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Percussion-drill method for casting concrete cube samples to assess the characteristics of precast zero-slump concrete

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Precast concrete products are load-tested to confirm compliance, but the workability of the concrete, being generally zero-slump concrete, is often not tested for quality control, as would be done with normal- or high-slump concrete. An industry practice in South Africa uses the percussive action of a rotary percussion drill to compact control cube samples. However, variability in specimen compaction leads to variations in the density and compressive strength results, making the procedure unreliable. This indicates a need for a simple, standardised quality control method for preparing zero-slump concrete cube samples with compaction equivalent to that achieved by precast machines. This technical note aims to (i) report on a practical and economical procedure (i.e. percussion-drill method) that has been formulated for quality control based on the concrete density achieved by precast machines, and (ii) apply this method to mix optimisation with the specific objective of partial replacement of the cement in a factory mix with a suitable fine filler to reduce cost and the carbon footprint of a precast facility. It was shown that the percussion-drill method was able to obtain reliable results (density, compressive strength) for quality control purposes and was successfully employed in the replacement of 17% to 32% of cement by volume with quartz flour in a factory mix. This resulted in a significant cost saving and a reduction in nett carbon emissions at the factory.

Keywords: precast concrete, no-slump concrete, concrete cube samples, percussion-drill method

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INTRODUCTION

Precast, pretensioned concrete elements are increasingly being made with zero-slump concrete due to its economic benefits (Najimi *et al* 2012). This concrete requires low water content and produces fresh concrete with a stiff consistency, enabling rapid stripping of moulds and transport of unhardened products (Hüsken & Brouwers 2012). The result is the production of high-quality concrete with optimal material usage. However, casting zero-slump concrete samples for quality control poses challenges due to difficulties in achieving full compaction.

In South Africa, a common but undocumented industry practice involves casting and compacting cube samples of zero-slump concrete using a percussion drill, also known as a 'small breaker'. This method uses a square plate welded to the drill to compact the concrete in layers within a steel cube mould (Figure 1). While operators assume that this method produces concrete cubes with mechanical properties similar to precast products, it lacks proper validation.

Alternative methods, such as vibrating tables or pneumatic presses, are sometimes ineffective for compacting zero-slump concrete due to its low workability and internal friction. Although an Intensive Compaction Tester (see endnote on page 46 for details) could produce representative cylinder samples, it is costly. Concrete cube samples are the preferred choice in South Africa. However, the current compaction process results in significant variation due to discontinuities at layer interfaces. Increasing the number of compaction layers in the percussion-drill method improves compressive strength consistency.

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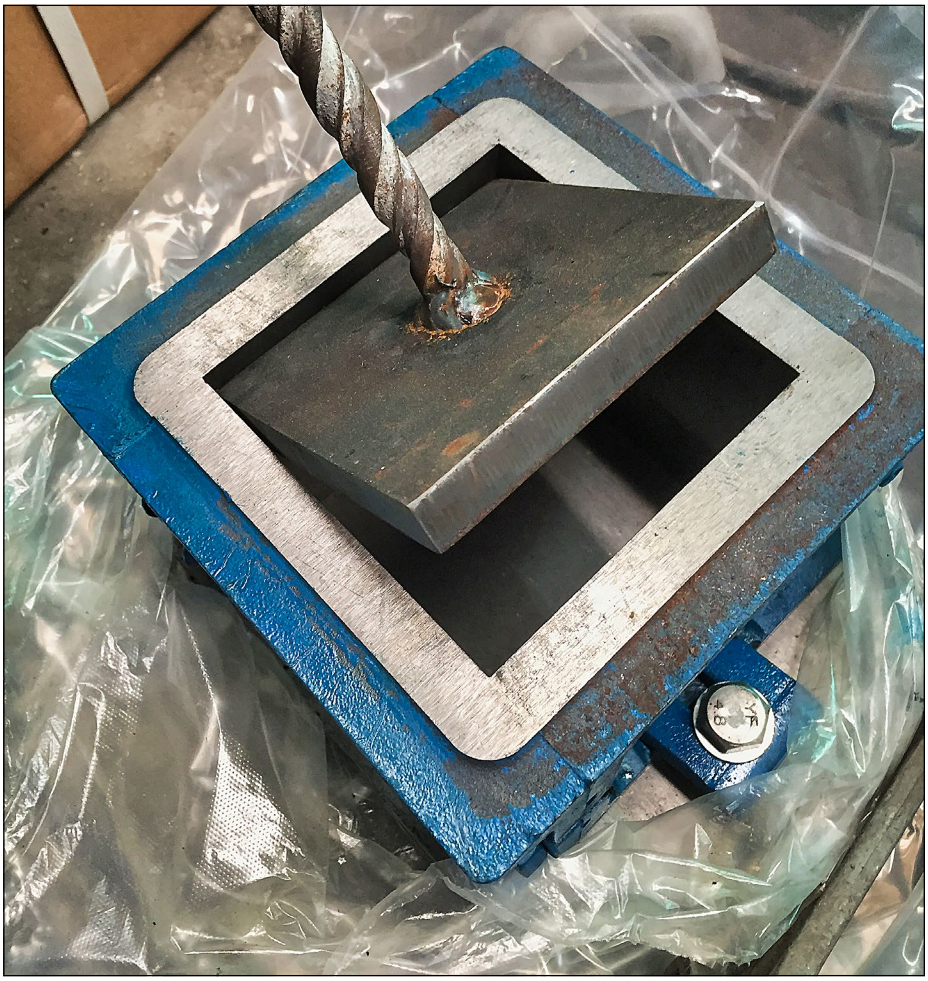

Figure 1 Image of a tool bit with a plate welded to the end to fit inside a steel cube mould

When the cube is turned on its side in the platen of the hydraulic press for compressive strength testing, it tends to fail along the discontinuities. Increasing the number of compaction layers in the percussion-drill method leads to compressive strength results that are more consistent.

For quality control and mix design of precast concrete, matching the density of concrete samples to machine-made products is suggested by Buchman (2010). He used a vibrating table with a weight to achieve this. This study aims to combine the percussion-drill method with a target density to produce concrete cubes suitable for precast concrete quality control using zero-slump concrete.

Zero-slump concrete has low water content and a loose, granular appearance (see Figure 2), and may have some un-hydrated cement acting as a fine filler. To replace the un-hydrated cement, quartz flour (or another suitable fine filler) could be considered based on physical characteristics, cost or carbon footprint. Hüsken and Brouwers (2012) observed that quartz flour in certain quantities improves the early-age compressive strength of zero-slump concrete. This study also explores the influence of quartz flour as a fine filler, considering its affordability and non-pozzolanic reaction properties.

Figure 2 The left-hand image shows the loose texture of the zero-slump concrete that was investigated in a particular precast plant, while the right-hand image shows precast lintels made with this mix

Figure 3 The left-hand image shows (A) the percussion drill, (B) the modified tool bit, (C) a steel cube mould and (D) the zero-slump concrete used (in a funnel); the right-hand image shows a de-moulded sample for the green-state strength test

MIXES AND METHODOLOGY

The following sections provide details on concrete mixes, equipment, casting procedures, and results from lab and field work, along with study conclusions.

Percussion drill equipment

Figure 3 shows the equipment used for casting and compacting concrete cubes, including a Hilti TE-45 rotary percussion drill labelled "A," a modified chisel bit labelled "B," and a cast iron cube mould labelled "C."

Densities

Target density determinations

The target density for laboratory concrete (i.e. in the specially compacted cubes) was determined by using density measurements on concrete core samples from three different precast elements produced by different machines using a factory mix from a precast plant in Atlantis, Western Cape Province, South Africa. The aim was to find a compaction density that matches the density of laboratory samples produced using the percussion-drill method. Laboratory samples were then made within a range of 25 kg/m^3 above or below the target density.

Density measurements were made using buoyant mass as per SANS 6251 (2006). Specimens cored from each precast element were measured as received, and then after exposure to three environmental conditions, i.e. saturated (submerged in water for three days), oven-dried (placed in a 105°C oven for three days), and in the environmental room (temperature controlled at 21°C at a relative humidity of 50% for three days). The rationale behind the three exposure conditions was to gain some insight into the possible range in pore water in the hardened concrete. For each density measurement, three specimens were used. The precast elements were a 155 × 595 mm hollow-core slab, a 145 × 65 mm lintel, and an 80 × 80 mm lintel.

Concrete mix details

Table 1 displays the factory mix used for precast elements at the factory. The mix was prepared in the laboratory using natural sand, 6 mm coarse aggregate, and CEM II A-L 42.5N cement. The cement was changed to CEM I 42.5R for the quartz flour mixes. Quartz flour mixes were also prepared with different cement replacement ratios.

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. Quartz particles were assumed to have similar surface texture, shape and size as

Table 1 Factory mix (based on dry ingredients)

Material	kg/m^3	Nominal proportions (mass ratio)	Lab batch (kg)
Sand (natural source Malmesbury)	959	2.53	9.81
Stone (crushed granite 6 mm)	1 010	2.67	10.33
Cement (CEM II / A-L 42.5 N)	379	1.00	3.87
Water	96	0.25	0.98
Total	**2 444**	**6.45**	**25.00**
w/b ratio = 0.25 design strength = 50 MPa			

Table 2 Quartz flour mix proportions

Material	Quartz (20%)		Quartz (30%)		Quartz (40%)	
	kg/m³	Batch (kg)	kg/m³	Batch (kg)	kg/m³	Batch (kg)
Sand	959.0	9.9	959.0	9.9	959.0	9.9
Stone	1 010.0	10.4	1 010.0	10.4	1 010.0	10.4
Cement (42.5R)	303.2	3.1	265.3	2.7	227.4	2.3
Quartz flour	63.8	0.7	95.7	1.0	127.5	1.3
Water	96.0	1.0	96.0	1.0	96.0	1.0
w/c ratio	0.32	0.32	0.36	0.36	0.42	0.42
w/b ratio	0.26	0.26	0.27	0.27	0.27	0.27
Total	**2 432.0**	**25.0**	**2 426.0**	**25.0**	**2 419.9**	**25.0**

cement, and to not undergo any pozzolanic reaction. Instead of CEM II / A-L 42.5 N, CEM I 42.5 R was used in the quartz flour mixes because of its higher clinker content which encourages earlier reaction and strength gain. Three cement replacement ratios by quartz flour were used, i.e. 20%, 30% and 40%.

The same compaction used for the factory mix was applied to prepare the concrete specimens for the quartz flour mixes. Cement was replaced by quartz flour by volume, to retain the same mix yield as for the plain cement mixes, and also to attempt to match similar compactive effort. A mass of quartz flour matching the volume to be replaced was calculated and used.

The sum of all the mix constituents gave the mass per cubic metre, equivalent to the target density to produce the cube samples. Table 2 shows quantities for the quartz flour mixes

Concrete casting procedure

For the factory mix, 2.44 kg of concrete was compacted into the mould in six layers using vibration. Similar compaction was applied to prepare the concrete specimens for the quartz flour mixes.

RESULTS

The measured densities for each exposure condition are shown in Figure 4. Based on these results, the average value from the environmental room (2 444 kg/m³) was used as the target density since the variations between saturated, as-received, and environmental room results were very minor (ca 0.6%) to justify different laboratory exposure conditions. As a practical quality control tool, the as-received density would also be appropriate since its density can be measured immediately, but this value might be subject to other variability from handling, premature drying, etc.

Figure 5 shows the compressive strength results of the factory mix and quartz flour mixes at 20%, 30% and 40% replacement, showing increasing compressive strength with time, as expected.

However, the ranking of compressive strength of the mixes varied for each testing time. In the green state (immediately after moulding, compacting and stripping), the 20% quartz flour mix showed the highest strength, followed by the factory mix, and then the 40% and 30% blended mixes. After 18 hours, the 20% quartz flour mix still had the highest strength, also followed by the factory mix, while the 30% blend showed higher strength than the 40% blend. After 28 days, the factory mix exhibited the highest compressive strength, followed by the 20% and 30% quartz flour blended mixes, with the 40% blended mix showing the lowest strength.

The higher 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, which exhibits more rapid early hydration and early strength gain. This tendency is not exhibited at 28 days. However, the superior 28-day strength for the factory mix can be associated with the higher cement content compared to the other mixes. With ongoing cement hydration, the factory mix reaches the highest compressive strength value.

Despite the 40% quartz flour mix showing the lowest compressive strength at 18 hours and 28 days, it still met the minimum criteria for producing hollow-core slabs at 18 hours (>30 MPa) and 28 days (>50 MPa). Increasing the quartz flour replacement percentage decreased the compressive strength of concrete. However, at 28 days the 20% and 30% quartz flour replacement mixes exhibited essentially the same strength. On this basis it can be concluded that a quartz flour replacement percentage of around 30% is sufficient to substitute cement in the precast concrete elements and still produce significantly higher strength than the minimum required for producing hollow-core slabs.

The factory mix was compared to the quartz flour replacement mixes using statistical t-tests, in terms of average values. For each comparison, the p-values were found to be less than 0.05, which indicates that the results are statistically significant at the 95% confidence level.

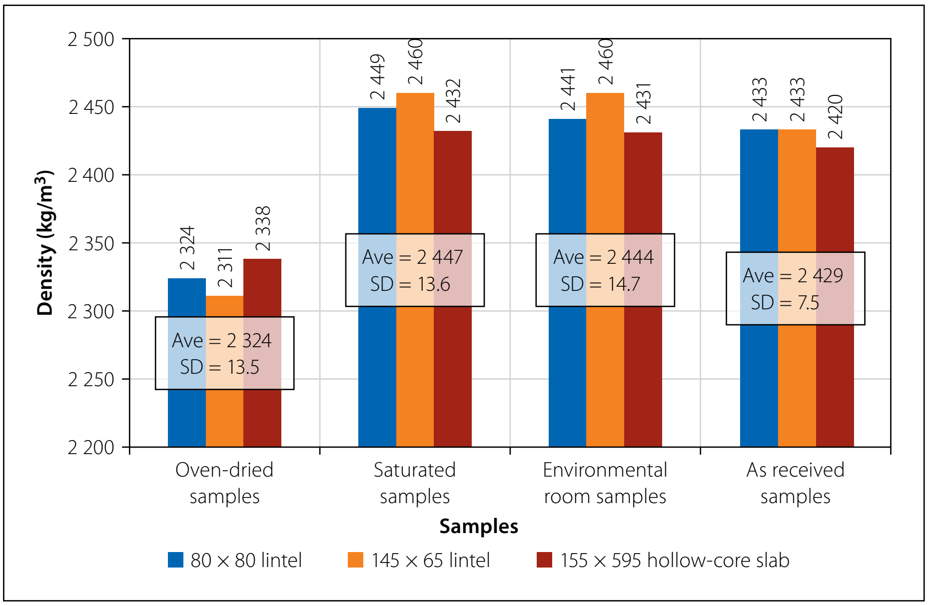

Figure 4 Density measurements

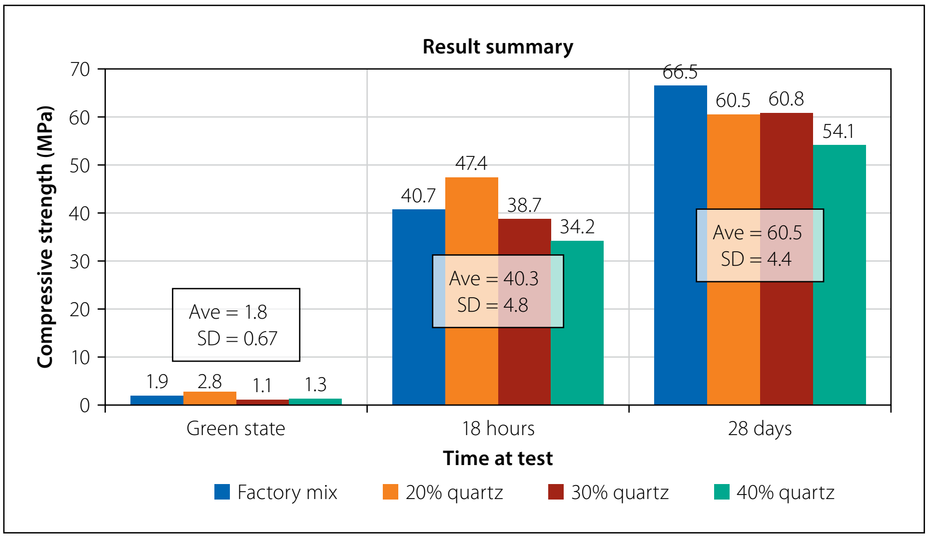

Figure 5 Summary of results for the four zero-slump mixes produced in the laboratory

REDUCTION IN CARBON FOOTPRINT

According to the compressive strength results, quartz flour is a viable fine filler to partially replace cement in precast concrete elements, offering a substantial reduction in carbon emissions. By replacing 33% of the cement by volume with quartz flour and switching to CEM I 42.5 R in the quartz flour mixes, the nett reduction in carbon emissions (CO_2 savings) amounts to approximately 120 kg per cubic metre of compacted concrete. This represents a significant decrease in the carbon footprint.

The reduction in carbon emissions was determined as follows:

- In a compacted cubic metre of concrete, 125.1 kg of cement is replaced by quartz flour. For cement, this amount emits about 123.2 kg of CO_2 (as per Table 3), while the equivalent volume of 105.2 kg of quartz flour only emits 0.8 kg of CO_2.

It should be noted that the estimation assumes a high clinker content (at the upper end of the 80–94% range) for CEM II / A-L 42.5 N. Consequently, the calculated CO_2 savings could be 15% lower.

In conclusion, the use of quartz flour as a cement substitute in precast concrete presents an effective strategy for significantly reducing the carbon footprint, contributing to more sustainable construction practices.

CONCLUSIONS

Density tests on hardened concrete products can give valuable information on the degree to which different machines compact concrete in a precast facility. They also provide information to choose a target density range which can be matched in laboratory samples using the percussion-drill method. Attributes such as early-age strength which cannot be tested on machine-made products can thus be assessed in the laboratory. Additionally, this approach can be employed to enhance zero-slump mixes by formulating trial mixes with diverse combinations of constituent types and ratios.

The zero-slump concrete used in this study achieved sufficiently high strengths at 18 hours, with all the mixes exceeding the minimum requirement of 30 MPa for the destressing of hollow-core slabs and lintels. There is therefore significant potential for mix optimisation using the percussion-drill method with a target density range.

In conclusion:

i. The percussion-drill method using a target density allowed the successful production of cube specimens with zero-slump concrete, for quality control and mix optimisation of factory mixes used for precast building elements such as hollow-core slabs, lintels, pipes and kerbs.

ii. Further improvements to the factory mix are likely possible, and many potential fine fillers can be investigated.

PRACTICAL RECOMMENDATIONS FROM THIS WORK

Percussion-drill method

i. A target density is recommended to reduce variation among specimens and to relate samples to compaction achieved by machines in production.

ii. Multiple compaction layers are recommended. In the samples produced for this work, six layers reduced variation sufficiently for reliable results.

Fine filler replacement recommendations

i. A replacement of 33% cement with quartz flour is recommended for trial in production. The reasons for the recommendation are:

   a. Batches are based on cement bags. The current production uses three bags of cement in every batch. Replacing one bag with an equivalent volume of quartz flour is a simple change in the production routine.

   b. The value is lower than the 40% replacement that achieved the minimum criteria in the laboratory, introducing robustness to the mix design to compensate for the factory environment which is less controlled than the laboratory in terms of temperature and curing.

ENDNOTE

The Intensive Compaction Tester, developed in 1984 by Paakkinen in Finland, is a device used for compacting cylinder samples. It applies pressure and cyclic kneading action with an angled disc, resulting in the development of shear planes within the concrete material. As a result, particles within the sample relocate relative to each other, leading to a reduction in voids, and increased compaction.

Table 3 Carbon footprint of selected materials, adapted from Fulton's Concrete Technology (Alexander 2021)

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

REFERENCES

Alexander, M (Ed.) 2021. *Fulton's Concrete Technology*, 10th ed. Midrand, South Africa: Cement & Concrete SA.

Buchman, C S 2010. *Testing dry-cast products.* Available at: http://web.archive.org/web/20230329005858/http://precast.

org/2010/05/testing-dry-cast-products/ (accessed on 5 March 2022).

Hüsken, G & Brouwers, H J H 2012. On the early-age behavior of zero-slump concrete. *Cement and Concrete Research*, 42(3): 501–510.

Najimi, M, Sobhani, J & Pourkhorshidi, A R 2012. A comprehensive study on no-slump concrete: From laboratory towards manufactory. *Construction and Building Materials*, 30(5): 29–536.

SANS (South African National Standard) 2006. *SANS 6251. Concrete Tests: Density of Hardened Concrete.* Pretoria: SABS Standards Division.