the tipper trucks. The trucks then take the concrete to the field where it is placed. A small track loader then spreads the batch to make it easier for the roller to compact the concrete.

However, to prevent displacement of the shutters the roller does not go close to the edges and a poker vibrator is used to compact the concrete at that area hence the name IV-RCC.

Figure 18: Placement of IV-RCC on the dam wall, note the use of poker vibrator near the formwork.

2.7. De Hoop Dam Abrasion results during construction

During the construction of De Hoop Dam in 2012, Soillab was sub-contracted to do abrasion testing on the dam wall (constructed the same way as spillway steps) to determine the abrasion on the concrete placed. The test method used was ASTM C 418: sandblasting method as described earlier in Section 2.4. The average values obtained from different positions on the dam wall are shown in Table 2. The average abrasion coefficients obtained from the dam wall steps and overflow base were 0, 0337 cm^3/cm^2 and 0, 0176 cm^3/cm^2 respectively. Both these values indicate average wear depth far less than 1 mm, which shows low values of abrasion depth compared to other values seen in the literature (Papenfus et al).

These results are included in this Chapter because they are the base against which the results from this investigation will be compared.

Table 2: Abrasion results of De Hoop Dam.

Test Point	Average amount of clay used to fill up abraded area (g) (SG of clay=1,879, test area=25 cm^2)	Volume (cm^3)	Abrasion Coefficient (cm^3/cm^2)
Dam Wall Step 1	15	0,7825	0,0313
Dam Wall Step 2	17	0,8914	0,0357
Dam Wall Step 3	16	0,8515	0,0341
Overflow Base 1	9	0,4590	0,0184
Overflow Base 2	8	0,4191	0,0168
Overflow Base 3	8	0,4391	0,0176

2.8. Acceptable abrasion values

The laboratory methods manual by C&CI (2001) provides a table (as shown below) of acceptance criteria for concrete surfaces subjected to severe conditions and this table is specific to the wire brush method. From Table 3, it is noted that beyond penetration depth of 2 mm the concrete surface is classified as poor, in terms of abrasion resistance, when assessed by the wire brush method.

Table 3: Assessment criteria for concrete surfaces subjected to severe conditions (C&CI, 2001).

Surface quality classification	Average penetration depth (mm)	
	General concrete	Concrete pavers
Excellent	<0,5	<0,5
Good	0,5 to 1,5	0,5 to 1,0
Fair	1,5 to 2,0	1,0 to 1,5
Poor	>2,0	>1,5

The ASTM C936: Standard Specification for Solid Concrete Interlocking Paving Units sets a limit of 0, 3 cm^3/cm^2 or average depth of 3 mm for concrete with adequate abrasion resistance. This limit was seen as too severe by Papenfus (2003) for local conditions, because out of the 48 mixes he had investigated, only two were below this limit and the rest ranged between 3 mm and 7 mm of average depth, refer to Figure 2 in Section 2.2.4 for his results.

From these reported values of abrasion depth and the values seen in the literature and those obtained from De Hoop Dam testing, it is not clear what limiting values can be used for conventional concrete or roller concrete.

2.9. Summary and gaps in the literature

Abrasion resistance of concrete plays an important role in the durability of hydraulic concrete structures. Aggregate/paste bond, hardness of concrete, curing method and surface finishes are the main factors influencing the abrasion resistance of concrete. Abrasion resistance of concrete can be improved by:

- Ensuring good quality surface of concrete.
- Curing of concrete at an early stage.
- Use of hard, absorbent, angular and sound aggregates.
- Use of surface protecting agents.
- Any improvement in the microstructure of the concrete.
- Selecting a suitable binder type.

It is agreed that abrasion wear is a slow process and needs to be assessed over a long term rather than the general assessment at 28 days. This gives opportunity for slowly reacting cements like fly ash to develop their properties and therefore indicate the long term properties when assessment is done. The industry research has established a correlation between compressive strength and abrasion resistance. Good quality high compressive strength concrete is expected to have high resistance to abrasion, and this decreases with decreasing strength. However, low compressive strength concrete can also achieve high resistance to abrasion by use of suitable aggregates and cement extenders and ensuring good surface finishing.

There are various test methods used in the construction industry to measure abrasion resistance of concrete. Most of these tests are from American standards and have been used by various authors and are applicable to different abrasive actions. Locally, a wire brush method was developed and has been used by various authors to evaluate abrasion values of concrete. There is a limit of 3 mm average wear depth specified by ASTM C936 for solid concrete interlocking paving units, meanwhile the wire brush method sets a limit of 2 mm. Values of concrete wear depth obtained from the literature range up to 7 mm which exceed both limits set above. This calls for further investigation or the agreement by relevant researchers on the limits of wearing depth of a concrete with adequate abrasion resistance.

DWS has never conducted abrasion tests of the spillway steps before the construction of De Hoop Dam, therefore there are no historical results available in the department, other than visual inspections. There is lack of local (South African) information on abrasion resistance values for roller compacted concrete. This research will add to the literature on abrasion values of roller compacted concrete which can be used to compare with values of conventional concrete. This information is important to the Department of Water and Sanitation which looks after the water resources structures, which are subjected to severe waterborne abrasion action.

The fact that DWS uses up to 70% of fly ash and most of the literature has researched up to 30% fly ash replacement leaves gaps as to what happens between 30% and 70% replacements, although there are few authors arguing that there is no improvement beyond 50% replacement. This research will again add to the literature, considering the abrasion values of concrete with up to 70% fly ash and GGBS replacements.

A perception exists that low compressive strength concrete will result in low resistance to abrasion. However, this is not always the case as low compressive strength concrete can still achieve high resistance to abrasion.

3. Research Methodology

3.1. Introduction

The laboratory work included testing of cubes made under controlled conditions using 8 different types of concrete mixes and tested at various ages with the same curing conditions(saturated under water until time of testing). Two different types of tests (sandblasting and wire brush method) were conducted to compare test results and to determine if the wire brush method can be used for assessing hydraulic structures. The specimens made in the laboratory were tested at different ages of 28, 56 and 90 days. The 90 days results are the most relevant to this research due to the strength specified at 90 days for IV-RCC concrete, and the fact that abrasion resistance is a long term property of concrete. During the 28 and 56 days period, testing was conducted for investigating time development of abrasion resistance.

This research made use of low compressive strength concrete (20 MPa at 90 days) with a total cementitious material of 215 kg/m^3, of which up to 70% was an extender. The results of abrasion values of this concrete were compared to those of a reference concrete mix of 20 MPa strength at 28 days (and at least 40 MPa at 90 days) and a comparison was made with other results from literature.

The other testing was done on the spillway steps of De Hoop Dam by drilling cores and then testing them in the laboratory. The results of the cubes produced in the laboratory and those obtained from the as-built structure were compared to establish if there was any correlation between the two. At the end a conclusion was made on whether laboratory produced cubes can be used to measure abrasion resistance of the as-built structure.

3.2. Materials

3.2.1. Aggregates

The major aggregates used in this research were extracted from De Hoop Dam construction materials. These aggregates were transported from De Hoop Dam and delivered to UCT Civil Engineering Laboratory by DWS. The other aggregates were the greywacke and dune sand already available in the University laboratory.

The gabbro aggregates (coarse and fine) from De Hoop Dam are derived from layered intrusive rocks of the Rustenburg Layered Suite, Bushveld Igneous Complex with the founding rock mass that comprises mainly of Gabbro with an average density of 2 900 kg/m³. The fineness modulus of the crusher sand from these aggregates is 2, 4.

Table 4 below gives grading results (size and distribution of the individual particles) of the 38 mm and 19 mm gabbro aggregates. These results indicate aggregates with well distribution of different sizes of individual particles, which is good for production of good concrete with desirable properties like impermeability which in turn enhances strength and abrasion resistance. The shape of these aggregates is sub-rounded to angular (see Figure 19 and Figure 20) which is good for concrete workability.

Table 4: Grading results of the gabbro aggregates.

38 mm stone		**19 mm stone**	
Sieve Size (mm)	% Passing	Sieve Size (mm)	% Passing
53,0	100		
38,0	93,9		
26,5	53,6	26,5	100
19,0	7,8	19,0	98,8
13,2	1,8	13,2	61,6
9,5	0,6	9,5	33,8
6,7	0,2	6,7	13,9
4,75	0,2	4,75	5,1

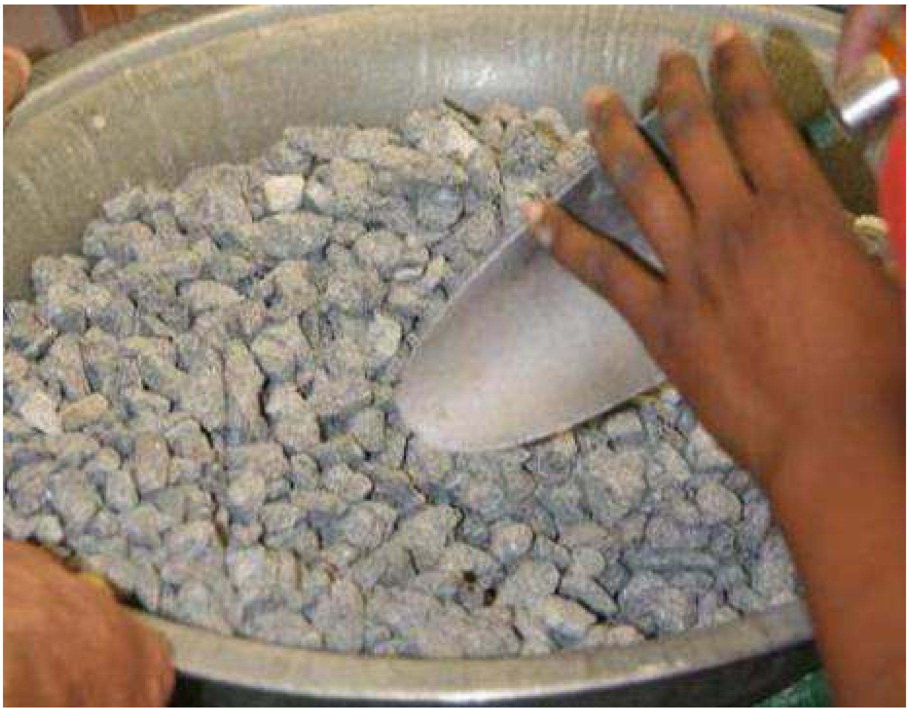

Figure 19: Photograph of the 19 mm gabbro aggregates (DWS, 2014).

Figure 20: Photograph of the 38 mm gabbro aggregates (DWS, 2014).

The greywacke stone is derived from Malmesbury shale with a density of 2 700 kg/m³. The dune sand used with greywacke aggregates has a density of 2 650 kg/m³ and a fineness modulus of 2, 3. Table 5 shows the grading results of the greywacke 19 mm aggregates. The distribution of size indicates poorly graded aggregates with a single size 19 mm and 13, 2 mm. The shape of these aggregates, as seen in Figure 21, is angular to sub-flaky which promotes good bonding abilities which in turn improve abrasion resistance of concrete.

Table 5: Grading results of greywacke 19 mm aggregates.

Sieve Size (mm)	26,5	19,0	13,2	9,5	6,7	4,75
% Passing	100	83,5	10,9	1,3	0	0

Figure 21: Photograph of the 19 mm greywacke aggregates.

3.2.2. Cements

The cement (CEM I 52, 5 and CEM II 42, 5) used in this research complied with SANS 50197-1 and the Portland cement extenders, GGBS and FA complied with SANS 1491-1 and SANS 1491-2 respectively.

3.2.3. Admixtures

The admixtures used in this concrete mix were similar to those that were used in the DWS RCC mix, these are MasterPozzolith 600R and MasterRheobuild 561 from BASF chemical company. These admixtures were chosen so that the concrete mix can resemble the one that was used by DWS for the construction of De Hoop Dam. The MasterPozzolith 600R is a retarder and was only used in one mix, that which represents the exact mix from the construction of De Hoop Dam, mix C in Table 6.

3.2.4. Core samples from site

The sources of materials used in this research were extracted from De Hoop Dam situated in the Steelpoort River, in the Limpopo Province.

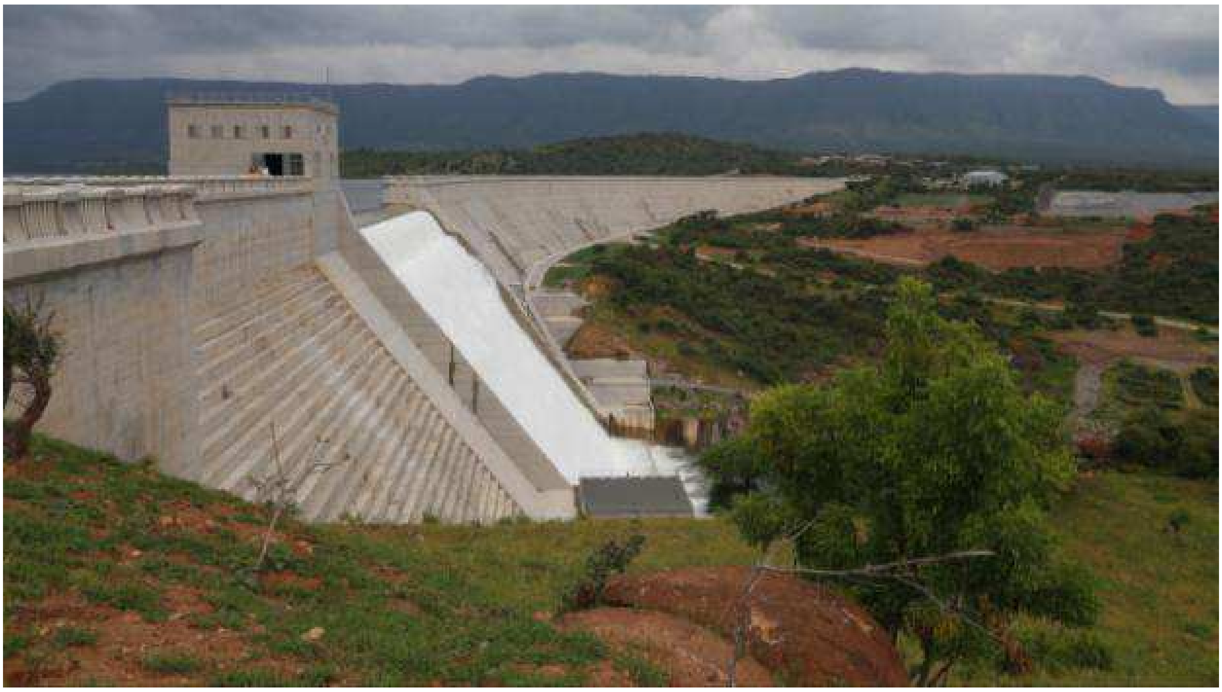

Figure 22: Photograph of De Hoop Dam taken from the right bank, the tested cores were extracted from the left bank steps of the dam wall.

Cores of 110 mm diameter were drilled from different positions of the dam wall at the left bank downstream steps to investigate abrasion resistance, compressive strength and durability index tests. The cores were cured in water for 48 hours prior to conducting any tests, this was done in order to get uniform moisture content from all the cores and to standardise the conditions of the test, as specified in SANS 5863 (2006) for concrete cube testing. Similarly, the wire brush method also specifies specimens to be pre-soaked with water for a minimum period of 24 hours prior to testing. The 48 hour soaking of the cores from site therefore relates to the requirements of SANS 5865 (2006).

The option of doing field tests instead of the laboratory tests was considered but could not be realised due to connection requirements of the sandblast test equipment.

Figure 23: Stepped spillway section of the Dam with some water passing over it, the durability of the steps is of importance especially with regards to abrasion resistance.

Figure 24: Cores drilled from De Hoop Dam NOC Steps and cut to size at the laboratory.

3.3. Concrete mix design

The concrete mix design of the IV-RCC used for the construction of De Hoop Dam was adopted in order to make a good comparison of the as-built results and laboratory results. Since the IV-RCC mix can be compacted using either a roller or a poker vibrator, it was possible to produce laboratory made cubes of the IV-RCC mix in a similar fashion as a conventional concrete.

A further two different mixes were designed, one is a GGBS concrete mix made with De Hoop Dam aggregates and the other one from the greywacke aggregates already available in the UCT civil engineering laboratory. The last concrete mix is a reference mix of a conventional concrete of grade 20/38 made with 55% CEM I and 45% Fly Ash and made from De Hoop Dam materials. This mix was used as a control mix, against which the various IV-RCC mixes were compared in terms of abrasion resistance. A total of 8 different concrete mixes were produced and their mix designs are as summarised in Table 6.

The fine aggregate reported in Table 6 is crusher sand derived from gabbro aggregates except for mix F which used the dune sand from UCT lab.

Table 6: Material proportions for the different mix designs.

Material	**Mix proportions**							
	A	**B**	**C**	**D**	**E**	**F**	**G**	**H**
CEM I (kg)	-	75	65	-	-	65	-	-
CEM II (kg)	160	-	0	65	65	-	65	75
Fly Ash (kg)	130	140	150	150	150	150	-	-
GGBS (kg)	-	-	-	-	-	-	150	140
19-37,5 mm gabbro aggregates (kg)	730	883	883	883	-	-	883	883
4,75 -19 mm gabbro aggregates (kg)	475	483	483	483	1 366	-	483	483
4,75 -19 mm greywacke aggregates	-	-	-	-	-	1366	-	-
Fine aggregates (kg)	938	879	879	879	879	879	879	879
Water (l)	145	122	122	122	122	122	122	122
Rheobuild M561 (BASF) ml	2 350	500	500	500	500	500	500	500
Pozzolith R600 (BASF) ml	-	-	500	-	-	-	-	-
28 day Strength (MPa)	20	15	15	15	15	15	15	15
90 day Strength (MPa)	>40	20	20	20	20	20	20	20
w/c	0,5	0,57	0,57	0,57	0,57	0,57	0,57	0,57

3.4. Production of cubes

150x150x150 mm cubes were made from the 8 different concrete types, for testing of abrasion resistance using two test methods. All the concrete casted had a specified concrete strength of 20 MPa at 90 days, except for the reference mix, mix A, which had a specified strength of 20 MPa and 40 MPa at 28 and 90 days respectively. One batch of cubes, mix C, was a representation of the IV-RCC used for the construction of De Hoop Dam Spillway Steps, the exact concrete mix as outlined in Table 6 was used. The test results from these cubes were compared with the results of field extracted cores from in-situ concrete from De Hoop Dam. The other batch of cubes was of IV-RCC made with GGBS instead of the fly ash extender as with the first case. Here a comparison was made between GGBS and fly ash concretes. One batch of IV-RCC was made from aggregates already available at the UCT laboratory. This was for comparison of aggregates and confirming their influence on abrasion resistance. The rest of the mixes differed by the percentage of the extenders from the above mentioned mixes.

Each mix was confirmed for a zero slump with the exception of the reference mix which has a slump of 75 mm. The Vebe apparatus was not available in the UCT laboratory to check the consistency of the RCC mixes.

The cubes were compacted using a vibrating table, vibration time was not measured but the cubes were vibrated until the air bubbles were out and the top surface was covered with mortar.

All the cubes were cured in water at a temperature of 23 ºC until their time of testing which varied between 28 days, 56 days and 90 days.

3.5. Test methods for abrasion assessment

There were two test methods available at the UCT laboratory for this research, these were:

- Standard test method for abrasion resistance of concrete by sandblasting ASTMC 418-05.
- Assessment of abrasion resistance of concrete using a wire brush.

Both these test methods, although amended were used to investigate abrasion mass loss of all the concrete types used as well as the cores drilled from De Hoop Dam.

3.5.1. Sandblast test method

The sandblasting test method was slightly amended from the ASTM 418 specified method, in order to make the test method suitable for cubes. Instead of blasting the concrete surface at 8 spots, 1 minute each, as outlined in the ASTM, the concrete surface was blasted 6 times, once each on the 6 sides of the cube, and instead of measuring the blasting time, the amount of sand for each surface was measured with a scoop and the surface was blasted until the measured sand was finished. The total time the specimen was subjected to sandblasting was between 8 to 9 minutes for all the sides of the cube, which still complied with the test specifications. Figure 25 shows the schematics of the sandblasting cabinet available at UCT laboratory.

It was considered to only blast 5 sides of the cubes and leave the top one, which has different properties compared to the rest. However the properties of the top side of the cubes are the most important where abrasion resistance is of concern because this side represents the concrete surface that gets exposed to waterborne abrasive actions. The other amendment was the measurement of mass loss due to abrasion action instead of measuring abraded volume. This was done to simplify the test procedure in order to save time and get more accurate results, avoiding human errors associated with procedure for measuring volume.

Three specimens of each mix were tested at ages of 28, 56 and 90 days to investigate time development of abrasion resistance. Figure 26 shows the abraded surface of concrete from the sandblasting action.

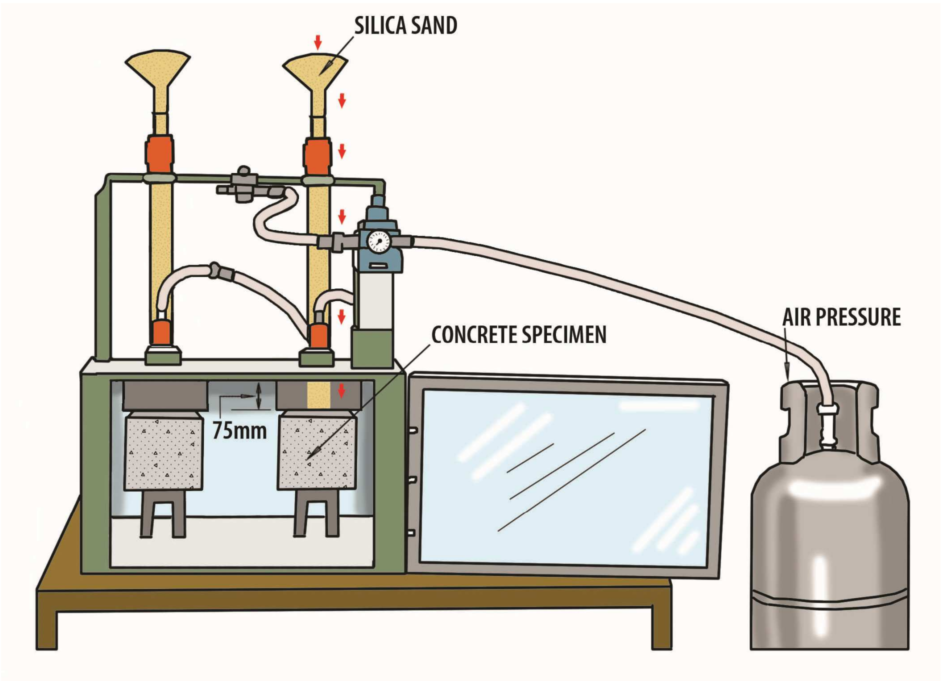

Figure 25: Sandblasting test cabinet available at UCT.

Figure 26: Typical concrete surface after being subjected to sandblasting, the abraded portion has an approximate diameter of 45 mm.

3.5.2. Wire brush test method

The wire brush test method was carried according to the outlined test procedure described in section 2.4. Slightly amendments were made to save time and costs. The first amendment was that, instead of using a new brush for each test, the wire brushes used in the test equipment were used until the wires got weary. Secondly, in order to be able to compare this test results with those of the sandblasting method, the mass loss after abrasion was measured instead of measuring the average depth of wear.

Similarly here, three specimens for each concrete mix were tested at the ages of 28, 56 and 90 days to investigate the development of abrasion resistance with time. The surface of the abraded area after being subjected to the wire brush action is shown in Figure 28.

Figure 27: Photograph of the wire brush test method.

Figure 28: Typical concrete surface after being wire brushed, the diameter of the abraded portion is approximately 80 mm.

3.6. Compressive strength testing

Three specimens (of the size 150 x 150 x 150 mm) from each concrete mix cubes were tested for compressive strength, as per SANS 5863 (2006), at the ages of 28, 56 and 90 days to establish time development of strength and whether the target strengths were achieved. The strength was also investigated to confirm the relationship between compressive strength and abrasion resistance of concrete.

3.7. Durability Index test

Two Durability Index test methods were conducted to evaluate the microstructure of the roller compacted concrete mix design and to assess the overall durability of the mix. These are the oxygen permeability index (OPI) and the water sorptivity test methods. These test methods are linked to transport mechanisms which are relevant to particular deterioration process. The OPI test method measures the decrease of pressure of oxygen passed through a 30 mm thick slice of a 68 to 70 mm diameter core of concrete placed in a falling head permeameter (Ballim et al, 2009). The OPI values of 9 and above indicate concrete with higher impermeability and thus a higher degree of interconnectedness of the pore structure. There is no correlation between OPI and abrasion resistance of concrete but it is expected that concrete with high OPI values will also yield high abrasion resistant concrete compared to concrete with low OPI value.

The OPI tests were conducted for both mixes made with greywacke and gabbro aggregates using mix designs E and F. The rest of the mixes which had 38 mm size stones were not tested since the test specifies a maximum aggregate size of 26, 5 mm in the concrete mix.

The sorptivity test method measures the mass of water absorbed by a concrete specimen immersed in a few millimeters of water. The same specimens used in the OPI were used to assess the sorptivity index values of the concrete.

4. Data Analysis

This chapter shows the results of all the tests carried out in this research, more detailed data can be found in Appendix A attached to this report. In terms of abrasion resistance, evaluation of the results was made from the 90 days data, since abrasion resistance is a long term property. This allowed observations to be made on the effects of cement extenders, which cannot be assessed at early ages due to delayed hydration reactions. However, some mixes were only tested up to 56 days due to these mixes being cast later during the laboratory work (there was not enough time to test them at 90 days). In this case some comparisons were made from 56 days data to accommodate these mixes.

4.1. Sandblasting results

Figure 29 shows the time development of abrasion resistance of all the mixes produced. All the mixes, except mix F (made with greywacke 19 mm aggregates), showed an increase in abrasion resistance with increasing age. This trend was expected since most properties of hardened concrete improve with increasing age. As stated in the literature, abrasion resistance of concrete is a property that develops over a long term and it is not representable to assess it at 28 days, especially if cement extenders are used. These results have proven this theory to be true because there was significant improvement in abrasion resistance from 28 to 90 days of testing.

In addition to Figure 29, Figure 30 shows the 90 days data for which comparison of the abrasion mass loss was made for the different concrete mixes.

- Concrete mixes A, B and H (the reference mix, the mix with 65% FA replacement and the mix with 65% GGBS replacement, respectively) performed relatively equally in terms of abrasion resistance, with the GGBS mix showing a slight superiority compared to the other two. The mean values of abrasion mass loss for these mixes were 23 g, 21 g and 18 g, respectively.
- It is important to note that the total cementitious content of mixes B and H was 75 kg/m³ less than that of the reference mix A, and the stone (coarse aggregates) content of these mixes was 160 kg/m³ more than that of the reference mix A.

- It was observed that there was a slight increase in abrasion resistance of concrete as the extender percentage was increased from 45% to 65%.
- An improvement in abrasion resistance was also observed with increasing stone content in the concrete mix, which was expected as the paste is the part of the matrix most affected by abrasive forces.

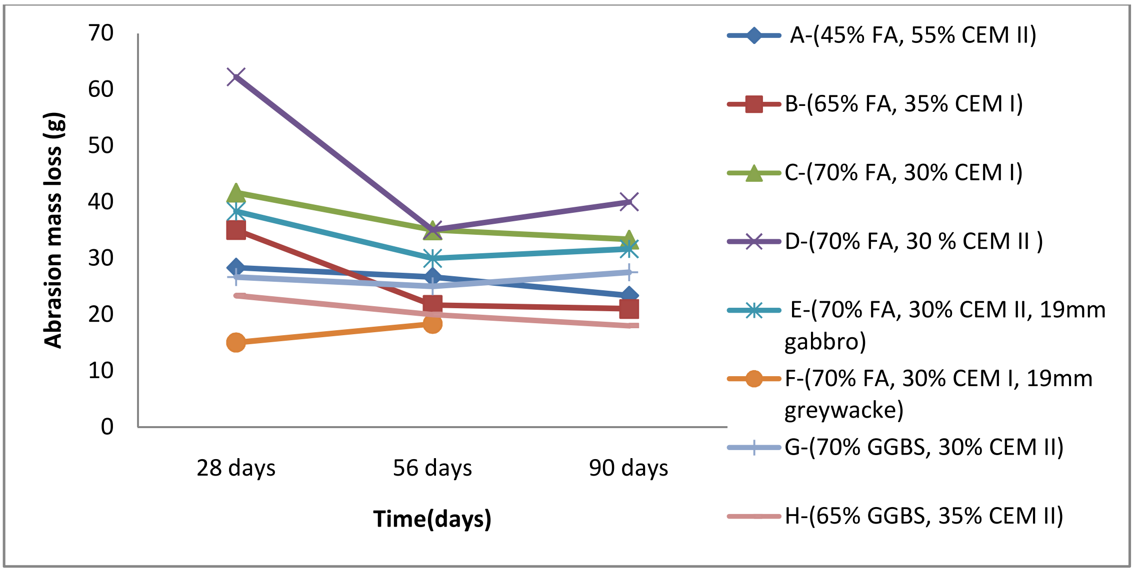

Figure 29: Time Development of abrasion test values for sandblasting method.

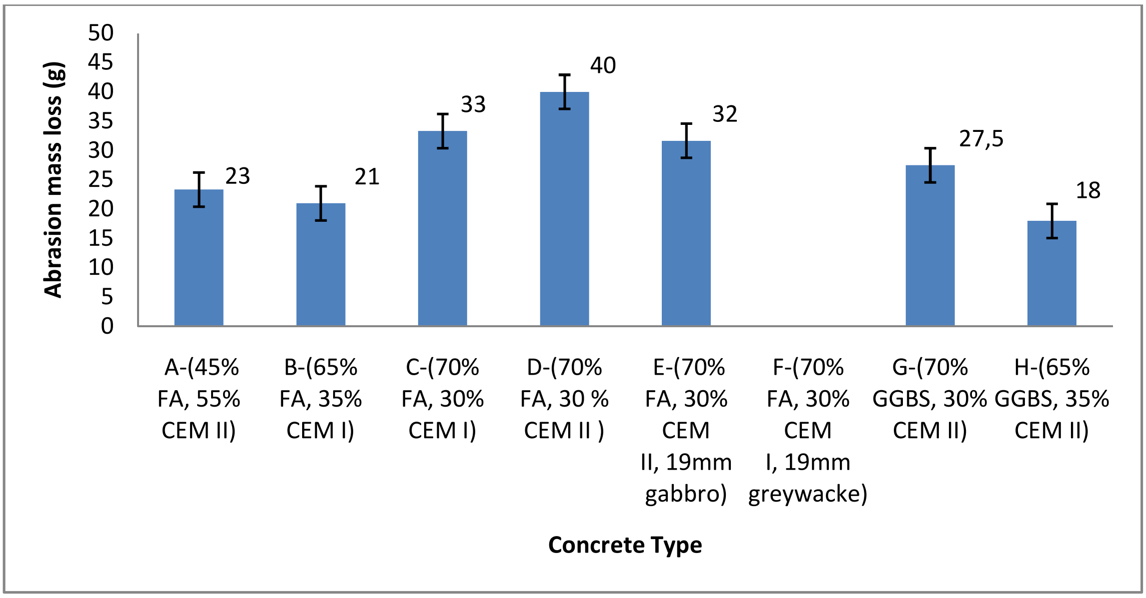

Figure 30: Comparison of all the 90-day values of abrasion mass loss as measured by the sandblasting method.

- The total cementitious content in the concrete mix influences the amount of paste in the concrete matrix and thus affecting abrasion resistance of concrete. The reference mix A, compared to the other two mixes mentioned above, had a high binder content (75 kg/m^{3}more). This influenced the surface properties of the concrete as it had more fines on the surface, resulting in more abrasion mass loss because the fines/paste is the weakest link in the concrete microstructure. Meanwhile the surfaces of the other two mixes were dominated by coarse aggregates and there was less paste to be abraded, resulting in a higher abrasion resistant surface.
- The concrete mix F (made with greywacke aggregates), which was only tested up to 56 days, showed unexpected trend of decrease in abrasion resistance with increasing age. At the age of 28 days the mean value of abrasion mass loss was 15 g and this increased to 18 g when measured at 56 days. The performance of this mix at 56 days was equal to the performance of the above mentioned mixes at 90 days, indicating superiority over all the concrete mixes but this could not be confirmed at 90 days.
- The concrete mix with 70% GGBS was ranked as a median mix in terms of abrasion resistance performance, with mean abrasion mass loss of 28 g at 90 days.
- Mixes C, D and E (made with 70% FA replacement and gabbro aggregates) had the lowest performance when compared to all the above mentioned concretes mixes. They all performed relatively the same (with reference to 56 days data) despite the difference in cement type and aggregate size. Their mean values of abrasion mass loss ranged from 30 g to 35 g at 56 days.

4.2. Wire brush test results

The results from the wire brush method generally showed a similar trend of slightly improvement in abrasion resistance with increasing age, with the exception of mixes B and F which showed an opposite relationship. These two mixes were only tested up to the age of 56 days and this trend could not be confirmed at 90 days. It is important to note though, that mix F showed similar trend when assessed with the sandblasting method. The abrasion resistance of this mix decreased with increasing age between 28 and 56 days, which could not be explained.

At 28 days, the performance of all the mixes was similar, with mean values of abrasion mass loss ranging between 17 g to 20 g, with exception of mix C which had an abrasion mass loss of 27 g, indicating poorer performance compared to the other mixes. However, this improved drastically when measured at 90 days. At the age of 90 days, all the mixes tested indicated significant improvement (by more than 5 g of mass loss) in abrasion resistance.

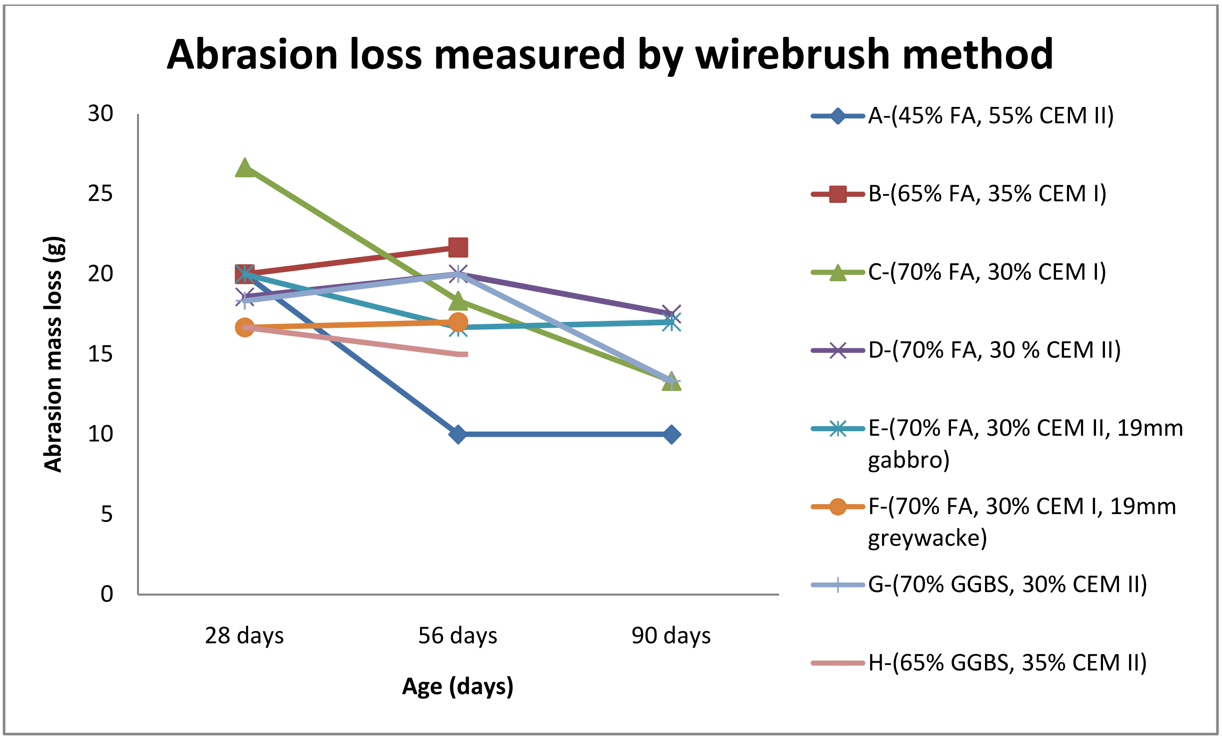

Figure 31: Time development of abrasion values for Wire brush method.

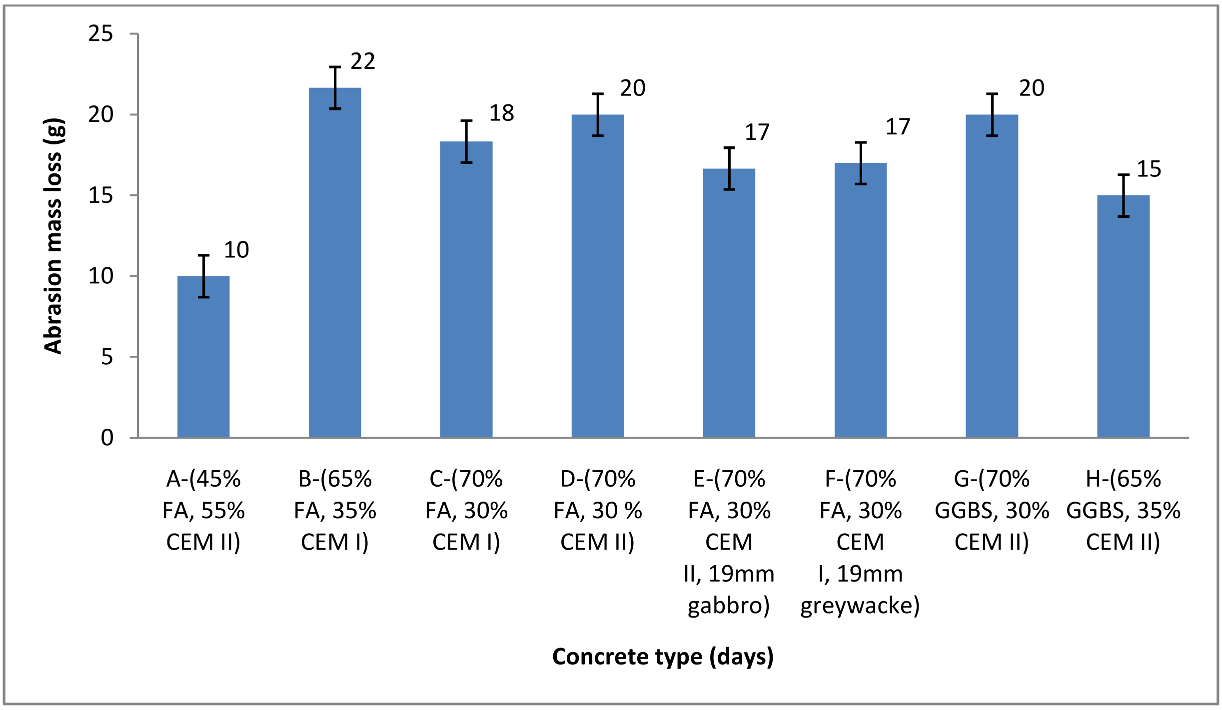

Figure 32: Comparison of the 56 days results of the different concrete mixes measured by the wire brush method.

With reference to both Figure 31 and Figure 32:

- At 56 days the performance of all the mixes, with the exception of mixes A and H, indicated little or no significant improvement of abrasion resistance with time.
- Concrete mixes A and H had mean values of abrasion mass loss of 10 g and 15 g respectively. They showed significant improvement in abrasion resistance when compared to 28 days results.
- The high performance of the reference concrete mix A, was expected, this mix had high content of cementitious material, which has positive effect on concrete strength and pore structure of the concrete, therefore the abrasion resistance was also expected to be relatively high compared to the other concretes, despite the high paste on the surface of the concrete which results to lower abrasion resistance as discussed earlier.

- Mix H showed the same trend of high performance similar to sandblasting results, confirming that GGBS concrete was superior in terms of abrasion resistance compared to fly ash concrete.

4.3. Comparison between the sandblasting and wire brush test methods

The 56 days results were used for the comparison of the two test methods investigated. Generally, the sandblasting test method showed higher values of abrasion mass loss when compared to the wire brush test method. The reason behind this was due to the severity of the impact of the abrasive action caused by the sandblasting method compared to that of the wire brush method. Therefore the sandblasting test method seems to be the more sensitive and reliable method to assess abrasion resistance of hydraulic structures. Whereas the wire brush method can be used for general quality control because it does not show significant differences in the abrasion values of the different mixes, and was also not sensitive to time. It was mentioned in the literature that the wire brush method is recommended when the wear is likely to occur through abrasion of the relatively weaker cementing matrix.

From Figure 33, it was observed that the sandblasting method can clearly distinguish between the different concrete mixes, therefore the data from this method was more reliable and the results were expected as compared to the wire brush method. The one factor that could have affected the results of the wire brush method was that the wire brushes were used until they got weary while the standard test method calls for a new brush to be used for each test. However, the standard test gives allowance in some cases for brushes to be used more than once given that adjustments are made to the results. This was not applied here as this adjustment method appears somewhat arbitrary and inexact.

Due to the reasons mentioned above, the sandblasting results will be used for further comparison of different parameters.

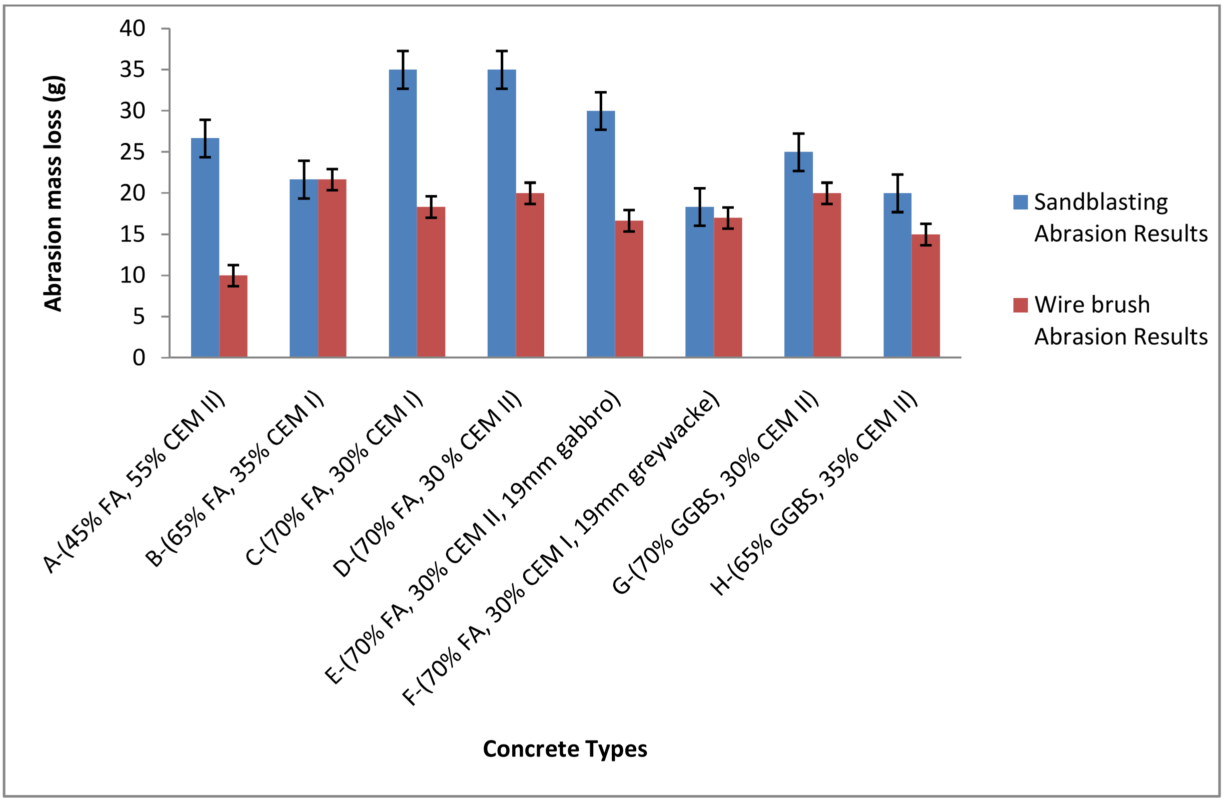

Figure 33: Comparison between the sandblasting and the wire brush test methods.

4.4. Compressive strength test results

Figure 34 shows results of the compressive strength of all the concrete mixes. An increase in compressive strength with increasing age has been observed from all the concrete mixes from 28 to 56 days. From 56 to 90 days all the concrete mixes did not show any significant increase in compressive strength (the increase was less than 3 MPa for all the mixes). The reference mix showed no increase at all between 56 and 90 days despite having high total cementitious material in the mix. Maybe because of the high cement clinker in the reference mixture the strength developed quicker as compared to the rest of the concrete mixes and it must have reached the maximum at the age of 56 days, or other factors influencing compressive strength applied.

The lack of increase in strength between 56 and 90 days was not expected because there were high percentages of fly ash or slag in all the mixes investigated. These extenders usually develop concrete properties over a long term, and it was expected that a significant increase in strength would be observed. However there are other extrinsic factors that influence the compressive strength of the concrete, maybe the lack of strength increase could be associated with those other factors.

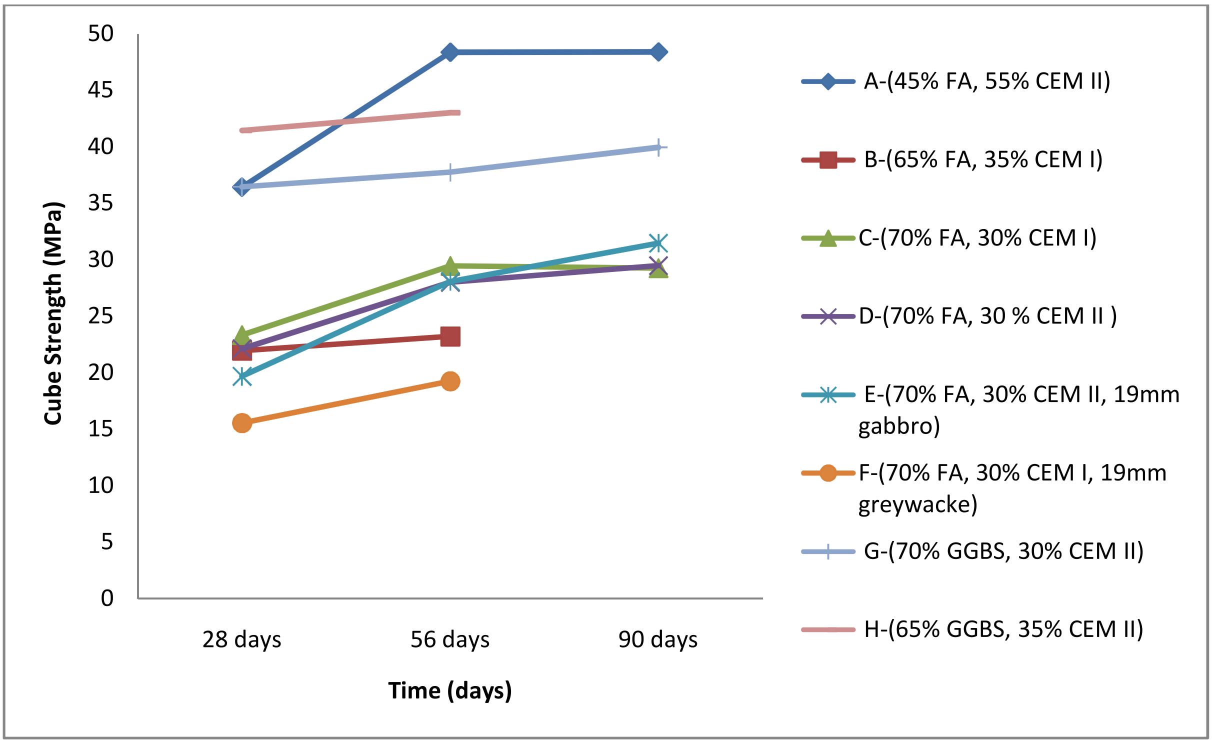

Figure 34: Time development of strength for all the concrete mixes.

Due to the lack of increase in strength between 56 and 90 days, and the fact that not all the concrete mixes were tested at 90 days, the comparison of compressive strength results will be based on the 56 days results only.

Referring to Figure 35:

- The reference concrete mix A, as expected, due to high content of cementitious material, had the highest in performance with a compressive strength of 48 MPa.
- This was followed by the concrete mix G made with 65% GGBS with a compressive strength of 43 MPa.

- Mixes C, D and E (made with gabbro aggregates, 70% fly ash and different types of cements or aggregate sizes) performed relatively the same with an average compressive strength of 28 MPa.
- Mixes B and F ranked the lowest with average compressive strengths of 23 MPa and 19 MPa respectively.
- It was noted that mixes made with the blends of GGBS yielded concrete with more compressive strength (more than 10 MPa difference) when compared to the fly ash concrete with same replacement values.
- At high volumes of extenders in the mix, it was also observed that compressive strength increased with decreasing extender replacement, this was consistent for both fly ash and GGBS concretes.

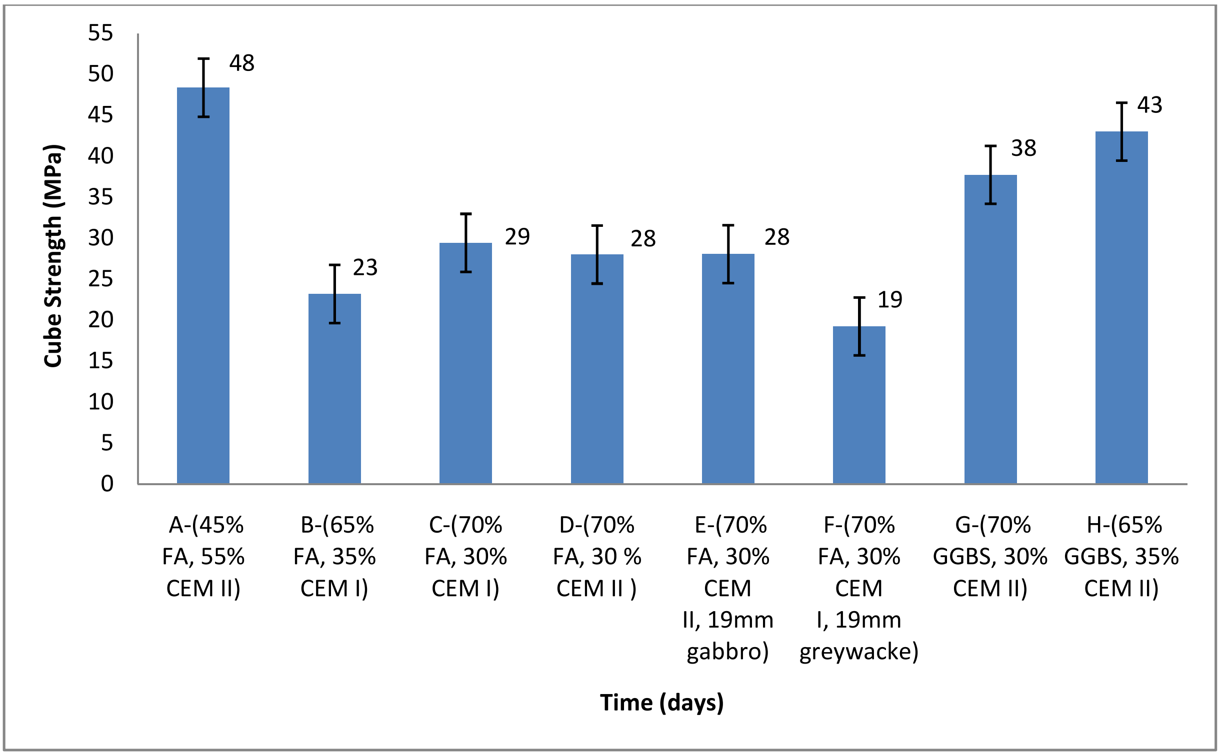

Figure 35: Comparison of the 56 days compressive strength results of all the concrete mixes.

4.5. Effects of compressive strength on abrasion resistance of concrete

The relationship between concrete compressive strength and its abrasion resistance was not well established from these results. The trendline as plotted in Figure 36 has a zero slope indicating no correlation between these two parameters. As it was stated in Section 2, low compressive strength concrete can still yield adequate abrasion resistance, which can be as good as the high compressive strength concrete, if good workmanship has been applied on the surface finishing, and suitable cement extenders like fly ash and GGBS have been used in the concrete mix.

The comparison between the concretes made with 19 mm gabbro aggregates and the 19 mm greywacke has proven that low compressive strength concrete can achieve high abrasion resistance, as the high compressive strength concrete. The concrete made with greywacke aggregates tested at 56 days had a compressive strength just below 20 MPa and an abrasion mass loss of 18 g. The concrete made from gabbro aggregates had a compressive strength of 28 MPa tested at 56 days and an abrasion mass loss of 30 g. This was a proof that not all concrete with low compressive strength has poor concrete abrasion resistance.

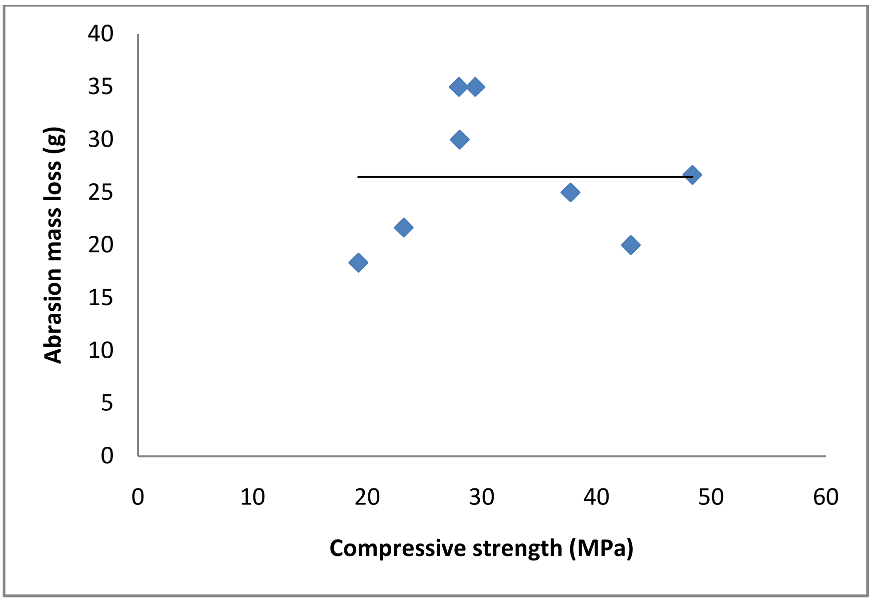

Figure 36: Effects of compressive strength to abrasion resistance of concrete.

4.6. Effects of fly ash percentage on abrasion resistance

Generally, as observed in Figure 37, at replacement levels between 45% and 70% of fly ash, abrasion resistance decreases with increasing percentage of fly ash in the concrete mix. It was also observed that concrete made with CEM I yielded higher abrasion results compared to concrete made with CEM II (17% difference in abrasion mass loss between mixes C and D).

With respect to the concrete mixes with high percentage of fly ash replacements, it was observed that, a further increase in fly ash, beyond 65%, resulted in significant reduction in abrasion resistance of concrete (difference of 12 g in mass loss as observed between mixes B and C). Up to date the literature sets a limit of 50% of fly ash replacement while on the contrary this research is leaning towards 65% limit. The concrete made with CEM II (which has 92% clinker and limestone extender) and 70% fly ash, has in fact 28% cement clinker and 72% of extenders, this mix had the lowest performance in abrasion resistance with abrasion mass loss of 40 g at 90 days.

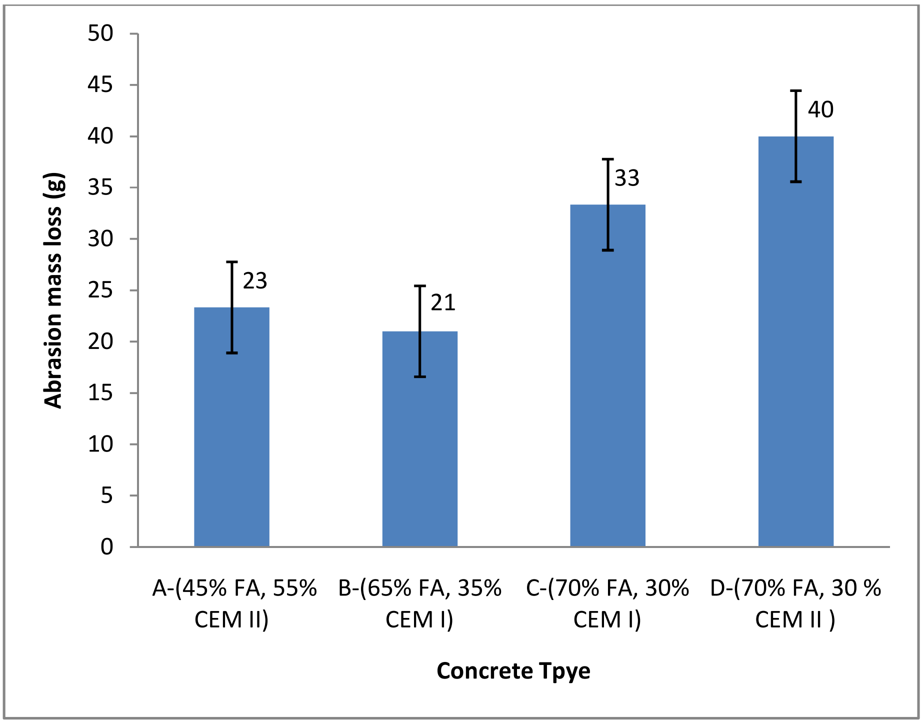

Figure 37: Effects of fly ash content on abrasion resistance of concretes (90 days results).

4.7. Effects of GGBS percentage on abrasion resistance of concrete

It was observed that a significant (10 g difference in mass loss) improvement in abrasion resistance was achieved as the percentage of GGBS was reduced from 70% to 65%. The trend was consistent with both the sandblasting and the wire brush test methods. This confirms the relationship established by Wu et al (2009), however their conclusion was that there is no improvement in abrasion resistance beyond 45% replacements. Since the focus of this research was on concrete with high volumes of extenders, only the reference mix had an extender below 65%. Therefore their findings could not be confirmed.

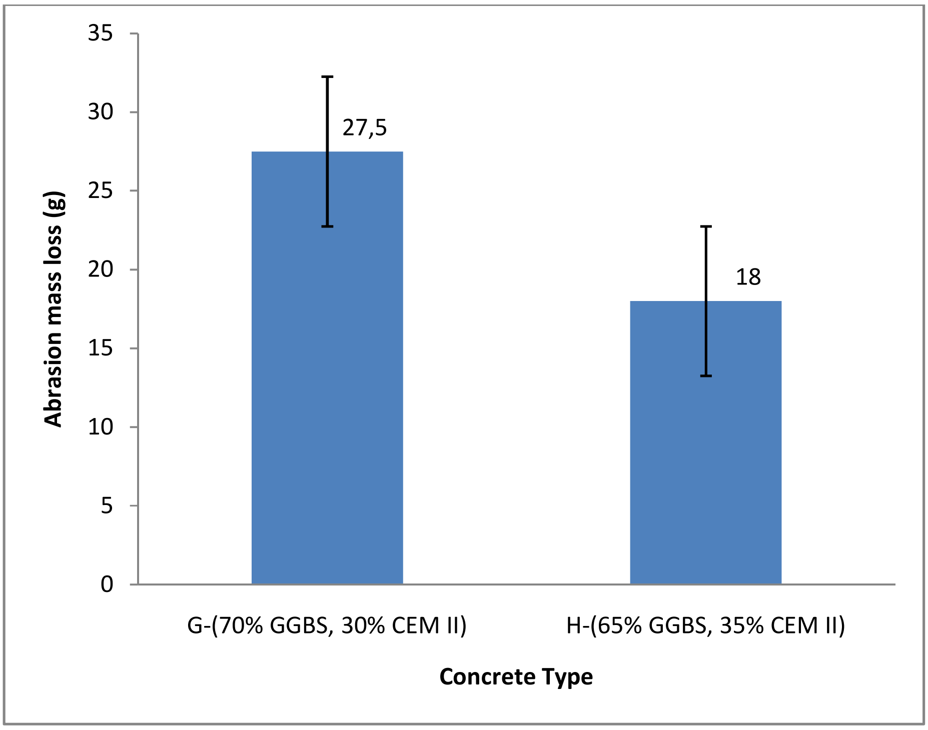

Figure 38: Effects of Slag on abrasion resistance measured at 90 days.

4.8. Effects of aggregates on abrasion resistance of concrete

The concrete made with 19 mm greywacke aggregates performed better than the concretes made with 19 mm or 38 mm gabbro aggregates. Even though two different cements were used in these mixes, the type of cement was not the only contributing factor to abrasion resistance. As it was discussed in the literature review, the characteristics of aggregates such as shape, texture and soundness have a significant influence in abrasion resistance of concrete. The greywacke aggregates are sub-angular to flaky in shape, have rough surface texture and are more absorbent and these properties permitted them good bonding ability which increased abrasion resistance. This confirms the argument by Papenfus (2003) that aggregate characteristics play a very important role in abrasion resistance.

The size of the aggregates did not have a significant effect on concrete abrasion resistance, this was observed between mixes C and E which are both made with gabbro aggregates that have different sizes and show relatively the same performance at 90 days.

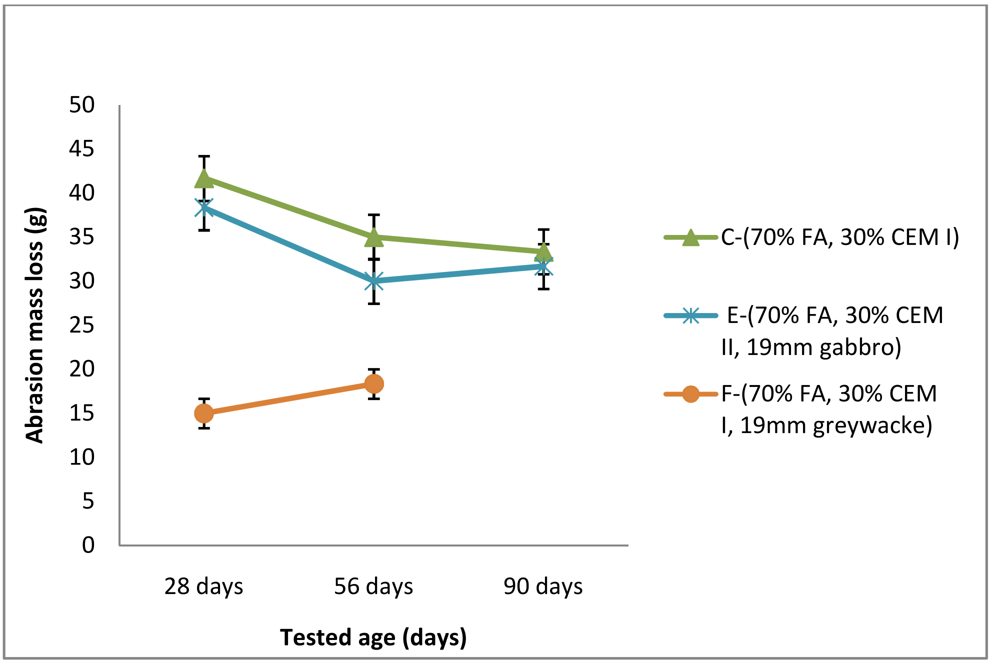

Figure 39: Effects of aggregates characteristics on abrasion resistance of concrete.

4.9. Comparison between IV-RCC and the conventional concrete

It was evident from both test methods that conventional concrete has higher abrasion resistance when compared to the IV-RCC concrete with 70% extender, however the percentages of Portland cement and the total cementitious content from these concrete types were different and should be considered before any conclusions are made. The conventional concrete had more than three times the amount of Portland cement per cubic meter, and had 75 kg/m³ more total cementitious material when compared to the IV-RCC (with 70% extender). This enabled it to have an improved pore structure when compared to the IV-RCC mix C due. The difference in mass loss was approximately 10 g throughout the ages tested, with the reference mix showing some superiority over the IV-RCC mix C. However, as discussed earlier on, when the percentage of fly ash in the IV-RCC mix was adjusted from 70% to 65%, it yielded similar performance to reference mix A when assessed at 90 days, this was evident between mixes A and B as shown in Figure 40. The type and amount of cement used in these mixes was different and also had influence on the results but this could not be investigated as other parameters were not fixed. However, it was observed that concrete made with CEM I was more abrasion resistant than concrete made with CEM II.

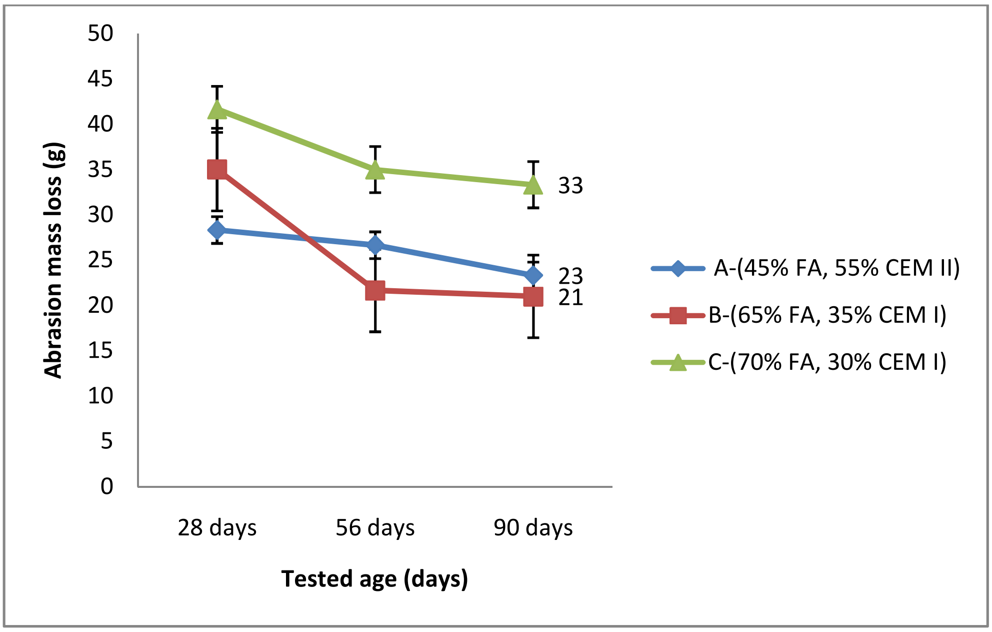

Figure 40: Comparison between the reference mix A and two IV-RCC mixes.

4.10. Test Results of the cores drilled from De Hoop Dam

Table 7 gives a summary of the results obtained from testing the cores that were drilled from De Hoop Dam. Fifteen (15) specimens of cores drilled were tested with the sandblasting test method and all but two (2) specimens had the exact same abrasion mass loss of 10 g. Ten (10) specimens were tested with the wire brush method and all the tested specimens had the exact same abrasion mass loss of 5 g. These results, like the previous results which were conducted on site during construction, indicate high abrasion resistance of the as-built structure. Similar trends as with the laboratory results were observed between the two (2) test methods used for investigations.

The average compressive strength tested from 9 cubes was 37 MPa.

Table 7: Summary of test results of the cores.

Test Method	Results
Sandblasting	10 g
Wire brush	5 g
Compressive Strength	38 MPa

4.11. Comparison between the laboratory cubes and the cores drilled from De Hoop Dam

From the sandblasting test method, the mix design from De Hoop Dam had an abrasion mass loss of 33 g at 90 days whereas the cores drilled from the structure had a mass loss of 10 g. From the wire brush test method, the laboratory made cubes had a mass loss of 13 g and 5 g from the cores. For both methods, the abrasion mass loss values obtained from the laboratory made cubes were approximately 3 times more than the values obtained from the cores. This suggests that the as-built structure may be more abrasion resistant compared to the cubes from the lab. There is not enough evidence to quantify this correlation between abrasion resistance of the laboratory produced cubes and the as-built structure, as other factors may have influenced these results.

There are many factors that might had influenced this, firstly the surface of the cubes from the drilled cores was very smooth and hard due to the core cutting method used to prepare the specimens for testing, also the surface texture was very different. On the site cores, as seen on Figure 41, more aggregate was exposed to abrasion, whereas in the laboratory specimens, there was more cement paste which has a lower hardness compared to the aggregates.

Secondly, the cores from the structure are older, more than 5 years since they were cast, and abrasion resistance just like strength, is a long term developing concrete property as it increases with increasing age. The other factor that could have contributed is the compaction method (roller compaction) used during construction of the structure, which has high energy compaction equipment (rollers) compared to the table vibration used in the laboratory. The table vibration was adopted because the IV-RCC concrete allows the use of a poker vibrator due to the high paste in the concrete mix.

Figure 41: Comparison of the abraded surface of the laboratory made cube on the left (with abraded portion of 45 mm diameter) and the core specimen from De Hoop Dam on the right.

4.12. Oxygen permeability index test results

Figure 42 shows the results of the OPI tests conducted on mixes E and F made with gabbro and greywacke 19 mm aggregates respectively. OPI testing from the rest of the concrete mixes was not conducted due to the presence of 38 mm aggregate size in those mixes. The OPI test specifies a maximum aggregate size of 26, 5 mm in the concrete mix. Results of the OPI values from De Hoop Dam cores were also plotted on the same bar chart. It is important to note that this mix had a maximum aggregate size of 38 mm, which exceeds the limit of the OPI test specification. This could have had an effect on the OPI values (increase in OPI values due to a bigger aggregate size that block the pathways for oxygen).

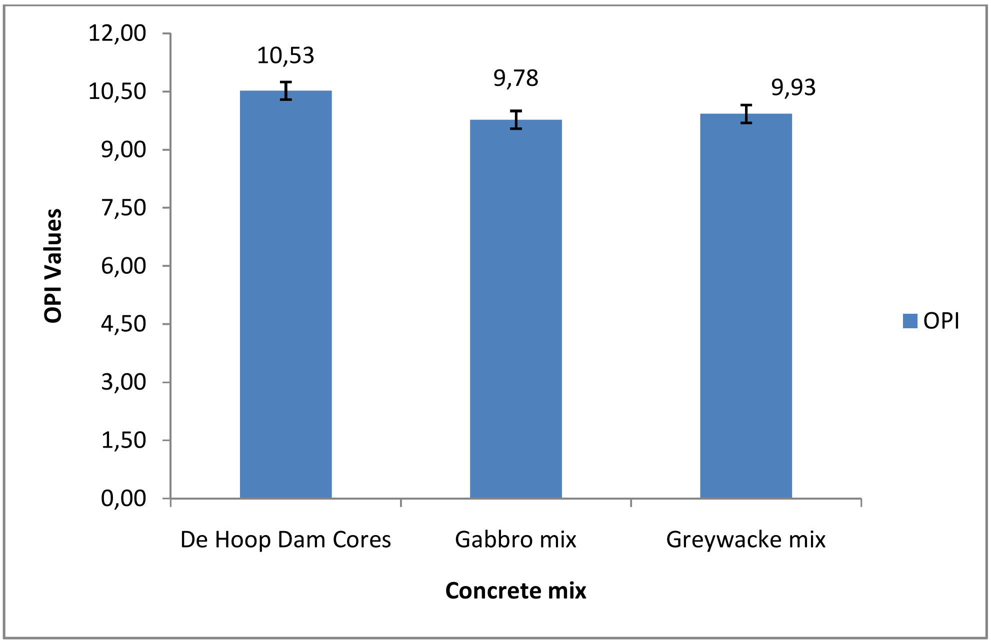

Figure 42: Comparison of mean OPI values of different concrete mixes.

The laboratory concrete mix made from gabbro aggregates from De Hoop Dam and the mix made with greywacke aggregates had mean OPI values of 9, 78 and 9, 93 respectively. Both these OPI values indicate a good quality concrete microstructure with concrete mix made with greywacke aggregates showing slightly better results than the concrete mix made from gabbro aggregates. This trend was also observed in the abrasion resistance of these two concrete mixes. The difference, besides the aggregates, between these two mixes was that the former was made from CEM II 42, 5 while the latter was made from CEM I 52, 5. Therefore the greywacke mix had an advantage to have a better microstructure since CEM I is finer than CEM II and the "fine-filler effect" of CEM I works much better than that of CEM II to improve the pore structure of the concrete subsequently improving other properties. From these observations it can be mooted that, any measure taken to improve microstructure of the concrete also improving the OPI values, will have a positive effect on abrasion resistance of concrete.

The mean OPI value of the cores was 10, 53 and was higher than the laboratory made mixes, indicating that its microstructure was superior. There are two factors that might had influenced this, first the maximum aggregate size was larger (38 mm) as compared to the laboratory mixes made with 19 mm aggregates. This means that the oxygen had more pathways to pass through the concrete made with 19 mm as compared to the one made with 38 mm aggregates. The second influencing factor, and probably the dominating one, was the compaction method used to produce these concretes. The cores were compacted on site with heavy rollers while the laboratory made cubes were compacted on a vibration table. The heavy compaction for the cores significantly improved the microstructure of the concrete because as the concrete was vibrated with heavy rollers, most of the voids within the concrete were filled and the removal of air bubbles was more effective with roller compaction than with table vibration. Also, the rollers removed all the excess water from the top surface of the concrete, with consequently improved quality of the subsurface concrete.

5. Discussion

Abrasion resistance of concrete is a long term property of concrete and should be measured after concrete has adequately developed its properties, at least three months after concrete placement, especial if slow reacting extenders have been used in the concrete mix. It was evident from both sandblasting and wire brush methods that abrasion resistance of concrete improves with increasing age, based on the comparison of 28 and 90 days results. Papenfus (2003) also agrees with this observation as he also observed an increase in abrasion resistance of concrete when assessed 6 years after concrete placements compared to concrete that was assessed at 28 days. The Department of Water and Sanitation already specifies long term strength (90 days) for roller concrete, therefore the assessment of abrasion resistance can be included in the 90 days testing.

In the literature review (Chapter 2) high compressive strength concrete has proven to have high abrasion resistance values but the experimental results have indicated that this does not necessarily mean that low compressive strength concrete has poor abrasion resistance. This was evident from the concrete made with greywacke aggregates which had low concrete strength but higher abrasion resistance values compared to the counterpart concretes (which had relatively high abrasion resistance). This investigation did not reveal any clear correlation between compressive strength and abrasion resistance. Other factors such as the aggregates characteristics, binder type, curing, and surface treatment play a significant role in abrasion resistance and durability of concrete in general.

It has been observed that, for high replacement percentages, abrasion resistance of concrete increases as the percentage of an extender decreases from 70% to 65%. The IV-RCC concrete mixes with 65% of fly ash or GGBS performed equally to the conventional concrete with 45% fly ash replacement. It was also evident that concrete made with GGBS had higher abrasion resistance than fly ash concrete with same replacement percentages. Therefore, the use of GGBS in roller concrete by DWS would bring a beneficial effect in terms of abrasion. It was discussed in Chapter 2 that abrasion resistance of concrete increases with increasing extender percentage up to a limit of 50%. This limit is not suited for roller concrete which has long term strength specification and higher percentages of extenders. It has been observed that when CEM I concrete is blended with 65% of fly ash, the improvement in abrasion resistance was significant compared to CEM II blends. Therefore, DWS should not be concerned about the high percentage of fly ash used in their roller concrete mixes, as long as this can be adjusted to 65% and blended with CEM I.

For a low strength concrete, aggregate characteristics play a far more significant role than hardness of the aggregates in abrasion resistance of concrete. The greywacke aggregates, because of their sub-angular to flaky shape produced concrete with higher degree of interconnectedness of the pore structure than the gabbro aggregates, and this resulted in higher abrasion resistant concrete. This degree of interconnectedness was also evident in the OPI results of the greywacke concrete. As it was expected, concrete with high OPI values also had high abrasion resistance values compared to concrete with relatively lower OPI values. In the process of selection of construction materials, consideration should be also given to the characteristics of the aggregates to be used for construction of the spillway steps.

The abrasion values obtained from De Hoop Dam during construction and those obtained from the cores drilled from the structure, indicate adequate values of abrasion resistance. At least at this point it can be stated that there is no significant difference, in terms of abrasion resistance, between the conventional concrete and the roller-compacted concrete. The adjustment of fly ash from 70% to 65% in the IV-RCC mix has a positive effect on abrasion resistance of concrete.

It was evident that the sandblasting test method is the most reliable and sensitive method to assess abrasion resistance of hydraulic concrete structures.

6. Conclusions

The following conclusions were drawn from the results of this investigation:

1. The percentage of the extender used in the concrete mix plays a significant role in abrasion resistance of the concrete. It can be concluded that abrasion resistance increases with increasing percentage of an extender, but that is so only up to a certain percentage of cement replacement. Papenfus (2003) argues that there is no improvement in abrasion resistance of concrete beyond 50% replacement with fly ash. This investigation did not see a significant difference in abrasion resistance between replacement levels of 45% and 65% of fly ash.
2. When the percentage of fly ash is adjusted to 65% in the IV-RCC mix, the performance (in terms of abrasion resistance) of the IV-RCC mix is similar to that of conventional concrete.
3. This research found no correlation between abrasion resistance and compressive strength of concrete. However, various authors have identified a trend of increase in abrasion resistance with increasing concrete strength. It is therefore concluded that compressive strength cannot be reliably used to assess the abrasion resistance of concrete. The reason for this is that abrasion resistance is largely a concrete surface property and as such partially influenced by factors other than those affecting strength, which is a bulk property. Consequently, to assess abrasion resistance of concrete, suitable abrasion test methods need to be used.
4. The characteristics of the aggregates play a significant role in the abrasion resistance of concrete. Absorbent, angular aggregates with rough surface texture enhance the bonding capability between the aggregates and paste, which in turn improves the strength, abrasion resistance and other properties of concrete. This has been evident with the greywacke aggregates, which, because of their sub-angular shape and rough texture, performed better than the gabbro aggregates, which are sub-rounded with less rough texture.
5. The hardness of the aggregates is not important in abrasion resistance of low strength concrete. The gabbro aggregates have higher hardness compared to greywacke aggregates but the abrasion resistance of concrete made with gabbro

aggregates was significantly lower than the abrasion resistance of concrete made with greywacke aggregates.

6. Where abrasion resistance of hydraulic structures is concerned, the standard test method of sandblasting is the most reliable and sensitive method that can be used to assess the abrasion resistance of concrete. The wire brush test method is not sensitive to different concretes or age and it is suggested that it can only be used for general quality control purposes.
7. It is further concluded that there is correlation between the laboratory made cubes and the as-built structure. The site cores were 3 times more abrasion resistant than the laboratory made cubes.
8. The average abrasion wear depth of the steps of De Hoop Dam wall was less than 0, 4 mm when measured more than 5 years after concrete placement.
9. The results of the site samples indicated that the actual structure has adequate abrasion resistance, based on the comparisons to the laboratory mixes (which were produced with strict quality control) and based on the evaluation guidelines (for abrasion results) in literature.
10. Abrasion resistance must be assessed on cores drilled from the structure or field tests conducted on the structure during construction. Alternatively, during construction phase, large specimens can be constructed next to the structure and be subjected to the same construction method and curing then be tested on site.

7. Recommendations

This chapter is relevant and useful to the Department of Water and Sanitation, in order to develop specifications for the concrete used to construct spillway steps. If these recommendations are followed, it is expected that the concrete of the spillway steps will have adequate abrasion resistance equal or more than that of the conventional concrete mix used by the department. Such concrete will also be durable enough to withstand the test of time from waterborne abrasion action.

The following recommendations were made based on the discussion and conclusions drawn from the results:

1. The 70% replacement of Portland cement with fly ash in the IV-RCC mix should be revised to a lower percentage not exceeding 65%. This does not have to be applied to all of the IV-RCC mix, but to the spillway steps concrete that will be exposed to waterborne action. This means that on the spillway steps the concrete next to the downstream formwork must have less than 65% replacement of cement and the rest of the concrete can be kept at 70% cement replacement with fly ash or another extender.
2. Characteristics of the aggregates should be scrutinised when selecting aggregates for the IV-RCC. Aggregates with rough texture, angular shape, more absorbent and with good hardness and toughness are preferred as far as abrasion resistance is concerned.
3. The Sandblasting test method is the preferred method to evaluate abrasion resistance of hydraulic concrete structures.
4. Based on the results obtained from De Hoop Dam, it is recommended that abrasion wear depth of field tests should not exceed 1 mm when assessed by the sandblasting method at 90 days. The abrasion wear depth obtained from De Hoop Dam was less than 0, 4 mm when measured a year after concrete placement.
5. Moist curing of the concrete surface immediately after the concrete has taken its initial set must be specified to improve the abrasion resistance. It is in the best interest of the department that the curing duration of 21 days currently specified for

RCC is enforced without interruption. The effect of increasing the curing duration further to 28 days should also be investigated.

6. It is already known that there is a correlation between concrete surface hardness and compressive strength. However, the correlation between surface hardness (as measured by Schmidt hammer test) and abrasion resistance of concrete is not clear. The Schmidt hammer test is a simple and easy method to test mechanical concrete surface properties. Therefore it is recommended that a study is conducted on the relationship between abrasion resistance and surface hardness. This technique can potentially be used for quality control of concrete during construction phase.
7. It is also recommended that a further research be conducted on this topic, where extensive laboratory and field tests will be carried out to confirm the conclusions made. The use of surface treatments should be added to the scope of the research. Replacement of the Portland cement between 45% and 70% should be investigated using both the fly ash and GGBS extenders.

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Appendix A: More detailed data of the experimentation results

Table 8: Abrasion results of all the concrete mixes indicating mean values of abrasion mass loss in grams.

Concrete type	Sandblasting Abrasion Results			Wire brush Abrasion Results		
	28 days	56 days	90 days	28 days	56 days	90 days
A-(45% FA, 55% CEM II)	28	27	23	20	10	10
B-(65% FA, 35% CEM I)	35	22	21	20	22	
C-(70% FA, 30% CEM I)	42	35	33	27	18	13
D-(70% FA, 30 % CEM II)	62	35	40	19	20	18
E-(70% FA, 30% CEM II, 19mm gabbro)	38	30	32	20	17	17
F-(70% FA, 30% CEM I, 19mm greywacke)	15	18		17	17	
G-(70% GGBS, 30% CEM II)	27	25	27,5	18	20	13
H-(65% GGBS, 35% CEM II)	23	20	18	17	15	

Table 9: Mean values of compressive strength of all the concrete mixes.

Concrete Type	Compressive Strength Results		
	28 days	56 days	90 days
A-(45% FA, 55% CEM II)	36	48	48
B-(65% FA, 35% CEM I)	22	23	
C-(70% FA, 30% CEM I)	23	29	29
D-(70% FA, 30 % CEM II)	22	28	29
E-(70% FA, 30% CEM II, 19mm gabbro)	20	28	31
F-(70% FA, 30% CEM I, 19mm greywacke)	16	19	
G-(70% GGBS, 30% CEM II)	36	38	40
H-(65% GGBS, 35% CEM II)	41	43	

Table 10: Compressive strength results of the cores drilled from De Hoop Dam.

Core ID	Average Height (mm)	Average Diameter (mm)	weight (g)	Load (kN)	Compressive Strength (MPa)
1	110	107,7	2580	300	**33**
2	109,5	108,1	2585	383	**42**
3	109,3	108,1	2550	345	**37,5**
4	109,5	107,6	2560	337	**37**
5	109	108	2565	336	**36,5**
6	109,3	108	2580	385	**42**
7	108,5	108	2480	336	**36,5**
8	109	108	2530	383	**42**
9	109	108	2585	335	**36,5**
Average	**109,2**	**107,9**	**2557**	**349**	**38**

Table 11: OPI test results of the gabbro aggregates from De Hoop Dam.

DURABILITY INDEX TESTING

Oxygen Permeability Test Analysis - Output summary

Project:	Thesis
Sample ID:	Gabbro aggregates
Date of testing:	06.06.2016
Operator:	Cmay
Company:	UCT

Test results *(Note: Mean OPI is based on average of at least three OPI values)*

Disk #:	1	2	3	4	Mean	S.D.	COV (%)
k (m/s):	2,013E-10	1,719E-10	1,227E-10	1,826E-10	**1,696E-10**	**#NAME?**	**#NAME?**
OPI:	9,70	9,76	9,91	9,74	**9,78**	**#NAME?**	**#NAME?**
r^2	0,9991	0,9974	0,9984	0,9987			
r^2 Validity	Valid	Valid	Valid	Valid			

Comment: Tests are only considered valid if the r^2 value is greater than 0.99. Based on engineering judgement, values indicated as invalid but where r^2 is close to 0.99 may be considered.

COV % (Mean k):	20
Variability Check:	Good

Table 12: OPI test results of the greywacke aggregates.

DURABILITY INDEX TESTING							
Oxygen Permeability Test Analysis - Output summary							
Project:	Thesis						
Sample ID:	Greywackle aggregates						
Date of testing:	23.06.2016						
Operator:	C May						
Company:	UCT						
Test results *(Note: Mean OPI is based on average of at least three OPI values)*							
Disk #:	1	2	3	4	**Mean**	**S.D.**	**COV (%)**
k (m/s):	8,776E-11	8,281E-11	2,316E-10	1,171E-10	**1,298E-10**	**#NAME?**	**#NAME?**
OPI:	10,06	10,08	9,64	9,93	**9,93**	**#NAME?**	**#NAME?**
r^2	0,9980	0,9985	0,9914	0,9992			
r^2 Validity	Valid	Valid	Valid	Valid			
Comment: Tests are only considered valid if the r^2 value is greater than 0.99. Based on engineering judgement, values indicated as invalid but where r^2 is close to 0.99 may be considered.							
COV % (Mean k):	54						
Variability Check:	Good						

Table 13: Sorptivity test results of the gabbro aggregates from De Hoop Dam.

DURABILITY INDEX TESTING

Sorptivity Test Analysis - Output summary

Project:	Thesis
Sample ID:	Gabbro aggregates
Date of testing:	06.06.2016
Operator:	Cmay
Company:	UCT

Test results

Disk #:	1	2	3	4	**Mean**	**S.D.**	**COV (%)**
Sorptivity (mm/hr$^{0.5}$):	7,61	7,10	7,48	6,91	**7,27**	**#NAME?**	**#NAME?**
Porosity (%):	12,25	13,11	11,34	12,27	**12,25**	**#NAME?**	**#NAME?**

Table 14: Sorptivity test results of the greywacke aggregates.

DURABILITY INDEX TESTING

Sorptivity Test Analysis - Output summary

Project:	Thesis
Sample ID:	Greywackle aggregates
Date of testing:	06.06.2016
Operator:	C May
Company:	UCT

Test results

Disk #:	1	2	3	4	**Mean**	**S.D.**	**COV (%)**
Sorptivity (mm/hr$^{0.5}$):	7,51	5,73	5,50	6,05	**6,20**	**#NAME?**	**#NAME?**
Porosity (%):	11,77	11,81	11,66	10,78	**11,50**	**#NAME?**	**#NAME?**

Table 15: OPI test results of cores from De Hoop Dam.

DURABILITY INDEX TESTING

Oxygen Permeability Test Analysis - Output summary

Project:	Thesis
Sample ID:	De Hoop Dam Cores
Date of testing:	11.11.2016
Operator:	Cmay
Company:	UCT

Test results *(Note: Mean OPI is based on average of at least three OPI values)*

Disk #:	1	2	3	4	**Mean**	**S.D.**	**COV (%)**
k (m/s):	3,083E-11	2,815E-11	2,999E-11	3,000E-11	**2,974E-11**	**1,13E-12**	**4**
OPI:	10,51	10,55	10,52	10,52	**10,53**	**0,02**	**0,16**
r^2	0,9994	0,9994	0,9994	0,9994			
r^2 Validity	Valid	Valid	Valid	Valid			

Comment: Tests are only considered valid if the r^2 value is greater than 0.99. Based on engineering judgement, values indicated as invalid but where r^2 is close to 0.99 may be considered.

COV % (Mean k):	4
Variability Check:	Good

Table 16: Sorptivity test analysis results of cores from de Hoop Dam.

Sorptivity Test Analysis - Output summary

Test results

Disk #:	1	2	3	4	**Mean**	**S.D.**	**COV (%)**
Sorptivity (mm/hr$^{0.5}$):	8,96	8,72	9,13	8,89	**8,93**	**#NAME?**	**#NAME?**
Porosity (%):	8,96	9,49	8,32	8,39	**8,79**	**#NAME?**	**#NAME?**

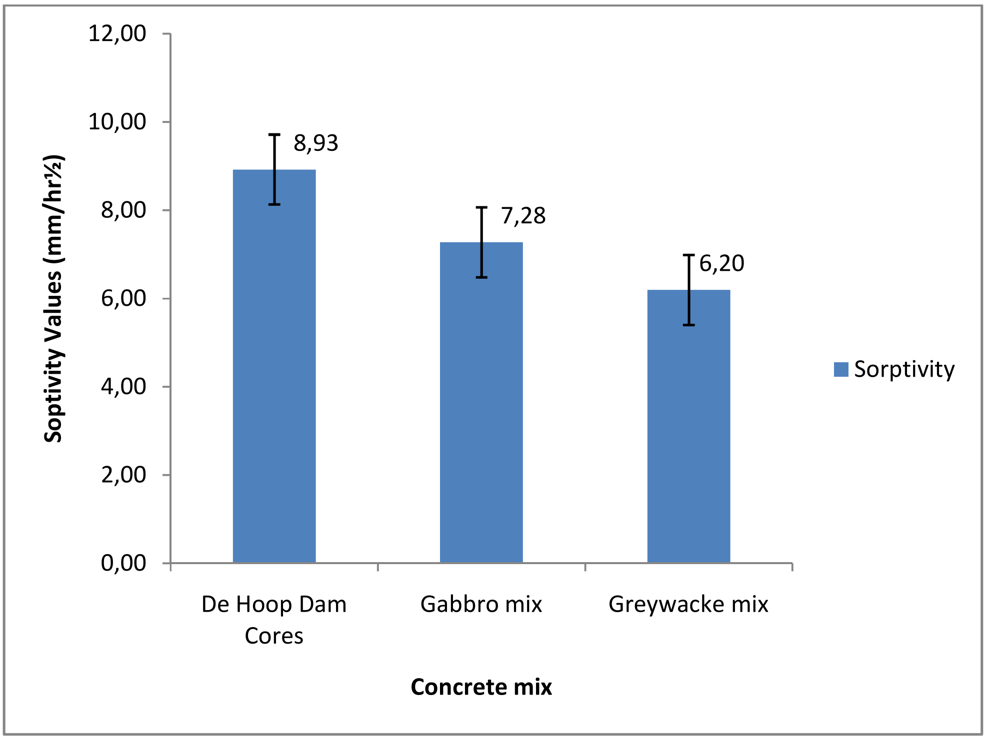

Figure 43: Comparison of mean sorptivity values of different mixes.

Appendix B: Grading curves of different sizes of gabbro coarse aggregates and Photos from the testing

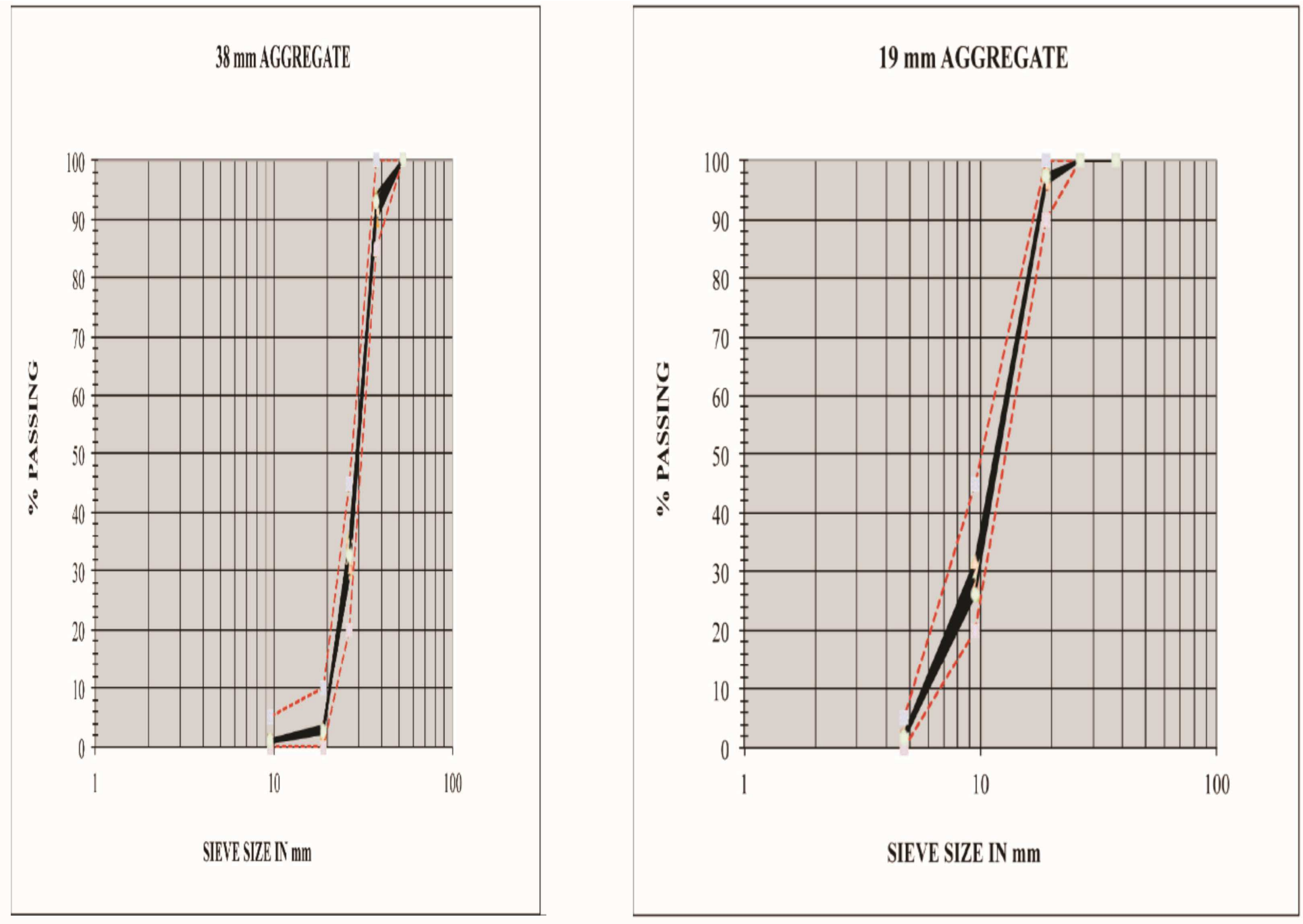

Figure 44: Grading curves of the 38 mm and 19 mm gabbro aggregates (DWS, 2014).

Figure 45: Samples tested with the wire brush and sandblasting method.

Appendix C: Assessment of Ethics in Research Projects form

EBE Faculty: Assessment ofEthics in Research Projects

Any person planning to undertake research in the Faculty of Engineering and the Built Environment at the University of Cape Town is required to completethis formbefore collecting or analysing data.When completed it should be submitted to the supervisor (where applicable) and from there to the Head of Department. If any of the questions below have been answered YES, and the applicant is NOT a fourth year student, the Head should forward this form for approval by the Faculty EIR committee: submit toMs Zakiya Chikte (Zakiya.chikte@uct.ac.za); New EBE Building, Ph021 650 5739).

Please note – It is important to keep a signed copy of this form as students must include **a copy of the** completed form with the dissertation/thesis when it is submitted for examination.

Name of Principal Researcher/Student: MYEZO POYO **Department:** CIVIL

If a Student: **Degree:** Masters CIVIL **Supervisor:** HANS BEUSHAUSEN

If a Research Contract indicate source of funding/sponsorship:

Research Project Title: ABRASION RESISTANCE OF IV-RCC USED TO CONSTRUCT SPILLWAY CONCRETE STEPS.

Overview of ethics issues in your research project:

Question 1: Is there a possibility that your research could cause harm to a third party (i.e. a person not involved in your project)?	YES	NO
Question 2: Is your research making use of human subjects as sources of data? If your answeris YES, please complete Addendum 2.	YES	NO
Question 3: Does your research involve the participation of or provision of services to communities? If your answeris YES, please complete Addendum 3.	YES	NO
Question 4: If your research is sponsored, is there any potential for conflicts of interest? If your answeris YES, please complete Addendum 4.	YES	NO

If you have answered YES to any of the above questions, please append a copy of your research proposal, as well as anyinterview schedules or questionnaires (Addendum 1) andplease complete further addenda as appropriate.

I hereby undertake to carry out my research in such a way that

- there is no apparent legal objection to the nature or the method of research; and
- the research will not compromise staff or students or the other responsibilities of the University;
- the stated objective will be achieved, and the findings will have a high degree of validity;
- limitations and alternative interpretations will be considered;
- the findings could be subject to peer review and publicly available; and
- I will comply with the conventions of copyright and avoid any practice that would constitute plagiarism.

Signed by:

	Full name and signature	Date
Principal Researcher/Student:	MYEZO	18/02/2016

This application is approved by:

Supervisor(if applicable):	HB	18/03/16
HOD(or delegated nominee): Final authority for all assessments with NO to all questions and for all undergraduate research.	MV	22/3/16
Chair : Faculty EIR Committee For applicants other than undergraduate students who have answered YES to any of the above questions.		