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CIV5017Z: DISSERTATION FOR THE DEGREE OF MASTER OF ENGINEERING SPECIALISING IN STRUCTURAL ENGINEERING AND MATERIALS [EM017CIV04]

CIV5017Z Minor Dissertation

The effectiveness of a percussion drill method for making concrete cube samples to assess the characteristics of precast zero-slump concrete

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Abstract

The precast industry in South Africa consumes about 28% of the total cement produced, and a large proportion of its concrete is prepared with zero-slump concrete mixes. Precast finished products are load tested to confirm compliance, but the zero-slump concrete is often not tested by cube or cylinder samples, as is the case with ready-mix concrete. There is an industry practice of using the percussive action of a rotary percussion drill to compact control samples when necessary. However, variation in the compaction of the specimens results in variation in the density and compressive strength results. Therefore, there is a need for a simple, standardised quality control method that considers the compaction achieved by precast machines.

A suitable procedure was pursued with the following specific objectives; i) to formulate a practical and economical procedure for quality control based on the concrete density achieved by precast machines, and ii) to apply this method (i.e., percussion drill method) to mix optimisation with the specific objective of partial replacement of the cement in a specific factory mix with a suitable fine filler in order to reduce cost and the carbon footprint of a specific precast facility.

The study methodology involved a literature review on available quality control methods, and a laboratory investigation that combined the percussion drill method with a target density method. The laboratory investigation produced representative samples of an industry mix based on density tests on core samples of the same mix produced by different precast machines. The method was then used to test different proportions of cement replacements by volume with a fine filler. The purpose of the partial cement replacement by fine filler mixes was to assess the effectiveness of using the percussion drill method in mix optimisation.

The experimental investigation involved determining the density of concrete produced by three different precast machines using the same industry mix. The density was measured for samples in different moisture conditions, i.e., the as-received state, oven-dried state, saturated state and in an environmentally controlled room. Based on the results, it was recommended to use the as-received density for quality control and mix optimisation at precast production facilities when measuring target density using the percussion drill method.

The specific factory mix used in producing the precast elements was employed in the laboratory to produce cube samples using the percussion drill method. The specific factory mix had a water-to-binder ratio of 0.25, a very stiff and dry mix. Therefore, the percussive action of a percussion drill was used for compaction to achieve a target density. The aim was to achieve a compressive strength of 30 MPa at 18 hours and 50 MPa at 28 days. The compressive strength achieved was 1.9 MPa at green state, 40.7 MPa at 18 hours, and 66.5 MPa at 28 days, higher than the target strengths. The green state strength was required to assess the ability of a mix to retain its shape without formwork after extrusion. Thus, the specific factory mix provided a benchmark value.

In achieving the second objective, quartz flour was selected as a fine filler and replaced cement in the concrete at replacement rates of 20%, 30%, and 40% by volume of cement. This selection was based on its lower cost and carbon footprint compared to Portland cement and the fact that the particle size and texture are similar to Portland cement. CEM I 42.5 R was used in this objective instead of CEM II / A-L 42.5 N used in the first objective due to its potential to provide sufficient early age strength.

The results indicate that the 20% replacement rate outperforms the specific factory mix and other replacement rates in strength at all three critical time intervals. This was either due to the quartz filling effect, which improved the concrete compaction, or a higher early hydration rate of the CEM I 42.5 R than the CEM II / A-L 42.5 N, or a combination of two. The lower strength performance of 30% and 40% replacement rate was related to the fact that quartz flour is inert, which reduces compressive strength with further cement reduction. However, the green state, 18-hour, and 28 days compressive strengths of the 40% replacement mix were still above the minimum requirements. Therefore, the 40% replacement mix was appropriate for industry application. However, it must be noted that these results were obtained in a controlled laboratory environment, which is not replicated at the specific precast facility. Therefore, the recommended trial replacement volume of cement by quartz flour is 33% for an industry trial to anticipate less ideal curing conditions at the production facility, resulting in a net CO_2 emission reduction of about 113.1 kg /m^3 of compacted concrete.

Generally, the results indicate that the percussion drill method can effectively provide adequate quality control measures, and mix optimisation if compaction achieves a predetermined density.

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1. Chapter One: Introduction

1.1. Background

Precast, pre-tensioned concrete elements are widely used in construction due to their construction speed and cost-effectiveness. These concretes generally require lower cement content, water to binder (w/b) ratios, and less steel than conventional concrete. These advantages result in producing high-quality concrete under optimal material usage. Precast concrete elements are fabricated in factories, where there is the possibility of greater control over the operational and environmental conditions. The concrete is designed for high early strength to allow destressing, movement for curing and then transportation to site for construction within a short period. On-site, a significant number of concrete elements can be placed by crane without formwork and additional waiting time associated with in-situ concrete casting.

The factory conditions during manufacture and lower w/b ratios in the concrete mixes improve the quality of the concrete. This is mainly due to better curing and temperature control in the factories. Also, the compressive strength increases with a decrease in the w/b ratio. One can, therefore, reduce the overall cement content whilst achieving acceptable compressive strength results. Since most shrinkage occurs in the paste component, concrete with less cement tends to be less susceptible to cracking.

The lower w/b ratios result in fresh concrete that is relatively dry and is known as zero-slump concrete. Placing such dry mixes on a normal construction site is impractical because the compaction effort required to compact the concrete cannot be achieved in normal shuttering.

Zero-slump concrete (or no-slump concrete) is defined as a concrete mix with a slump of 6 mm or less (Hüsken & Brouwers, 2012). The zero-slump is achieved by restricting the water content. Sometimes these mixes are called earth-moist concrete, dry mix concrete or dry cast concrete (Najimi, Sobhani & Pourkhorshidi, 2012). Zero-slump concrete has gained popularity since the elements can be formed by extrusion, which involves extruding concrete through a die of the desired cross-section.

In the case of the hollow-core slabs and lintels assessed in this investigation, zero-slump concrete is vibrated and compressed into the shape of the slab or lintel. There are circular or oval voids in the cross-section and typically a notch at the sides of the hollow core slabs. This complex form is made by extrusion. The zero-slump concrete is designed to maximise particle packing and friction between particles so that the extruded voids and edges retain their shape in the green state. The concrete, therefore, needs appropriate cohesive strength from the outset and before the main cement hydration occurs. In cases where moulds are used, they can be stripped immediately, and the elements can be moved to curing beds.

Quality control during production and the optimisation of concrete mixes requires representative samples that have properties similar to those produced by precast machines. Precast machines compact concrete under a high vibration frequency combined with compressive forces. A dry mix concrete is fed into the hopper of the precast machine, and the concrete is then vibrated and simultaneously compressed as the machine moves along the beds. With such dry mixes, representative cube samples for density- and compressive strength testing cannot be manufactured using the standard procedures for making concrete cube samples. This is because the tamping and vibrating table methods cannot compact the zero-slump concrete sufficiently to achieve the representative quality of precast concrete.

During preliminary testing cube samples were made using a pneumatic press. Cube moulds were damaged during the process and on inspection, the samples had more voids than the precast products. Performing quality control with core samples drilled from precast elements was also considered. However, it was found impractical for the following reasons. Firstly, the concrete sample element after coring is damaged, leading to unnecessary material waste and cost. Secondly, the profiles of hollow-core slabs and lintels with circular voids and cables do not provide a convenient area where a core of standard dimensions can be drilled. Lastly, drilling samples from green-state (newly cast concrete) products could easily damage the concrete before cement hydration and hardening are sufficiently achieved. Waiting for appropriate strength also introduces potential variability in curing and compressive strength.

In contrast, cube samples are cured in temperature-controlled baths. The controlled curing environment helps to ensure consistent results. Since one of the critical parameters that needs to be tested is green state compressive strength, and it is impossible to core a sample at green state, an alternative method is needed to produce representative samples which allow for green state testing and curing of samples that are to be tested at later intervals. SANS 5861-3 (2006) recommends using a vibrating table or an electric or pneumatic hammer to compact samples for the minimum duration necessary to achieve full compaction. The standard specifies that concrete with less than 25 mm slump should be compacted by vibration. However, the duration of vibration and compaction force is not specified. The density of the cube sample is therefore likely to differ from that of the machine products.

In South Africa, there is an industry practice whereby cube samples are made using a percussion drill, also known as a ‘small breaker’, with a steel plate welded to a sawn-off drill bit. The zero-slump concrete is placed in a sturdy 100 mm steel cube mould in layers. Each layer is compacted by the percussive action of a square plate with 99 mm dimensions to fit into the 100 mm mould with 1 mm available for movement. The plate is welded to a sawn-off tool bit. The percussive vibration compacts the zero-slump concrete so that the surface glistens with moisture after a few seconds. This method is presumed to produce concrete cubes with similar properties as concrete produced by precast machines.

Therefore, this study examines, assesses and uses the so-called “percussion drill method” to produce concrete cubes that can be used for precast concrete quality control and zero-slump concrete mix design.

1.2. Problem Statement

Zero-slump concrete specimens made by percussive action can have variable properties because it is difficult to control the degree of compaction. The force applied, the percussive frequency and the duration of compaction have an impact on the compaction achieved and consequently also on the compressive strength of a specimen.

The variability of compaction affects results obtained at precast facilities and during laboratory investigations. At precast facilities that use zero-slump concrete, it is often easier to rely on load tests of products than to test concrete quality directly. In laboratories, purpose-made devices, such as the Intensive Compaction Tester, can replicate the same compaction effort on all the specimens. However, the cost of this device prevents it from being used in industry. There is, therefore, a need for a cost-effective and efficient method to test concrete quality directly.

Achieving a “target density” can mitigate the effect of minor variation in the process caused by differing compaction force, time of compaction and frequency of the vibration. A target density can be obtained from hardened concrete samples taken from precast machines. The density measured on these samples serves to indicate variation among machines and can serve as a target density to replicate during the manufacturing of cube samples in a laboratory. This density gives a measure of mass per unit volume that needs to be compacted into a cube mould to match the chosen machine density. Aiming at and achieving a target density, therefore, helps to resolve the problem of variations in the process.

1.3. Objectives

1.3.1. Main Objective

The main objective of this study is to formulate a practical and economical procedure for quality control based on the concrete density achieved by precast machines, and to apply this method (i.e., percussion drill method) to mix optimisation

1.3.2. Specific objectives

In achieving the main objective, the following were identified as specific objectives:

- Determining the density of different precast products that used a similar specific factory mix, which is standard to the particular facility, with the aim of identifying a target density to match in the production of laboratory samples made with the percussion drill method.
- To assess the effect of partial replacement of cement with quartz flour, as a fine filler in a precast concrete mix, using the percussion drill method.

1.4. Research Questions

This study seeks answers to the following research questions:

i) Is the percussion drill method a reliable and effective tool for assessing the quality of precast concrete?
ii) Is the partial replacement of cement by volume with a fine filler for the assessed industry mix viable? This question was assessed in terms of the 28-day compressive strength. However, minimum strength criteria at green-state and 18 hours need to be met.

1.5. Research Significance

This research significantly contributes toward standardising a simple quality control- and mix enhancement tool for zero-slump concrete. The specific benefit of the fine filler replacement mixes is reducing cost and environmental impact in a specific precast production facility.

1.6. Scope and Limitations

The main focus of this dissertation is the percussion drill method using density as a guide to standardise compaction and match results to actual products. The replacement of a portion of cement with a fine filler is intended to demonstrate that the method could facilitate improvements in zero-slump mixes because it is relatively fast and simple to assess the compressive strengths at critical stages. There are many potential fine fillers to investigate and mix improvements that can still be done. For this dissertation, only three cement replacement rates, i.e. 20%, 30% and 40% were investigated along with CEM I 42.5R cement instead of the CEM II /A-L 42.5N cement that the specific factory mix uses.

The concrete density was assessed for three machines. Other machines are likely to compact the concrete to different densities. This method relies on the densities of concrete elements from each machine being confirmed. Over time machine compaction may also vary due to maintenance and wear on parts. Periodically, density from machine products should be tested.

This quality control method is not intended to replace the testing of final products. It can reduce cost and improve quality by providing more information on the zero-slump mix being used. Any variations in the concrete produced can be monitored more closely by using the percussion drill method as a part of standard quality control. The percussion drill method will give more information than product testing because the performance of a mix can be assessed in the early stages: at green state and 18-hours. A large part of the concrete performance in these stages relates to particle size distribution and particle shape of the fine particles. Improving the material use can have a significant impact on cost and environmental impact.

1.7. Thesis outline

This dissertation consists of five chapters: Chapter 1 presents the introduction to the study, the background, the problem statement, the objectives which includes the main objectives and specific objectives, the research questions, the research significance and the scope and limitations of the study. Chapter 2 presents the literature review. This chapter consists of an introduction, background to zero-slump concrete in the literature, zero-slump concrete compaction methods used in the manufacture of samples, properties of zero-slump concrete, the carbon footprint of cement and quartz flour and a closure. Chapter 3 presents the experimental methodology. This chapter consists of an introduction, the density measurements done on hardened samples from industry, a concrete mix summary which covers the materials used, the specific factory mix (standard to the specific precast facility) assessed, and the quartz flour fine filler replacement mixes. The percussion drill method is explained in detail which covers the equipment used, the concrete mixing procedure and the concrete casting procedure. The concrete compressive strength test is explained with reference to the applicable standards used. The methodology set out in Chapter 3 is summarized in the closure. Chapter 4 presents the analysis and discussion of the results. This chapter is divided into density measurement results and analysis, the specific factory mix results and analysis, the quartz flour replacement mixes results and analysis and a closure. Chapter 5 presents the conclusions and recommendations.

2. Chapter Two: Literature Review

2.1. Introduction

This chapter summarises the literature review on the following topics: background on zero-slump concrete, test methods for zero-slump concrete, the effect of quartz flour as a fine-filler in zero-slump concrete, and the carbon footprint of quartz flour compared to cement. The background on zero-slump concrete covers the applications and characteristics of zero-slump concrete. The test methods for zero-slump concrete as referenced in the literature are: the Intensive Compaction Tester, compaction by vibrating table with weight, hand compaction and SANS- and ASTM code recommendations relevant to making zero-slump concrete samples with the percussion drill method. The importance of matching the density of precast machine samples to the quality control samples is studied while emphasising the essential elements incorporated in the percussion drill method. The study also follows the SANS code's test method to examine properties of zero-slump concrete, such as density. The influence of quartz flour as fine filler in the early strength of zero-slump concrete is also reviewed. Finally, the carbon footprint of cement is examined and compared to the carbon footprint of quartz flour to motivate the substitution of a portion of the cement in the specific factory mix by quartz flour.

2.2. Background on Zero-slump concrete

Zero-slump concrete produces mass products such as kerbstones, roofing tiles, concrete paving blocks, sewage pipes, masonry blocks, lintels and hollow core slabs. This type of concrete offers early age strength characteristics and stiffness that allow for the stripping and moving of elements within relatively short periods. Therefore, this type of concrete speeds up production time. The early age strength in zero-slump concrete results from low w/b ratios, granulometric properties of the fines and the content of fines in the mix (Hüsken & Brouwers, 2012).

2.3. Zero slump concrete compaction methods

In the literature, numerous techniques are used in preparing zero-slump concrete samples. Such techniques include using a vibrating table with weight, hand compaction with impact weight, vibrating hammer compaction, and the Intensive Compaction Tester. The vibrating hammer, also known as a percussion drill, is referenced in the SANS code (SANS 5861-1:2006) and explained in detail in the ASTM code (ASTM, 2018).

Hand compaction with an impact weight prepares zero-slump concrete samples by compacting concrete with a specific impact weight in layers, whereby a certain number of blows is applied per layer. A similar method was used by Mukherjee, Mandal and Adhikari (2013) during the compaction of the zero-slump cubes, where concrete samples were compacted in three layers by 12 to 15 blows with a 600 g weight. This method standardises the compaction effort between the samples but does not relate to the compaction effort applied by precast machines during elements preparation.

The zero-slump concrete used in Mukherjee, Mandal and Adhikari (2013) was similar to the zero-slump concrete in precast applications but with higher w/b ratios, which means it was easier to compact. Sets of zero slump concrete samples with 40%, 50%, 60% and 70% fly ash and 0.35 w/b ratio were prepared and compared with high slump concrete with similar composition but prepared with a superplasticiser. The results showed that the zero-slump mixes had higher compressive strengths and were more porous than the high-slump mixes.

The Intensive Compaction Tester is favoured in the laboratory due to its advantage of standardising the compaction effort on samples. This device was developed in 1984 by Paakkinen in Finland (Hüsken & Brouwers, 2012:503). It only works with cylinder samples, where an angled disc applies pressure and rotates with a cyclic kneading action, as illustrated in Figure 2.1. The kneading action causes shear planes to develop, which leads particles within the sample to relocate relatively to each other while voids are reduced (Sørensen, 2013:658). Shear planes develop in the concrete material, and the particles move relative to each other by dynamic action while increasing the compaction. The advantage of this method is that the device gives a printout of the amount of work exerted by the machine to compact different samples to specified densities. The cylinder inclination, compaction pressure, working speed and duration can be specified and kept consistent. Improved compaction behaviour with variations in mixes might cause higher packing fractions which are compensated for by increased mass to keep the cylinders at 100 mm height. In these cases, where additional material was added, the density measurement is higher. This device is expensive compared to a percussion drill.

Vibrating tables with weights can prepare zero-slump concrete but do not work well for dry mixes. ASTM C192/C192M-19 specifies an external vibrator to use a frequency of 60Hz or higher with cylinder samples made in two layers of equal depth (ASTM C192, 2018). The ASTM C192 demands that vibration should be applied for long enough to achieve proper concrete consolidation. The vibration duration should then be kept consistent for the specific concrete, vibrator and specimen mould involved. This code does not provide procedures for matching the density of samples with those produced by precast machines.

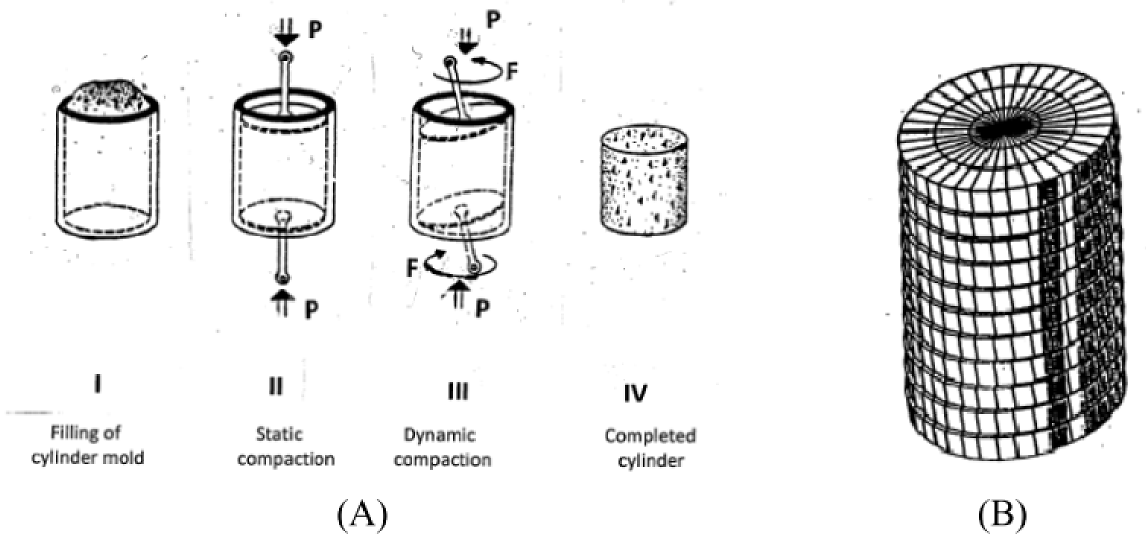

Figure 2.1: Illustration showing the operating principle of the IC-Tester A, and the shear compaction principle B. (Sørensen, 2013)

A process similar to the percussion drill method is sometimes used to compact samples for roller-compacted concrete. The ASTM C1435 describes a method that applies to other cementitious material types, such as soil-cement (ASTM C1435, 2010). The process described uses a vibrating hammer with a mass of 8.5 to 13.5 kg and provides 2000 ± 200 impacts/min. The code recommends observing the visible ring of concrete between the tamping plate and the mould wall to determine the appropriate duration of compaction. Sufficient compaction is achieved when a mortar ring forms completely around the tamping plate. In the case of the percussion drill method where steel cubes are used, there is a line of concrete visible along the perimeter of the square tamping plate, showing mortar forming similarly. This code also does not provide a method of matching the density of samples with those produced by precast machines.

In the case of the percussion drill, producing samples in three layers and topped off by a final layer produced a large variation in results. This is possibly due to the clear discontinuities that form at each layer. When the cube is turned on its side in the platen of the hydraulic press, the cubes tend to fail along the lines of discontinuity. In contrast, the cylinder samples formed by following the ASTM C1435 are tested along the same axis as that of the compaction. Variation along layers would therefore be less likely to cause early failure of samples. By increasing the number of compaction layers in the percussion drill method, it was found that variation decreased.

Carl Buchman suggests matching concrete density in *Testing Dry-Cast Products* to match concrete samples to the specific precast machines at a precast facility (Buchman, 2010). The need for the method arose due to machine adjustments, timing changes and concrete mix variations, which means samples do not necessarily match the machine-made products. Compressive strength and density determine the quality of concrete samples by matching the concrete produced by precast machines of the same concrete mix design. As described in the ASTM C192 (the vibrating table and weight), Buchman uses the same process but changes the specified endpoint by compacting until the same compacted density is achieved as in the machine-made product. The process requires obtaining hardened samples of precast products from each machine, determining the specific gravity (SG), and fabricating the testing cube with matching density.

The specific gravity of hardened samples is obtained using equation 2.1, where W1 is the initial weight of the sample before coated with wax, W2 is after waxing, and W3 is when suspended in water. The specific gravity of wax (SG wax) is taken as 0.9. The specific gravity obtained using this method reflects the as-received density.

$$\mathrm{SG} = \frac{\mathrm{W1}}{\mathrm{W2}-\mathrm{W3}-\left(\mathrm{W2}-\frac{\mathrm{W1}}{\mathrm{SG\ Wax}}\right)} \tag{2.1}$$

By multiplying the specific gravity obtained from equation 2.1 by a factor of 1000, the density of the material is obtained in kilograms per cubic meter. The exact volume of the mould is determined, and the exact mass of fresh concrete required to match the density of the machine-made sample is determined. Half the mass of the concrete is compacted until it fills the mould halfway. Then the balance of the material is compacted into the mould. Buchman used a vibrating table and weight as described in ASTM C192.

The density of the concrete samples can be tested according to SANS 6251 (2006), which prescribes testing samples with as-received water content, saturated, and oven-dried. The test procedure involves determining the mass of the as-received samples, recorded as m_0, then immersing the sample in water until the increase in mass is less than 0.2% over 24 hours. The mass of the saturated samples is then determined and recorded as m_1. The sample mass is then dried in a ventilated oven at 105° until the decrease in mass is less than 0.2% over 24 hours. The mass of the dried sample is recorded as m_2. The mass of the sample suspended in water using a hydrostatic device of balance is recorded as m_3. This is also called the buoyant mass. An accurate calculation of the volume of the samples can be made using equation 2.2, where D_w is the density of water. The density of the as-received sample can be calculated using equation 2.3, the density of the saturated sample can be calculated using equation 2.4, and the density of the oven-dried sample can be calculated using equation 2.5.

$$\mathrm{V} = \frac{m_1-m_3}{D_w} \tag{2.2}$$

$$D_o = \frac{m_0}{V} \tag{2.3}$$

$$D_1 = \frac{m_1}{V} \tag{2.4}$$

$$D_2 = \frac{m_2}{V} \tag{2.5}$$

According to the SANS code, determining the density of samples eliminates the need to use wax, unlike Buchman's method. The advantage of Buchman's method is that the density of as-received samples can be determined immediately, without the need to saturate the samples for three days to get an accurate volume.

2.4. Properties of zero-slump concrete

Zero-slump concrete is made with low water content, which means the uncompacted concrete is unsaturated and loose. The particle shapes and degree of compaction determine the internal friction. A portion of the cement content might not hydrate with the low water content, thus acting as a fine filler. A different fine filler could then be used in the place of the un-hydrated cement portion based on its physical characteristics, cost or carbon footprint. The choice of fine filler impacts early and later strength development. Certain fillers contain finer particles than cement, which influences the amount of water available for hydration, improving the internal friction and thus improving the green-state strength. Certain fine fillers are also pozzolanic, which increases the long-term strength results.

Fillers with finer particles than cement tend to increase the green state strength only up to a point. As fine particles receive more water per contact point, the capillary forces increase, up to a limit, after which more water decreases the capillary force (Sørensen, 2013:658).

The relevance of the Sørensen (2013) work to the percussion drill used in this study is in two areas: The first area is the method used for sample production, i.e., the Intensive Compaction Tester, which can be compared with the samples produced by percussion drill. The second area is the concrete mix design, where cement content was reduced by adding a fine filler while maintaining the required characteristics for precast production. The Intensive Compacter Tester was set to consistent cycles and pressure for all samples to ensure equal compaction effort. The results obtained in this work showed a correlation between air content and fresh zero-slump concrete stability. For mixes that had higher stability, more air voids were observed. The air content and the green state concrete strength increased with higher fine filler replacements because meniscus forces on particles strongly increased with decreasing water content. Even though the water content was kept consistent at a w/b ratio of 0.31 throughout the experiments, the water available at particle contact points decreased. This is because the finer particles of the fine fillers increase the effective surface area so that the same water content is spread over a greater area.

Early strength is critical for the extrusion process and cutting of pretension cables in precast production. Hüsken & Brouwers (2012:502) studied the effect of quartz and fly ash in influencing the early-age behaviour of zero-slump concrete. It was observed that spherical fly ash particles improved the packing fraction and decreased green state strength. On the other hand, quartz flour improved the green state strength due to reduced interlocking and friction between particles. Therefore, it was concluded that the granulometric properties of the fines mainly influence the early age strength of zero-slump concrete. The strength results from the internal friction and adhesive forces generated by "liquid bridges that are formed between the fines (Hüsken & Brouwers, 2012:510)." The industry mix that Hüsken & Brouwers investigated was intended for paving, and they successfully reduced the cement portion using fine fillers whilst maintaining the required performance. Hüsken & Brouwers used an Intensive Compacter Tester to make the samples. The results obtained provide a range for green-state strength from 0.04 MPa for the industry mix used in paving to 0.16 MPa for the industry mix optimised with fly ash. The green-state results obtained in the current study ranged from 0.08 MPa for the industry mix to 0.1 MPa for the 30% quartz replacement and 0.13 MPa for the 40% quartz replacement. Therefore, using quartz flour as a fine filler is convenient because quartz does not react to water and has similar granulometric properties to cement.

2.5. The carbon footprint of cement and quartz

Supplementary cementitious materials (SCM's) are materials used as partial replacement of Portland cement in concrete to improve both fresh and hardened concrete properties. Most SCM's, such as fly ash (FA), ground granulated Corex slag (GGCS), condensed silica fume (CSF) and metakaolin (MK) form predominantly different hydrates. The main hydrates are calcium silicate hydrates (CSH). The primary Portland cement hydrates are also calcium silicate hydrates. These hydrates give concrete it's hardened properties. By contrast quartz flour, which consists of silica (SiO_2), is a fine filler which may be slightly reactive (Alexander, 2021:53). The purpose of fine fillers is to reduce cost and carbon footprint of concrete by diluting the cement through partial replacement. Fine fillers improve mechanical performance by improving the packing and distribution of small particles in the concrete mix. Furthermore, fine particles can act as 'nucleation' sites for primary hydration which enhances strength. Nucleation is the initial process that occurs in the formation of a crystal in a solution where a small number of ions or molecules become arranged in the pattern characteristic of the specific crystalline solid. This process of nucleation occurring at fine filler particles is known as the 'fine filler effect.'

The carbon footprint of cement is around 985 kg of CO_2 per ton of Portland cement produced as shown in Table 2.1 (Alexander, 2021:18), which is higher than that of quartz flour. Quartz flour only has a carbon footprint based on energy requirements and probable fossil fuel usage during mining. This data was not readily available for quartz flour, so a comparable product was sought to use as an approximation. It is assumed that mining and processing the quartz has a comparable CO_2 emission to aggregate and limestone. The typical CO_2 emission per aggregate ton is 6-8 kg (Alexander, 2021:18).

Table 2.1: Carbon footprint of selected materials

Material	Typical kg CO_2 e/ton
Portland Cement (CEM I)	985
Aggregate (sand and crushed rock) and Limestone	6-8

2.6. Closure

In this section available literature on the following aspects of zero-slump concrete was reviewed: background on zero-slump concrete, test methods for zero-slump concrete, the effect of quartz flour as a fine-filler in zero-slump concrete, and the carbon footprint of quartz flour compared to cement. There appeared to be no literature on the use of a target density method combined with the percussion drill method. This research therefore fills a gap in the available information.

The potential improvement to zero-slump mixes in terms of performance, cost and carbon footprint by incorporating fine fillers or other supplementary cementitious materials as partial cement replacement was identified in the literature. This area of study has the potential to significantly improve the environmental impact of zero-slump mixes in the precast industry. The use of the percussion drill method combined with a target density, as explored in this study, has the potential to facilitate investigations into the use of supplementary cementitious material and fine fillers due to the lower cost of the percussion drill method and the relevance of the results to actual machine-made pre-cast products.

3. Chapter Three: Experimental Methodology

3.1. Introduction

This chapter describes the methods used for the laboratory investigation to achieve the main objective of this study. The study focuses on employing the percussion drill method to prepare concrete cube samples for testing the quality of precast concrete and for use in mix optimization.

This chapter consists of four sections, in addition to the introduction and closure. The first section discusses density measurements which were conducted on hardened concrete samples taken from precast elements that used a similar specific factory mix, which is standard to the specific precast facility. The second section discusses the concrete mix. This covers the materials used, the specific factory mix and the fine filler mixes which used quartz flour. The third section discusses the percussion drill method and covers the equipment used, the concrete mixing procedure and the concrete casting procedure. The fourth section discusses the compressive strength testing procedure based on relevant standards. The chapter concludes with a closure which summarizes the methodology.

3.2. Density measurement

Density measurements were done on samples cored from three different precast elements produced by different machines which used the specific factory mix. The measurements aim to find a compaction density to match the density of laboratory samples produced by the percussion drill method.

The source of the precast elements was Qcrete in Atlantis in the Western Cape province. The elements used were a 155 mm by 595 mm hollow core slab, a 145 mm by 65 mm lintel, and an 80 mm by 80 mm lintel, as shown in Figure 3.1. All three elements were cast using the specific factory mix, which is standard for the particular facility. This mix is referred to as the “specific factory mix” in this paper. All the specimens from the three samples had extruded voids which caused dimensional irregularities in the cores, as shown in Figure 3.2.

Figure 3.1: Image showing A. 155 x 595 mm hollow core sample, B. 145 x 65 mm lintel and C. 80 x 88 mm lintel.

The density measurement was conducted as described in SANS 6251:2006. Firstly, the samples were cored using a 45 mm diameter core drill to obtain a total of twenty-seven samples, nine samples from each precast element. The mass of the as-received core samples was determined and recorded as m_0. Samples were taken from all three elements. Each sample consisted of nine specimens. One set was placed in a 105°C oven for three days, another set was submerged in tap water for three days, and the last set was placed in an environmentally controlled room at 21 - 23°C, also for three days. The mass of all samples was taken after three days and recorded as m_2.

All the samples from each set were further submerged in tap water for four days, then removed, surface-dried using a damp cloth, and weighed to obtain the saturated mass, recorded as m_1. The samples were also weighed while submerged underwater. The balancing apparatus, which consists of a specimen-supporting stirrup suspended in water from a scale, was zeroed with the stirrup submerged underwater. The samples were placed on the stirrup, and the buoyant mass was recorded as m_3. Sample volume was calculated using equation 3.1. The variable D_w is the density of water, 1000 kg/m^3. The density of samples is then calculated using equation 3.2, where '*m*' stands for the mass of the sample and '*v*' its volume.

$$V = \frac{m_1 - m_3}{D_w} \tag{3.1}$$

$$\rho = \frac{m}{V} \tag{3.2}$$

Equation 3.2 was also used to determine the 'as-received state' concrete density, where 'm_0' is the 'as received' mass of the sample and 'v_o' is the volume of each sample. Similarly, the concrete densities of the saturated, oven-dry and environmental room samples were determined using equation 3.2.

Figure 3.2: Images showing a typical core sample with a void from extrusion, an uneven top surface (left), and the lintel profile in the cross-section from which it was cut (right).

3.3. Concrete mix design

The specific factory mix used in producing the two lintels and hollow core slab, on which the density measurements in section 3.2 was conducted, was prepared in the laboratory to cast concrete cube specimens using the percussion drill method for compaction. The degree of compaction was based on the density measurements described in section 3.2.

The specific factory mix has previously been made at the facility in production with CEM I 42.5R. There were however quality problems such as unacceptable cracking which may be related to the relatively high binder content in the mix. The cracking may have been related to heat of hydration or to shrinkage or to another unknown problem. The lower content of cement in the fine filler replacement mix could potentially resolve these problems. If the problem was caused by heat of hydration, less cement would generate less heat. If the cracks were shrinkage related, a lower cement content could reduce the cracks since shrinkage occurs in the paste component and less cement reduces this component. A definite answer to this is however outside the scope of this study. As stated in the research objective, the purpose of this research is to investigate whether the percussion drill method combined with a target density could be used for effective quality control and mix design.

The mix was then modified with a fine filler cement replacement. The cement used in the fine filler replacements was changed from the CEM II A-L 42.5N used in the specific factory mix to CEM I 42.5R. Three fine filler replacement mixes were made, substituting 20%, 30% and 40% of the cement volume with quartz flour. The purpose of the cement change was to improve early age strength to facilitate the reduction in the cement content of the mix.

3.3.1. Materials

The concrete was made using natural sand, 6 mm coarse aggregate and CEM II A-L 42.5N cement for the specific factory mix, which was changed to CEM I 42.5R cement for the fine filler mixes and quartz flour was used as the fine filler.

The natural source sand was mined at the Sibathathu mine in the Malmesbury area of the Western Cape Province. The 6 mm stone was a crushed granite from the Elsana quarry in the Malmesbury area.

The quartz flour was supplied by Kaolin Group and was processed at their production plant in Atlantis. It is an extra fine quartz powder described as high purity by the manufacturer (Fine Quartz, 2022).

The cement was produced by Pretoria Portland Cement (PPC). The CEM II / A-L 42.5 N cement is branded as *Surebuild PPC* and has the designation CEM II / A-L 42.5 N. The II / A-L designation means that the cement is a blend with limestone which consists of 80-94% clinker and 6-20% limestone as a supplementary cementitious material (SANS 50197-1:2013). This was used because it is the same cement used in the specific factory mix in production. The CEM I

42.5 R cement is branded as *Surecast PPC* and has the designation CEM I 42.5 R. The I designation means that it consists of at least 95% clinker. The CEM I 42.5 R is well suited for prestressed concrete applications and has a shorter early set time of 180 minutes, compared to 230 minutes for the CEM II / A-L 42.5 N (PPC, 2018). The limestone is a pozzolanic material that hardens over a longer period of time which explains why the CEM I 42.5 R with the higher clinker content reaches a higher strength sooner than the CEM II / A-L 42.5 N with the limestone content.

The quartz flour produced by Kaolin Group at their Atlantis facility was selected due to the assumed similarity in particle shape, size and texture compared to cement and because quartz is an inert material. The quartz flour is assumed to have a shape factor (ξ) of about 1.4 (Hüsken & Brouwers, 2012:504) compared to a shape factor of around 1.68 for CEM I 52.5 N (Hunger & Brouwers, 2009). The shape factor describes how angular a particle is compared to a perfect sphere. It is the expression of the ratio of the effective surface area of a particular particle to the surface area of an ideal sphere of equal volume. A value (ξ) equal to 1 would represent perfectly spherical particles. Quartz flour also has a similar particle size distribution compared to cement, as shown in Figure 3.3. These values may differ for the specific quartz flour and cement used. The probable similarity was used to inform the choice of fine filler. The testing of the quartz flour and cement used falls outside the scope of work for this paper. The objective of the work i.e. to determine whether quality control and mix design can effectively be done using a percussion drill combined with a target density method, would be achievable even if the particles were slightly dissimilar.

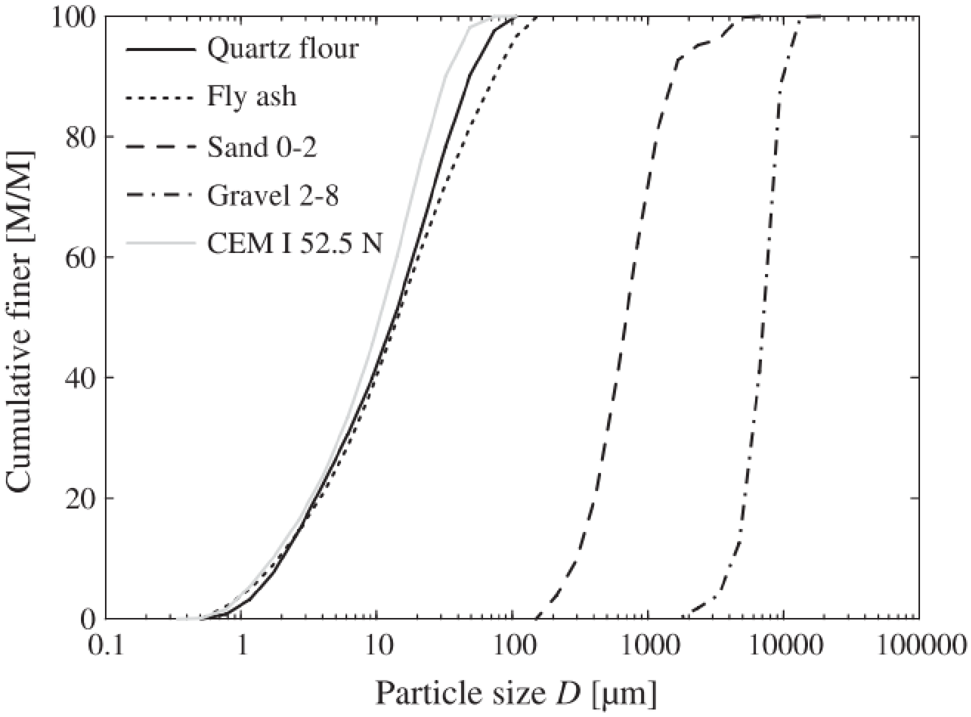

Figure 3.3: Graph showing particle size distribution of quartz flour compared to cement, sand, fly ash and gravel (Hüsken & Brouwers, 2012).

3.3.2. Specific factory mix

25 kg of the specific zero-slump factory mix was prepared to match the 2444 kg/m^3 density measured in section 3.2. A total of nine cubes of 100 mm dimension were filled by compaction with concrete to achieve a mass of 2.44 kg each using the percussion drill method. The total mass of concrete required for nine cubes was about 22 kg. However, about 10% of the concrete mass was added and rounded to 25 kg to account for material loss during casting. The water-cement ratio of 0.25 was used in this mix design, and a mass balance scale of 5 g accuracy was used for mass measurements. Table 3.1 shows the specific factory concrete mix used as a standard mix in the precast facility and this study.

Table 3.1: Specific factory mix proportions.

	kg/m^3	Nominal Proportions (ratio)	Batch (kg)
Sand	959	2.53	9.81
Stone	1010	2.67	10.33
Cement (42.5N)	379	1.00	3.87
Water	96	0.25	0.98
Total	2444.00	6.45	25.00

3.3.3. Quartz flour mixes

Quartz flour is significantly less dense than cement, with a relative density of 2.65 compared to cement's relative density of 3.15. The quartz particles are assumed to have similar surface texture, shape and size as cement (Hüsken & Brouwers, 2012:502). However, quartz is inert and does not undergo any pozzolanic reaction. The CEM I 42.5R was used in this mix design because it has a higher clinker content which encourages earlier reaction and strength gain.

The same compaction used for the specific factory mix in section 3.3.2 was applied to prepare the concrete samples for the quartz flour mixes. In order to match the density of 2444 kg/m^3 in section 3.3.2, 2.444 kg of material was compacted into a 100 mm^3 cube mould. Thus, the density obtained by density measurement in section 3.2 matched the cube samples for the industry mix.

Where a cement replacement was used, the mass of the replacement was divided by the density of cement (3.15 x1 000) to give a volume. This volume multiplied by the relative density of the replacement and scaled by 1 000 gives the new mass of the replacement portion of the mix. The sum of all the constituents gives the new density. The reason for using this method as opposed to a simple mass replacement by equal mass is that the volumes were kept consistent in order to keep the compaction consistent. Table 3.2 shows the quartz flour replacement mixes with the reduced densities.

Table 3.2: Quartz flour mix proportions

	Quartz (20%)		Quartz (30%)		Quartz (40%)	
	kg/m^3	Batch (kg)	Kg/m^3	Batch (kg)	Kg/m^3	Batch (kg)
Sand	959	9.86	959	9.88	959	9.91
Stone	1010	10.38	1010	10.41	1010	10.43
Cement (42.5R)	303.20	3.12	265.30	2.73	227.40	2.35
Quartz Flour	63.77	0.66	95.65	0.99	127.54	1.32
Water	96	0.99	96	0.99	96	0.99
Total	2432	25.00	2426	25.00	2420	25.00

3.4. Percussion drill method

The zero-slump concrete prepared for the specific factory mix and quartz flour replacement mixes have the same water content, 96 l/m^3, and a w/b ratio of 0.25. Due to this significantly low w/b ratio and water content, these mixes are extremely dry, which results in little cohesion, as observed in Figure 3.4 by the loose appearance of the mixed concrete. When dealing with such concrete in the industry, precast machines, which combine vibration and compression, are applied to compress and compact the mix. Therefore, in this study, the percussion drill method aims to mimic this action to produce cube samples similar to precast machine-produced products in terms of compaction and density.

3.4.1. Equipment used

The equipment used for casting and compacting concrete cubes is shown in Figure 3.4. The percussion drill used was a Hilti TE-45 rotary percussion drill labelled “A.” This drill was explicitly chosen because its percussion function can be operated separately from the rotation function. It is colloquially called a “small breaker.” A modified tool bit for the percussion drill labelled “B” was a chisel bit modified by sawing off the tip and welding a sturdy (10 mm thick) 99 mm by 99 mm plate to the tip. The cube mould used was cast iron labelled “C.” These are sturdy moulds that are resistant to surface damage from the vibration of the steel plate. They strip conveniently into four parts to remove newly cast samples without damage. A 350-litre electric pan mixer was used for concrete mixing. The mixed concrete is labelled “D.”

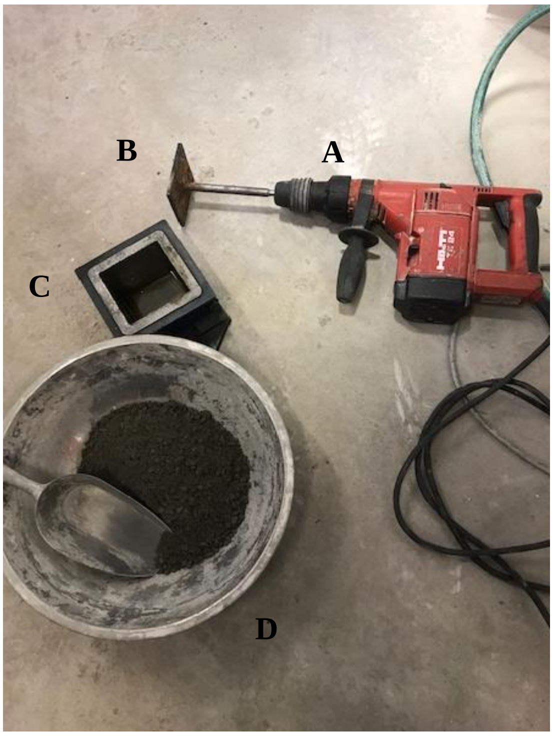

Figure 3.4: Image showing A. the percussion drill, B. the modified tool bit, C. a steel cube mould and D. the zero-slump concrete used

3.4.2. Concrete mixing procedure

The dry aggregate, cement and quartz flour in the replacement mixes were placed in the 350-litre electric pan mixer and thoroughly mixed before the water is added. It was mixed continuously until all the material was thoroughly mixed. This took around three minutes.

3.4.3. Concrete casting procedure

Before concrete mixing, the mass of each mould was weighed and recorded accordingly. The zero-slump concrete was then mixed in an electric pan mixer. 2.44 kg of concrete was weighed and compacted into the mould in six approximately equal layers to achieve the target density and the same compaction as the machine samples. Each layer was compacted by vibration for three to five seconds. When the plate is lifted, the top of the concrete should appear smooth. The final layer was placed in a dome shape and then vibrated to level with the top of the cube mould. The mould filled with concrete was weighed to ensure that the concrete mass was 2.44 kg. The de-moulded samples were weighed again to confirm that the target compaction was achieved. Figure 3.5 shows a sample de-moulded immediately after compacting.

This study produced nine cube specimens for each mix design. Three samples were demoulded immediately for the green-state strength test. The remaining six samples were covered with plastic to limit moisture loss to the atmosphere. After 18 hours, the remaining six samples were demoulded and weighed. Three of these samples were tested for the 18-hour compressive strength. The remaining three samples were kept in a temperature-controlled water bath at 23° for the 28-day compressive strength test.

Figure 3.5: De-moulded sample for the green state strength test

3.5. Compressive strength test

Compressive strength tests were performed in accordance with SANS *Concrete tests - Compressive strength of hardened concrete* (SANS 5863:2006).

The dimensions of the cubes were 100 mm on all sides. The cubes were inserted into the platen of the press on their sides to ensure that the sides in contact with the press were even, as shown in Figure 3.6. The green-state strength test was done within an hour of compacting and the samples for the 18-hour and 28-day tests were kept in the moulds, covered with plastic. At 18 hours, the 18-hour samples were tested and the 28-day samples were placed in curing baths.

The mass was determined before the sample was placed in the platen of the compression testing machine, with the specimen centred. This final mass measurement was used to determine specimen densities. The loading rate was set to 0.3 MPa/s ± 0.1 MPa until the specimen failed. The compression testing machine used was a 2000 kN capacity Amsler machine, an electro-hydraulic-type machine controlled by hand-operated valves. Equation 3.3 was used to calculate the compressive stress (f_{cu} in MPa) where F is the maximum load (in Newton) at failure and A_c the cross-sectional area (in mm^2) of the specimen (SANS 5863:2006).

$$f_{cu} = \frac{F}{A_c} \tag{3.3}$$

Three specimens were tested at each time period and the average value was used. For the test to be valid, the range of strengths within the set of three cubes must not exceed 15% of the average (Gill Owens, 2013:85). Variability was recorded in terms of standard deviation.

Figure 3.6: Image showing a cube sample centred in the platen of the hydraulic press (Amsler compression tester)

3.5. Closure

This chapter consists of five sub-sections. The introduction presented the scope of the chapter. The section on density measurements described the relevant procedure in the SANS code to determine the volume of an irregularly shaped hardened concrete sample using the buoyant weight of the sample. This volume is used to calculate an accurate density. The concrete mix design section describes the materials used along with their sources, the specific factory mix, its density and proportions, and the fine filler replacement mixes. The section on the percussion drill method described the equipment used and the compacting procedure. Finally, the SANS procedure for testing the compressive strength of cube samples was summarised.

4. Chapter Four: Analysis and Discussion of Results

4.1. Introduction

This chapter analyses and discusses the results obtained in the laboratory investigation. The chapter aims to provide a basis for a standard test method using the percussion drill method to manufacture cube samples that can be applied to quality control and concrete mix development. The chapter is divided into three sections, i.e., density measurements and analysis, specific factory mix results and analysis, and quartz flour replacement mix results and analysis.

4.2. Density measurement results and analysis

Density measurements were conducted on samples from products produced in the specific precast factory with the specific factory mix, which is standard for this facility. Specimens from each sample were subjected to different environmental conditions in terms of humidity. Three specimens from each sample were tested after exposure to the following environmental conditions: as-received, saturated, oven-dried, and environmental room. Three specimens for each density measurement were taken from three precast products produced by different machines but with a similar specific factory mix. As explained in Chapter 3, the precast elements used were: a 155 mm by 595 mm hollow core slab, a 145 mm by 65 mm lintel, and an 80 mm by 80 mm lintel. The averages of three density measurement results for each parameter are shown in (values in kg/m3).

The difference in density between the oven-dried samples and the saturated samples ranged from a low value of 3.9% for the 155 x 595 mm hollow core sample to a high value of 6.1% for the 145 x 65 mm lintel sample. Since the density difference between oven-dried and saturated samples reflects the mass of water lost due to oven-drying the sample, this mass loss needs to be converted to a volume to determine the porosity. The volume occupied by water is summarized in Table 4.1. The water absorption values show that the concrete has many voids and pores. Entrapped air voids can clearly be seen in Figure 4.2.

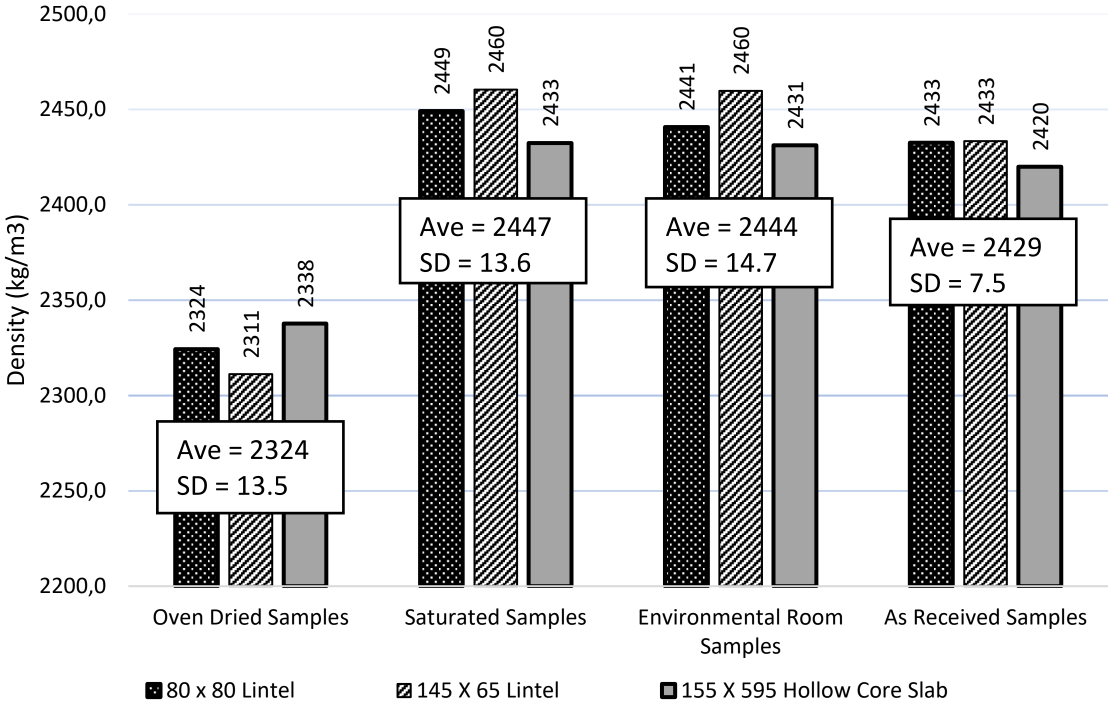

Figure 4.1: Density measurement results for each parameter (values in kg/m^3)

Table 4.1: Water content of samples obtained from density difference between saturated and oven dried state.

Element	Water content (%)
80x80 mm lintel	12.5
145x65 mm lintel	15.1
155x595 mm hollow core slab	9.5

The density difference between the saturated and environmental room samples was 0.339% for the 80x80 lintel, 0.024% for the 145x65 lintel, and 0.053% for the 155x595 hollow core slab. These small differences show that the pores and voids are close to saturation for the environmental room samples. The difference between the as-received and environmental room samples was 0.34% for the 80x80 lintel, 1.08% for the 146x65 lintel and 0.47% for the 155x595 hollow core slab.

Figure 4.2: Image showing visible entrapped air (compaction void) on a core sample used in density measurements

Therefore, in this study, the environmental room density was selected to represent the density of concrete designed and cast in the laboratory for this study. With this density, the mass of concrete ingredients in the concrete mix can be approximated. The reason for the decision was that variations in the atmospheric humidity cause slight density variations of the hardened samples. Also, it was thought that keeping the samples in an environmentally controlled room with constant humidity would introduce standardisation. However, the difference between the environmental room samples and saturated samples is only 0.1%, which does not justify using an environmental room compared to the as-received samples. As a practical tool for quality control and to assess the effect of mix modifications, the as-received samples should be sufficient.

The difference between the maximum and minimum density for the environmental room samples, i.e., 2459.8 kg/m^3 (145x65 lintel) and 2431.2 kg/m3 (155x595 Hollow Core Slab), is 28.6 kg/m^3. This difference represents 1.1% of the average value (2444 kg/m^3). This number was deemed sufficiently small to justify the use of an average value and not to make samples representing each machine in this case. The average density of the environmental room samples selected for the current investigation was 2444 kg/m^3. This density was used as a target density to prepare the laboratory mix design.

4.3. Specific factory mix results and analysis

4.3.1. Sample Densities

Table 4.1 shows summarised results of the concrete sample densities after casting and demoulding. The mass of mixed concrete required to achieve the target density of 2444 kg/m^3 was 2.44 kg for the 100 mm cube mould. The observed density variations were due to material loss during the compaction and mass added to compensate for the losses, which resulted in a slightly higher density than the target.

The highest density was 2500 kg/m^3 for sample XB5, which is higher than the target density by 2.29%. The second-highest density was 2450 kg/m^3 for samples 1, 3 and 6, with a difference of 0.25% from the target density. Due to the percussive action, this slight density reduction was due to fresh concrete sticking on the compaction plate and some falling on the floor while compacting the last layer. In some cases, more concrete had to be added to achieve the target density, which resulted in a 2.9% higher density than the target density for sample 5.

The lowest density obtained was 2420 kg/m^3 for sample 2, which is 0.98% lower than the target density. Initially, this sample had a density of 2470 kg/m^3 measured by the mass difference between the mould containing the sample and the mould alone. However, it lost some concrete due to edge damages during the demoulding. The second-lowest density value was 2435 kg/m^3 for sample 9, which differs from the target density by 0.37%.

Demoulded samples tended to be slightly lighter than the moulded mass due to small material losses during demoulding. The most significant difference was observed for sample 2, which had damaged concrete edges at the top and loose concrete grains from the sides, representing about 2% of the intended mass. The lost grains were brushed away after de-moulding the sample, see Figure 4.3.

The sample standard deviation is 22.5. One standard deviation in this population represents 0.9% of the target value. This means 66.8% of the results fall in the range of 2417.5 to 2462.5, an increase or decrease of less than 1%.

Table 4.2 Concrete density determination

Sample label	Actual sample density (After demoulding) (kg/m^3)
1	2450
2	2420
3	2450
4	2445
5	2500
6	2450
7	2430
8	2440
9	2435
Standard Deviation (SD)	22.5

4.3.2. Green state strength of specific factory mix

The green state strengths of concrete, measured immediately after compaction, are presented in

. After demoulding the samples, they were put into the compressive machine and tested. In the green state the samples needed to be handled carefully to avoid damage since they were fragile in this state. A de-moulded cube is shown in Figure 4.3. The strength obtained from this test gives an indication of the concrete's ability to retain its extruded shape, since the compaction and particle packing in early age determine early age strength and this is related to the ability of the mix to retain the extruded shape until the concrete is set.

Table 4.3: Green State Strength of industry mix (Within 1 hour of casting)

Sample label	Green state strength, f_{cu} (MPa)
1	2.5
2	1.5
3	1.8
Average	1.9
Standard Deviation	0.51

Sample 1 had the highest green state strength of 2.5 MPa, and it also had the highest density value (2500 kg/m^3). The remaining samples had similar densities and compressive strength values: 2440 kg/m^3 and 1.5 MPa for sample 2 and 2435 kg/m^3 and 1.8 MPa for sample 3, respectively. The correlation between green state compressive strength and compaction can be explained by the increased friction between particles at higher densities and an increased number of contact points, increasing the capillary forces (Hüsken & Brouwers, 2012).

Figure 4.3: Image showing de-moulded sample for the green state strength test.

4.3.3. 18-hour compressive strength of industry mix

The 18-hour compressive strength results had an average value of 40.7 MPa, as shown in Table 4.4. The target value for the specific prestressed hollow core slab application used for the concrete is 30 MPa at 18 hours.

4.3.4. 28-day compressive strength of industry mix

The 28-day compressive strength results had an average value of 66.5 MPa, as shown in Table 4.4. The design value used for the specific hollow core slabs is 50 MPa.

Table 4.4: 18-hour and 28-day compressive strength of industry mix

Sample	**18-hour strength f_{cu} (MPa)**	**28-day strength f_{cu} (MPa)**
1	43.7	70.6
2	42.4	61.0
3	36.0	68.0
Average	40.7	66.5
Standard Deviation	4.1	5.0

4.3.5. Discussion

The specific factory mix compressive strength results are significantly higher than the minimum performance requirements in terms of 18-hour and 28-day compressive strength. The low w/b ratio of 0.25, combined with a cement content of 15.5%, indicates a significant amount of un-hydrated cement in the concrete. Based on this, the investigation with fine filler cement replacements is required to reduce the cement content in the concrete.

4.4. Quartz flour replacement mixes

The quartz flour mixes were prepared by replacing three different percentages of the cement content by volume with quartz flour, namely 20%, 30% and 40%. The cement was also changed from CEM II /A-L 42.5N to CEM I 42.5R for these mixes. The results are discussed below.

4.4.1. 20% Quartz flour

The 20% quartz flour replacement samples were compacted to achieve a density of 2430 kg/m^3. The lower target density of the 20% replacement compared to the specific factory mix's target density was outlined in Section 3.3.3 which showed that the volume replacement 20% cement by 20% quartz flour, resulted in the lower target density value due to the lower relative density of quartz flour compared to cement. The compressive strength results of the 20% quartz flour concrete at green state, after 18 hours, and after 28 days are presented in Table 4.5. The average compressive strength at the green state was 2.8 MPa, higher than the 1.9 MPa result for the specific factory mix.

Table 4.5: Compressive strength results of 20% Quartz Flour concrete at green state, after 18 hours, and 28 days

Concrete sample label	Green-state strength f_{cu} (MPa)	18-hour strength f_{cu} (MPa)	28-day strength f_{cu} (MPa)
1	3.3	52.3	64.5
2	2.9	44.5	42.3*
3	2.2	45.3	56.4
Average	2.8	47.4	60.5**
Standard Deviation	0.56	4.29	5.73

*Rejected result due to defect in specimen, In** Adjusted value

The 18-hour compressive strength result had an average value of 47.4 MPa, significantly higher than the 30 MPa minimum requirement for destressing hollow-core slabs. This strength is also significantly higher than the 40.7 MPa achieved by the specific factory mix.

This higher strength is associated with changing cement from CEM II / A-L 42.5 N for the specific factory mix to CEM I 42.5 R for the quartz flour mixes. Quartz flour could also increase strength due to the 'fine filler effect.' The particles assist in improved particle packing and also become nucleation sites for crystal formation, which assists the development of the calcium silicate hydrate (CSH) crystals formed by the cement. The increased strength is likely the result of a combination of these factors.

The 28-day strength result for the 20% quartz flour replacement mix has an average value of 60.5MPa. The variation among the three results is very high, with a 22.2 MPa difference between the highest value of 64.5 MPa and the lowest of 42.3 MPa. In South African practice, a variation exceeding the mean value by 15% should render the outlying value not valid (Alexander, 2021:711). Based on this method, both the highest value (64.5 MPa) and the lowest value (42.3 MPa) exceed the mean (54.4 MPa) by more than 15%.

Figure 4.4: Image showing sample Q2H, which has two visibly uneven corners and 10 g of lost material.

However, the low value of 42.3 MPa was excluded for two reasons. The first reason was the trend observed in the higher quartz replacement mixes. When considering the mean compressive strength at 28 days for the 30% quartz replacement (60.8 MPa) and the 40% quartz replacement (54.1 MPa), it is considered that the low value of sample 2, of 42.3 MPa, is an anomaly and should therefore be rejected. One would have expected a value higher than that of the 30% and 40% replacements for the 20% replacement due to the higher cement content. The second reason for rejecting sample 2 is the specimen's physical condition. Figure

4.4 shows an image of sample 2 with two corners of visibly uneven material. This defect likely reduced the area in contact with the machine platen. A reduced area would increase the stress (σ) experienced by the sample under the same force. The specimen was, therefore, likely to fail at a lower load. The remaining values of 64.5 MPa for sample 1 and 56.4 MPa for sample 3 differ from their average value (60.5MPa) by less than 15%, which is acceptable.

4.4.2. 30% Quartz flour

The compressive strength results of the 30% Quartz Flour concrete at the green-state, after 18 hours, and 28 days are presented in Table 4.6. The green state strength result for the 30% replacement mix was 1.1 MPa, significantly lower than the 2.8 MPa for the 20% replacement mix. The 18-hour result was 38.7 MPa, significantly lower than the 47.4 MPa result for the 20% quartz flour cement replacement. Quartz is inert, which explains the trend where increasing quartz content correlates to decreases in compressive strength. The 28-day test result for the 30% replacement mix was 60.8 MPa, which is similar to the 28-day result of the 20% replacement mix, which was 60.5 MPa.

Table 4.6: Compressive strength results of 30% Quartz Flour concrete at green state, after 18 hours, and 28 days

Concrete sample label	Green-state strength f_{cu} (MPa)	18-hour strength f_{cu} (MPa)	28-day strength f_{cu} (MPa)
1	1.1	40.0	64.0
2	1.0	38.0	56.5
3	1.3	38.0	61.8
Average	1.1	38.7	60.8
Standard Deviation	0.15	1.15	3.86

4.4.3. 40% Quartz flour

Compressive strength results of 40% Quartz Flour concrete at green state, after 18 hours, and 28 days are presented in Table 4.7. The green state strength result for the 40% replacement mix was 1.3 MPa, similar to the 1.1 MPa result for the 30% replacement mix. The 18-hour result was 34.2 MPa, which is lower than the 38.7 MPa result for the 20% quartz flour cement replacement.

The further increase in the quartz component corresponds with a further decrease in the strength gain. The 34.2 MPa result is still above the minimum 30 MPa requirement at 18 hours to destress the pre-tensioned slabs. The 28-day result of the 40% replacement was 54.1 MPa, which is significantly lower than the 28-day result of the 30% replacement mix, which was 60.8 MPa. However, the result is still above the 50 MPa design requirement.

Table 4.7: Compressive strength results of 40% Quartz Flour concrete at green state, after 18 hours, and 28 days

Concrete sample label	Green-state strength f_{cu} (MPa)	18-hour strength f_{cu} (MPa)	28 days strength f_{cu} (MPa)
1	1.3	36.5	56.0
2	1.4	34.1	50.2
3	1.1	32.1	56.0
Average	1.3	34.2	54.1
Standard Deviation	0.15	2.2	3.35

4.4.4. Discussion

The 40% quartz replacement mix met the minimum criteria for producing hollow-core slabs at 18 hours and 28 days, even though the results were lower than the specific factory mix, 20% and 30% quartz replacement mix, as observed in Figure 4.5. An increase in quartz flour correlated to a decrease in compressive strength.

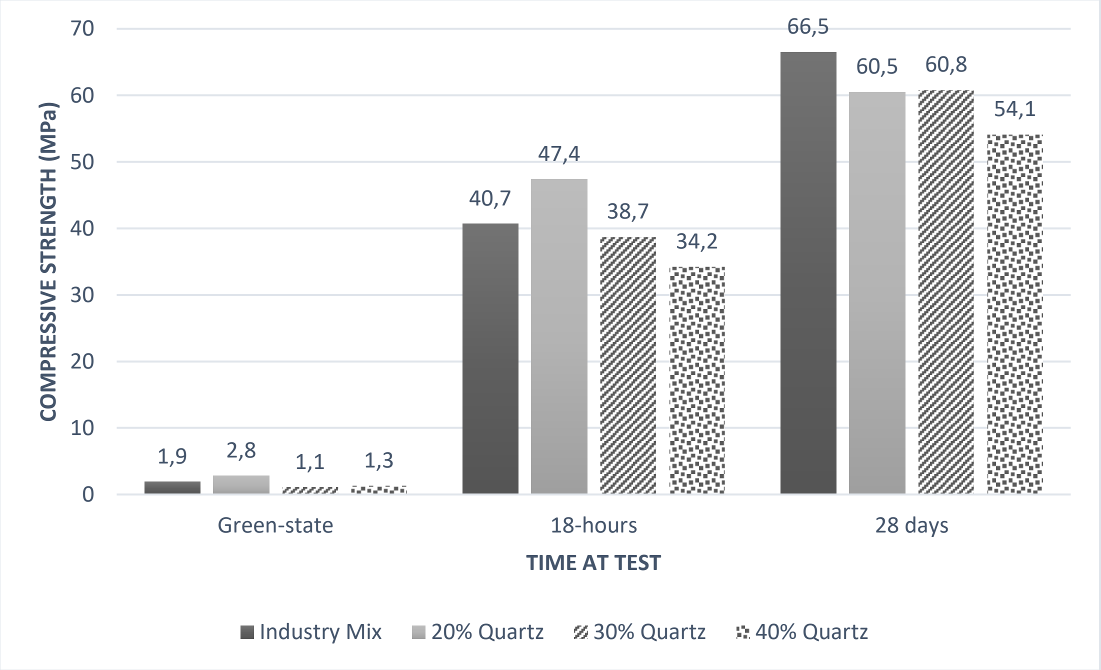

Figure 4.5: A summary of the results for the four zero-slump mixes produced in the laboratory

Compared to the specific factory mix, the highest 18-hour value for the 20% quartz flour replacement can be explained by the change in cement from CEM II / A-L 42.5 N to CEM I 42.5

R. The high 28-day strength for the specific factory mix is due to this mix having the highest cement content. Once the cement has hydrated, the specific factory mix reaches the highest compressive strength value.

Even though the 40% replacement mix meets the minimum requirements for use in production, the recommendation for a trial replacement in a production run is 33%. There are two main reasons for this recommendation. The first reason is that there needs to be some robustness in the concrete mix to compensate for environmental conditions in the precast facility that are not controlled to the extent that conditions for laboratory samples are controlled. Temperature variations and humidity variations are likely to be less controlled at the production facility. The second reason is that batching is done with 50 kg cement bags. A batch of the specific factory mix is made with three bags (150 kg) of cement. Therefore, only one bag needs to be substituted for quartz flour and all the other components can remain consistent. This will reduce the possibility of errors occurring in production.

4.5. Carbon footprint

Given that quartz is ground to a fine powder, the CO_2 emissions are assumed to be at the higher end range of 8 kg per ton as per Table 2.1. A 40% cement replacement by quartz flour in the specific factory mix was found to be appropriate for use since the green-state strength (0.13 MPa), 18-hour strength (34.2 MPa) and 28-day strength (54.1 MPa) were found to be acceptable for use in hollow core and lintels. At 40% replacement, the reduction in cement mass replaced by quartz flour in a compacted cubic meter of concrete is 151.6 kg, which emits about 149.3 kg of CO_2 for cement and 1.2 kg of CO_2 for quartz. Therefore, one can conclude that the nett reduction in carbon emissions (saving on CO_2 in the cement portion minus the CO_2 requirement of the quartz flour) with the proposed 40% quartz replacement will be 148.1 kg of CO_2 per compacted cubic meter of concrete. For the recommended 33% replacement a nett reduction in carbon emissions of about 113.1 kg /m^3 of compacted concrete can be expected.

4.6. Closure

This chapter was divided into an introduction and four sections. The introduction presented the scope and context of the chapter. The density measurements done on samples produced by three different precast machines using the same specific factory mix were discussed in the second section. The density measurements showed minimal variation among the three machine samples. The samples that were kept in an environmentally controlled room at constant humidity and temperature were selected to represent the density of the concrete. The third section describes the same specific factory mix prepared in the laboratory using the percussion drill method and matching the average density of the three machine samples kept in the environmental room. Samples were tested for compressive strength at green state, after 18 hours and 28 days of curing. The density measurements showed significant pores and voids in the hardened concrete. The very low w/b ratio combined with the observed porosity indicated that a large portion of the cement was unhydrated and functioned as a fine filler in the mix. Therefore, it made sense to investigate replacing a portion of the cement with a fine filler. Quartz flour was selected due to the similarities in particle shape and size to cement, its relatively low cost and the fact that quartz flour is mostly inert. In the fourth section, the specific factory mix was modified by changing the cement from CEM II /A-L 42.5 N to CEM I 42.5 R and making three batches where 20%, 30% and 40% of the cement was replaced by volume with quartz flour. The three replacement mixes were tested for compressive strength at green state, 18 hours, and 28 days. An increase in quartz flour corresponded to a decrease in compressive strength. However, the highest replacement mix (40% quartz flour) still met the minimum criteria required for precast production of zero slump hollow core slabs and lintels.

5. Chapter Five: Conclusions and Recommendations

5.1. Introduction

This chapter draws conclusions based on the main objectives of this study outlined in chapter 1, the gaps observed in the literature review chapter (chapter 2), the methodology described in the experimental methodology chapter (chapter 3), and the findings obtained in the experimental results and analysis (chapter 4). The main objective of this research was to determine the effectiveness and limitations of the percussion drill method to produce concrete cube samples for zero-slump concrete. In achieving the main objective, the specific objectives were assessed, namely assessing the effectiveness of the percussion drill method as a quality control tool and its potential application to mix enhancement for the use of zero-slump concrete used in the precast industry were assessed. Therefore, this chapter analyses whether this study has met its specific and main objectives. The chapter concludes by outlining the main conclusions and recommendations for future study and application of the percussion drill method.

5.3. Specific objectives

The specific objectives were to assess the effectiveness of the percussion drill method as a quality control tool and its effectiveness as a tool for mix enhancement. The former specific objective was assessed by density measurements and producing representative concrete cube samples from the production concrete mix, referred to as the specific factory mix, and the latter was assessed in fine filler replacement mixes.

5.4. Density measurement

Density measurement formed the basis of sample manufacturing. Density is important because its variation significantly influences the early age strength of zero-slump concrete samples. The value of this research is to combine a target density with the percussion drill method. As explained in chapter 2.3, the only method the author could find similar to the percussion drill method with a detailed description was the ASTM C1435, which produces samples for roller compacted concrete and can be applied to other zero-slump concrete applications. The percussion drill and compaction plate used were similar to the percussion drill method in this study. In this method however, the observation of a mortar ring around the compaction plate is used to determine if compaction is sufficient. This measure causes high variability in early age strength results when applied to the specific factory mix that was assessed and when tested at green state and 18 hours. Therefore, it is essential to match density among samples that represent a machine, and it is also essential to check whether there are significant variations in density among different precast machines. This is because a precast production facility can use the zero-slump concrete density of precast products manufactured by a specific machine and taken at regular intervals to give information on the machines’ quality and indicate if there are problems with specific machines.

5.4.1. Representative cube samples and strength

Samples made using the percussion drill method and matching their densities with the machine products’ densities can indicate green state strength, which relates to the concrete’s ability to retain its extruded shape before any concrete hydration takes place. The 18-hour strength is essential for destressing when cable slip is a potential problem if the minimum 30 MPa target strength is not achieved. The 30 MPa value is often used in precast and post-tensioned design as a benchmark value for destressing cables or tendons. This value may, however, differ for different situations based on the force applied to the cables and the surface area of the cable in contact with the concrete. The 28-day strength offers confirmation that the desired design strength has been achieved.

Generally, similar procedures adapted for higher slump concrete, used in the ready-mix industry, and acceptance criteria as per SANS 5861 are applied for curing and crushing cube samples produced by this method. For example, the percussion drill method as a quality control tool will use concrete from the same batches used in production, which is similar to producing concrete cubes in ready-mix facilities with specified allowable variations among samples, specified maximum deviation from the average target strength, and statistical analysis that should be done over time.

5.4.2. Fine filler replacement

The three salient time periods at which compressive strength tests were conducted were green state, 18 hours and 28 days. Quartz flour was selected as the fine filler to replace 20%, 30%, and 40% of the cement content combined with a change in cement from CEM II/A-L 42.5N to CEM I 42.5R. Quartz flour tended to decrease the compressive strength in all three phases, with higher replacement values correlating to lower compressive strength results and vice versa. However, at the highest cement replacement, i.e., 40%, the results still exceeded the minimum requirements for hollow core slabs and lintels produced by zero-slump concrete. This indicates that a percussion drill is an effective tool for mix development. Therefore, the specific objective of optimising the zero-slump specific factory mix as used in the specific precast facility was successful and thus, could result in significant financial savings and a reduction in the carbon footprint of the precast facility if a portion of cement is replaced by quartz flour. As a starting point, a replacement of 33% is recommended for trial in production. The reasons for the recommendation are:

i. Batches are based on cement bags. The current production uses 3 bags of cement on every batch. Replacing one bag with quartz flour is a simple change to the production routine.
ii. The value is significantly lower than 40% which introduces some robustness to compensate for the environment being less controlled than the laboratory in terms of temperature and curing.

It was calculated that the 40% cement replacement by volume with quartz flour could reduce the nett carbon emissions by 151.1 kg per compacted cubic meter of concrete. The recommended replacement for the trial production of 33% cement replaced by quartz flour is likely to result in a nett reduction 113.1 kg carbon emission per compacted cubic meter of concrete.

5.5. Achieving project objectives

The percussion drill method proved to be successful in making cube samples with zero-slump concrete. The experimental investigation showed certain aspects of the process that need to be carefully controlled to improve the quality of the results. These aspects are density and homogeneity. It was observed that density was a critical variable that must be kept consistent to obtain reliable results. Along with keeping density consistent, it was also found that creating homogenous samples reduced the variation among samples in terms of compressive strength. Samples compacted in six or more layers tended to produce consistent compressive strength results with less distinct discontinuities visible between layers.

The percussion drill method is more cost-effective and practical than purpose-built machines such as the Intensive Compaction Tester. Both tests need to relate to the density of precast products. The advantage of this is that the occasional density tests on products produced by precast machines will detect mechanical problems in machines that influence the compaction of the concrete. Both test methods allow for green state strength tests on the concrete, which is impossible with samples cored from machine-made products. An advantage of the Intensive Compaction Tester that the percussion drill cannot provide is the ability to measure the amount of work required by the machine to compact a sample to a specified density (Sørensen, 2013:659).

Given that the equipment required for the percussion drill method is easily obtained and at a significantly lower cost compared to the Intensive Compaction Tester, the percussion drill method is a useful and practical tool for quality control and mix optimisation of zero-slump concrete. The Intensive Compaction Tester can only produce cylinder samples. In the South African context, the use of cubes is simpler because the industry uses cubes predominantly in quality control of higher slump mixes. Therefore, there is no need to convert the cylinder strength result to an equivalent cube strength result.

5.6. Research questions

The first research question which asked whether the percussion drill method is a reliable and effective tool for assessing the quality of precast concrete can be answered in the affirmative. The process of measuring the density of hardened concrete samples from different precast machines can also help to identify problems with machines which will further assist in quality control.

The second research question which asked whether the partial replacement of cement by a fine filler in the specific factory mix is viable, can also be answered in the affirmative. A replacement of 33% of the cement in the industry mix is recommended based on the test results.

5.7. Conclusions

The following are the specific conclusions of this study:

i. The percussion drill method is a cost-effective and practical method of making concrete cube samples for quality control and mix optimisation of zero-slump concrete.

ii. The testing procedure of the percussion drill method must comply with the same statistical approach used on high-slump mixes.
iii. The density and homogeneity of cubes need to be consistent to obtain reliable results.
iv. The percussion drill method can be applied to mix design and enhancement processes.
v. Quartz flour can effectively replace a portion of cement in the specific factory mix used at the precast facility.

5.8. Limitations of the method

The limitations of the percussion drill method are:

i. The method is time-consuming compared to making high-slump concrete cubes.
ii. The compaction effort or work cannot be measured as the Intensive Compaction Tester does.
iii. The procedure needs to be done as meticulously as possible to reduce variation in densities, which results in less reliable results.

5.9. Recommendations

The following are the recommendations:

i. Density is critical in matching cube samples to machine samples to ensure that other concrete properties, such as compressive strength, are comparable. It is recommended that density tests are conducted on the precast products of each machine at regular intervals.
ii. Variation in density of the cube samples relates to variation in compressive strength among the samples. Therefore, the density of samples must be kept the same to provide reliable results.
iii. Homogeneity of compacted material is important since samples with visible discontinuities between compaction layers tended to fail at lower compressive strength values. It is recommended that samples be compacted in six or more layers of zero-slump concrete mix since this produces samples with less variation in compressive strength results.

iv. The compaction plate welded to the machine bit needs to be reasonably thick. A 3 mm plate was found to compact less effectively than an 8 mm plate.

v. The green-state strength tests were time-sensitive. Tests conducted on the first samples of a batch after all nine samples were significantly stronger than those conducted on the last three samples. It is recommended that the final three samples are used for the green-state strength test.

The following are the recommendations for further study:

i. Other SCM's and fine fillers could be looked at as partial cement replacements in the specific factory mix used at the specific precast facility. Some of the potential replacements are: fly ash (FA), ground granulated blast-furnace slag (GGBCS), flash calcined clay (impure metakaolin), condensed silica fume (CSF) or ground limestone.

This study adds a practical methodology to the percussion drill method used in the precast industry in South Africa and as referenced in the SANS code (SANS 5861-1:2006). The inclusion of a target density improves the results by keeping density consistent among specimens and relating the density to the density achieved by precast machines. This method can improve quality control and promote the efficient use of the material at precast facilities that use zero-slump concrete.

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