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Evaluating the Strength and Performance of Backfill Support in Deep Level Gold Mines

Fhatuwani Sengani[1*], Tawanda Zvarivadza[1], Rinae Netshithuthuni[2]
[1] School of Mining Engineering, The University of the Witwatersrand, Johannesburg, South Africa
[2] School of Mining and Environmental Geology, University of Venda, Thohoyandou, South Africa

Abstract: The backfill operations at the deep level gold mine consist of a Cyclone Classified Tailings (CCT) Plant as well as a Full Plant Tailings (FPT) Plant with both producing cemented backfill. Due to the high demand of backfill at the mine, including a backlog of voids that need to be filled, both the CCT and FPT Plants are being operated at the moment. The mine will require an increased capacity of backfill going forward, with monthly throughputs in the order of 200 000 to 250 000 tonnes being required. The current mining methods includes destress cuts, long hole stoping as well as drift and fill mining with cemented backfill as a support medium. These concerns have led to the review of the entire backfill operations of the mine with a need for optimising, reducing costs and reducing operational complexity going forward. The research provides strength test work (solids density, particle size distribution, slurry pH, temperature, conductivity, freely settled bed packing concentration, permeability, particle micrographs, water quality, mineralogy, boger slump tests, cement mortar tests (ISO bars), and unconfined compressive strength (UCS) tests) and audit the current backfill operations at the mine. The data showed that both materials had similar top particle sizes of approximately 500 µm. The CCT has a d30 and d10 of 63.4 and 18.2 µm, respectively, compared to the FPT with a d30 and d10 of 13.1 and 3.1, respectively, which is significantly finer. The freely settled bed packing concentration by volume was calculated from the volume of the freely settled bed formed by a known volume of solids. A slurry sample was allowed to settle for 24 hours in a measuring flask. The actual solids volume was determined from the dry mass of material and the solids density. The results were as follows: CCT 45.2 %v (69.1 %m) and FPT 40.0 %v (63.8 %m).

Keywords: CCT, FPT, UCS, backfill, deep level gold mines, support

1 Introduction / Background

South African gold mines are considered to be generating a significant amount of waste; the most important of the waste are waste rocks and tailings (Amaratunga 1991, Aubertin et al 2002). This waste material is usually stored in surface facilities. By so doing, the waste material often leads to environmental problems such as acid mine drainage. Owing to that, one way of managing the mine waste is through cemented backfill, which is a mixture of tailings, water and cement or binding agents (Grice 1998, Benzaazoua et al 1999, 2002, 2004, Belem et al 2000, Aubertin et al 2002, Yilmaz et al 2009, Abdul–Hussain & Fall 2011, Tariq & Yanful 2014, Mashoene & Zvarivadza 2016). The primary role of paste backfill is it assists in ground control (Benzaazoua et al 1999, Belem et al 2002, De Souza et al 2003, Belem & Benzaazoua 2008, Belem et al 2005, Yilmaz et al 2014) by playing the role of secondary mine support. The secondary role of underground paste backfill is to reduce the environmental impacts of mining activities by reducing the number of tailings to be stored in tailings storage facilities (Grice and Street 1998, Aubertin et al 2002, Benzaazoua et al 2002, Yilmaz et al 2009, Abdul-Hussain & Fall 2011, Tariq & Yanful, 2014).

The test results of backfill material properties have been reported by many researchers, such as Aubertin et al (2002). Previous studies have shown that the variation of backfill material properties is quite large even with the same cement content. Furthermore, studies have indicated that the variation is due to several factors that influence backfill stability, such as the grading of aggregate, the mixing process, the method of fill placement, cement content and water contents, etc. Backfill material properties are essential to numerical studies of backfill stability because these parameters are used in numerical models for the prediction of backfill behaviour. Therefore, due to the high variability of properties from one type of backfill to another, testing is still required for any study, even though there are many test results on backfill material properties that have been published. Before the implementation of backfill in the mine, it is of paramount importance to understand the properties and performance of backfill material to be used in different conditions. The main objective of this paper is to present the mechanical characteristics of cemented FPT and FPT un-

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* Corresponding Author: Fhatuwani Sengani, Email: fhatugeorge@gmail.com, Phone: +2772 4430 982

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cemented. The FPT un-cemented type of backfill is composed of a mixture of tailings, water and a binding agent.

2 Research Methodology

In order to achieve the objectives of the study, several research methods were implemented. These include; material property and bench top test (solids density, particle size distribution, slurry pH, temperature, conductivity, freely settled bed packing concentration, permeability, particle micrographs of the material, water quality within the backfill types, mineralogy of the material and boger slump), cement mortar tests (ISO bars) and unconfined compressive strength (UCS) tests.

2.1 Samples used for tests

The sizes and quantity of the material used for the tests are presented in the Table 1.

Table 1 Sample used for the study with their description

Sample type	**Quantity**
Full Plant Tailings (FPT)	1 x 200 litre drum
Cyclone Classified Tailings (CCT)	1 x 200 litre drum
Re-mined tailings	1 x 200 litre drum
Process water	1 x 200 litre drum
Conbex	1 x 200 litre drum
Cement (CEM I)	3 x 50 kg bags
Ground Granulated Blast-furnace Slag (GGBS)	5 x 25 kg bags
Pozzfill	5 x 25 litre drums
Conbex F	5 x 25 litre drums

2.2 Samples preparation

The supernatant water from each of the CCT and FPT slurries were decanted and stored as process water. The content of each drum was thoroughly mixed up on a plastic sheet to ensure that uniform samples are used. The tailings, binder and process water were mixed together to the consistency or density required for each of the mixtures for the CCT and FPT.

2.3 Binders used for the project

The following binders were supplied and used for the project:
(1) CEM I
(2) Conbex
(3) Conbex F
In addition to the binders supplied as listed above, the constituted binders were used:
(1) CEM II 70:30% CEM I: Pozzfill
(2) CEM III 50:50% CEM I: GGBS
(3) CEM V 50:30:20% CEM I: GGBS: Pozzfill

2.4 Binder addition

The mass of binder added to the tailings was calculated using the following formula (see equation 1):

$$\% \text{ Binder} = \frac{\text{Mass of dry binder}}{\text{Mass of dry binder+Mass of dry tailings}} \qquad (1)$$

In order to perform variations on the water to binder ratio, binders of 6%, 8% and 10% were added to tailings and water separately.

3 Results of the Study

The results of the study include the following sections; solids density, particle size distribution, slurry pH, temperature, conductivity, freely settled bed packing concentration, permeability, particle micrographs of the material, water quality within the backfill types, mineralogy of the material and boger slump, cement mortar tests (ISO bars) and unconfined compressive strength (UCS) tests results.

3.1 Solids density, ρs

The solids density of the materials and binders were determined using a helium pycnometer, which determines the skeletal solids density of the particles. Table 2 presents the solids density results. Based on the results of the study it was found that the density the material was ranging was from a minimum of 2123 kg/m^3 to a maximum of 3091 kg/m^3.

Table 2 Solids Densities

Material	**Solids density (kg/m^3)**
Full Plant Tailings (FPT)	2646
Cyclone Classified Tailings (CCT)	2708
Conbex	2874
Cement (CEM I)	3091
Ground Granulated Blast-furnace Slag (GGBS)	2855
Pozzfill fly ash	2123
Conbex F	2461

3.2 Particle size distribution

The particle size distribution was determined by a combination of wet sieving (+25 µm fraction) and laser diffraction (-25 µm fraction). Figure 1 presents the particle size distribution for the FPT and CCT material. The data shows that both materials have similar top particle sizes of approximately 500 µm. The CCT has a d30 and d10 of 63.4 and 18.2 µm, respectively, compared to the FPT with a d30 and d10 of 13.1 and 3.1, respectively, which is significantly finer.

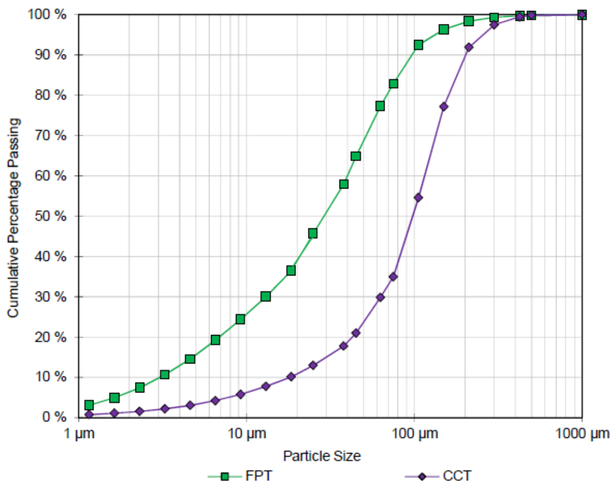


Figure 1 Particle size distribution

3.3 Slurry pH, temperature and conductivity

The pH, temperature and conductivity of the slurry are measured by using a handheld meter. The pH data for the CCT before and after binder addition was 7.0 and greater than 12.0, respectively, with the conductivity increasing from 2.1 to a magnitude greater than 4.0 ms/cm after the addition of the binder. The pH data for the FPT before and after binder addition was 7.6 and greater than 12.0, respectively, with the conductivity increasing from 1.9 to greater than 3.0 ms/cm after the addition of the binder.

3.4 Freely settled bed packing concentration, C_{bfree}

The freely settled bed packing concentration by volume is calculated from the volume of the freely settled bed formed by a known volume of solids. A slurry sample was allowed to settle for 24 hours in a measuring flask. The actual solids volume were determined from the dry mass of material and the solids density. The results were as follows:
(1) CCT 45.2 %v (69.1 %m)
(2) FPT 40.0 %v (63.8 %m)

3.5 Maximum settled bed packing concentration, C_{bmax}

The maximum bed packing concentration was determined from the volume of a compressed bed of solids formed by a known mass of solids. The bed was compressed by applying a hydraulic pressure of over 400 kPa across the settled bed with the water being allowed to drain through the solids bed. The actual volume of the solid sample was determined from the dry mass of the sample and the solids density. The maximum packing concentration was calculated from the volume of the compressed bed and the known volume of solids. No values could be recorded for the FPT tailings since the material was too fine. The maximum settled bed packing concentration for the CCT was 53.5 %v (75.7 %m).

3.6 Permeability

The permeability of the samples was determined using a falling head permeability rig as shown in Figure 2. The test involved the flow of water through a relatively short sample connected to a standpipe. The coefficient of permeability was determined by filling the standpipe with water and allowing it to flow through the soil sample while simultaneously measuring the head loss in the standpipe as well as the volume of water passing through the sample in a given time. After the falling head permeability test was completed the soil sample was dried to determine the void ratio and porosity.

The permeability for the FPT was measured for un-cemented material only, whereas the permeability for the CCT was measured for both un-cemented and a cemented mixture using 6% Conbex over a period of 13 days. Figure 2 shows the permeability measured over time for a cemented CCT sample with 6% Conbex. The data indicates that as the cement cures, the permeability decreases. The initial sharp decrease in the permeability occurs within the first 4 days of curing with very little change seen from 4 days to 13 days.

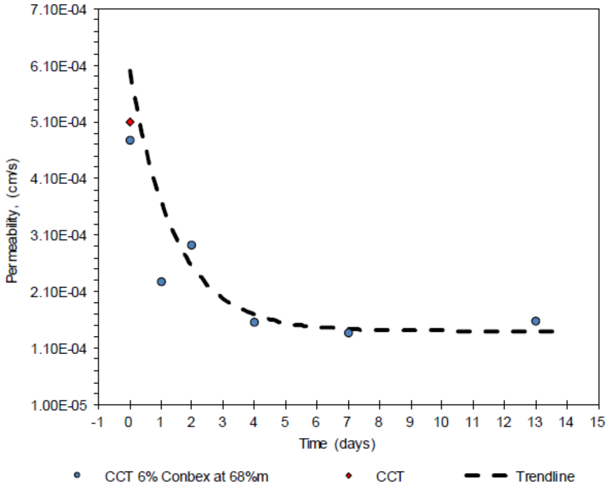


Figure 2 Permeability versus time for the cemented CCT

3.7 Water quality

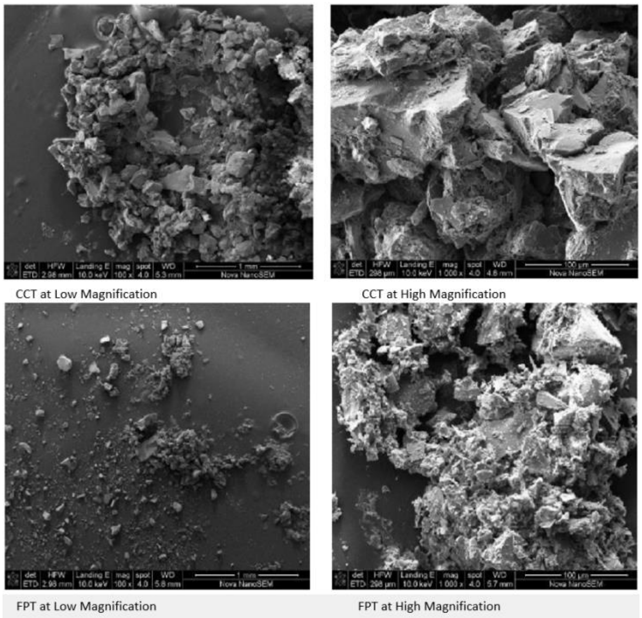
The water results have shown that there were significant amounts of sulfate ions present in the process water. These sulfates were readily available for reactions with the binders and could form undesirable reaction compounds. Sodium and calcium ions were also available and to a lesser extent potassium and magnesium ions. These ions would also participate in the early hydration reactions, potentially accelerating setting compared to potable water.

3.8 Mineralogy

The CCT were composed mainly of quartz (crystalline silica) at 97% with some minor constituents such as pyrite at 1.6% and clay mineral components such as chlorite and mica. The FPT were composed mainly of quartz at 84% and mica (muscovite) at 12%, with various additional minor components. Quartz is an unreactive crystalline mineral that would not participate in any cementitious reactions. The mineralogy tests has shown that mica was the main component which was removed in the cyclone classification. Mica has a deleterious effect on concrete and backfill and reduces strengths; however due to the very fine aggregates in backfill the physical influence was decreased. As mica is an aluminosilicate mineral, it has the potential to form geopolymers if exposed to alkali activation and the right conditions.

3.9 Particle micrographs

Figure 3 shows the particle micrographs at low and high magnifications for the CCT and FPT respectively.


CCT at Low Magnification

CCT at High Magnification

FPT at Low Magnification

FPT at High Magnification

Figure 3 Particle micrographs of both CCT and FPT

3.10 Boger slump tests

The slump test measures the consistency or "stiffness" of the slurry and is a quality control measure for paste. The variation in slump as a function of solids concentration is a visual indication of the stiffness of the material. A standard 75 mm by 75 mm boger slump cylinder was used for all the tests. The slump is the distance between the top of the cylinder and the top of the slurry expressed as a percentage of the slump cylinder height. No slumps were measured for the CCT since the mixtures were too diluted. The boger slumps ranging from 51% to 60% were measured on the FPT for different binders.

3.11 Cement mortar tests

The cement mortar (ISO bar) tests confirms the strength of the cement after a fixed curing time. Samples were made up using 66.7 %m (3 parts) neutral silica sand and 22.2 %m (1 part) cement, mixed with 11.1 %m (½ part) water to obtain a water: binder ratio of 0.5. The cement mortar test data showed that the CEM V, Conbex and Conbex F do not meet the 28 days compression strength requirements (greater than 32.5).

3.12 CCT test results

Figure 4 to Figure 6 show the 7, 14 and 28 days test results for the CCT. The early strength gain (7 days) of the Conbex F was better when compared to the Conbex with the Conbex yielding significantly better in the 14 and 28 days results. The 28 days data showed that the CEM I and CEM III yield in a similar manner for the compressive strength data for the same water: binder ratios. These two binders were also the best performing compared to the other binders tested.

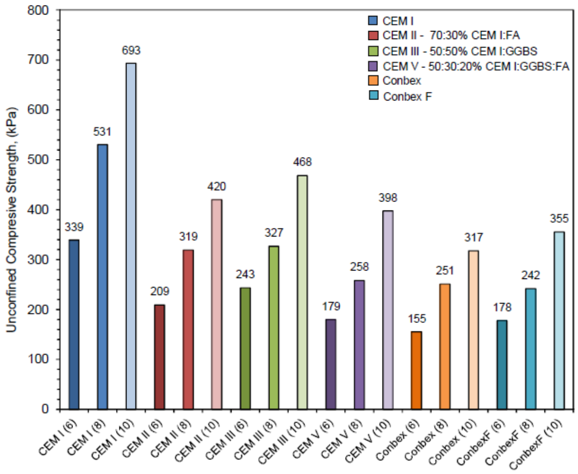


Figure 4 7 days strength results for CCT

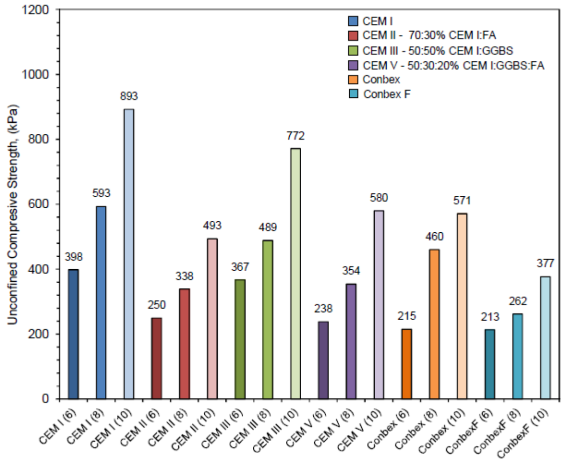


Figure 5 14 days strength results for CCT

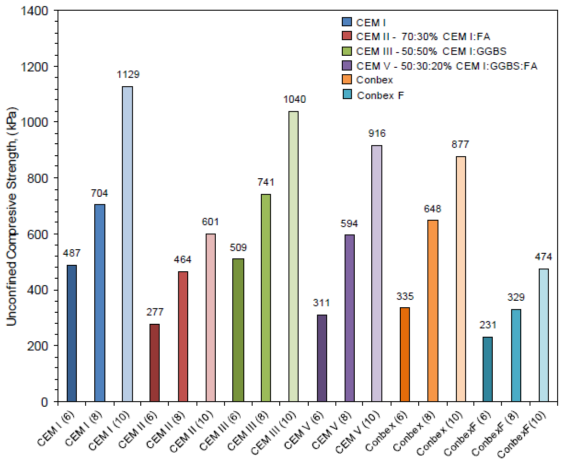


Figure 6 28 days strength results for CCT

3.13 FPT test results

Conbex F Results

In general, it was expected that, as the binder cures, the compressive strength increases over time. However, the results for Conbex F after 14 days showed a decrease in strength, which was uncommon. The Conbex F material was recast and observed similar results. Figure 7 and Figure 8 show the strength versus time graphs for the 1st and 2nd castings. The data for the 6% and 8% binder additions show similar trends with the 14 days strengths lower than the 7 days strengths. There was an increase in strength from 14 to 28 days with the 28 days strengths being comparable to the initial 7 days strengths. The data for the Conbex F with 10% binder showed a similar trend, but with the 28 days strength being stronger than the 7 and 14 days recorded strengths.

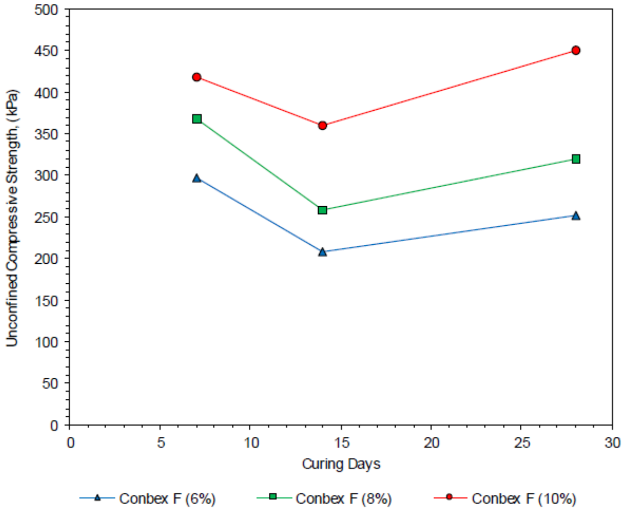


Figure 7 Conbex F – 1st Castings

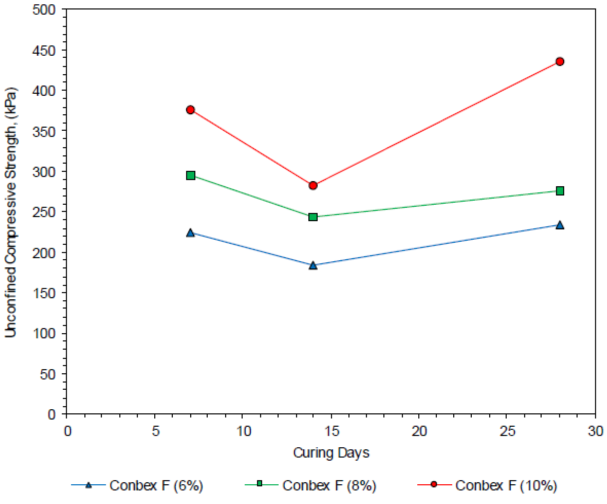


Figure 8 Conbex F – 2nd Castings

The reason for the loss in compressive strength was due to both calcium sulfate formation as well as delayed ettringite formation. The process water results show that a high sulfate concentration was present. The sulfates would react with calcium hydroxide to form calcium sulfate, which was an expensive product. These secondary reactions would induce micro-cracks in the matrix due to expansion, which would in turn lead to reduction in strength. In this case a supplementary cementitious material would be beneficial to prevent strength loss due to the sulfates present in the water. However, the calcium hydroxide addition for the Conbex F, which was added to accelerate the pozzolanic reactions of the fly ash, would have the opposite effect. The additional strength development observed after the 14 days results was due to the supplementary cementitious reactions that start to take precedence, as well as the depletion of the sulfates.

The effect could also be observed in the CCT mixes where the strength gain flattens out. However, the CCT had its own residual strength and could accommodate micro-cracking better as it was a coarser material. In addition, more of the sulfates could drain from the material as it had a higher permeability.

Figure 9 to Figure 11 present the 7, 14 and 28 days test results for the FPT. The behaviour of the Conbex F was similar to that observed with the CCT samples, with the Conbex F yielding better early strength results. The Conbex was outperforming the Conbex F after 14 and 28 days. The CEM I and CEM III binder again yields the best strength results after 28 days, with the CEM III being the best performing binder of all tested.

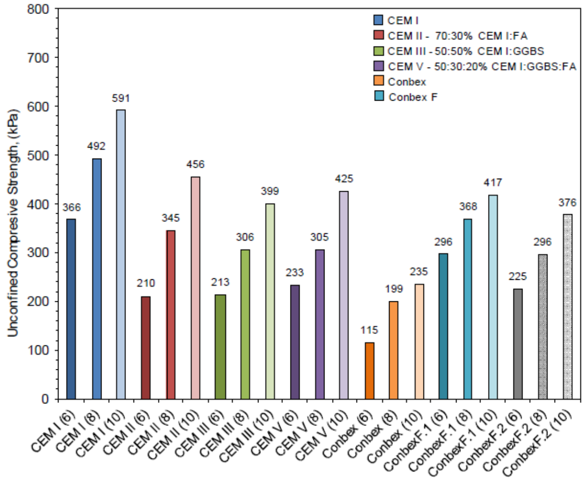


Figure 9 7 days strength results FPT

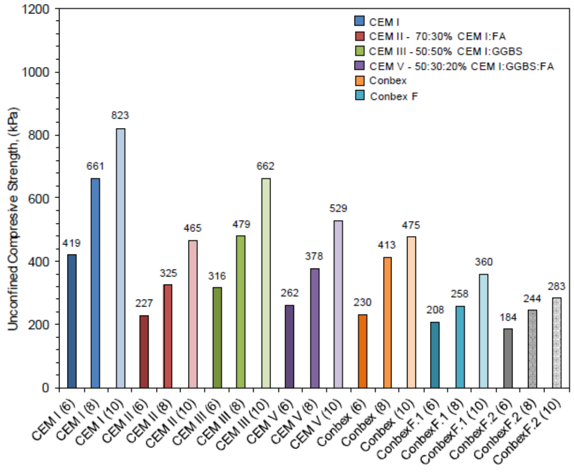


Figure 10 14 days strength results FPT

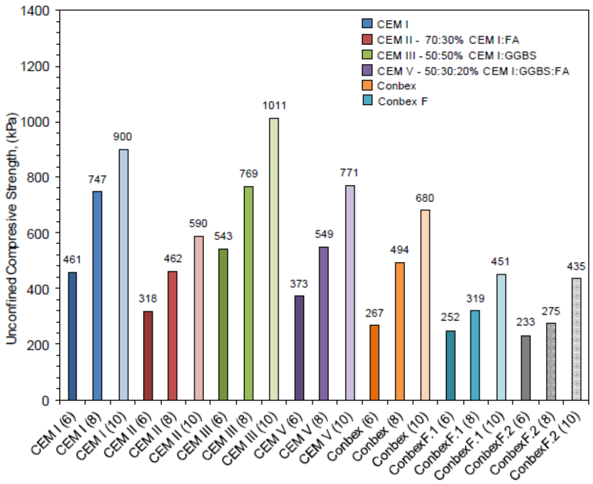


Figure 11 28 days strength results FPT

4 Conclusions

Based on the results of the study, the CCT and FPT had solids densities of 2708 and 2646 kg/m^3 respectively. Owing to that, the particle size distributions has shown that the CCT was significantly coarser with a d30 of 63.4 µm compared to a d30 of 13.1 µm for the FPT. Further results on pH data for the CCT before and after binder addition was 7.0 and greater than 12.0 respectively, with the conductivity increasing from 2.1 to greater than 4.0 ms/cm after the addition of the binder. The pH data for the FPT before and after binder addition was 7.6 and greater 12.0 respectively, with the conductivity increasing from 1.9 to a magnitude greater than 3.0 ms/cm after the addition of the binder. The long term permeability test results for the cemented CCT showed a decrease in permeability of 67 % within the first 4 days due to the cement hydration where after it stabilises.

Water process results has indicated that sulfate ions were present in the process water which may have led to deleterious secondary reactions for certain binders. The cement mortar test data showed that the CEM V, Conbex and Conbex F do not meet the 28 days compression strength requirements (greater than 32.5). The 28 days CCT strength results with CEM I and CEM III were the best performing binders and yielded similar compressive strength results at the same water: binder ratio. The 28 days FPT strength results with CEM I and CEM III yielded the best strength results, with the CEM III being slightly better. The Conbex F yielded better early (7 days) strengths when compared to the Conbex. However, due to deleterious reactions caused by the sulfates, the Conbex F experienced limited strength gain after 7 days. The effect was less pronounced in the CCT mixes as it was composed of coarser material.

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