Properties of pervious concrete for hydrological applications

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ABSTRACT

This paper presents an experimental investigation that was conducted to examine those properties of interest with regard to the passage of water through pervious concrete. A total of 30 mixtures of pervious concrete were prepared at water-cementitious ratios (w/cm) varied from 0.25 to 0.40. Three aggregate types and sizes were used consisting of 13.2, 9.5 and 6.7 mm granite stone; 6.7 mm shale and 9.5 mm dolomite. Extenders were incorporated into mixtures in proportions of 20, 30 and 50% fly ash (FA) or 30% and 50% ground granulated blast furnace slag (GGBS). Compressive strength development in the mixtures was monitored at 7, 14, and 60 days. It was found that strength gain after 14 days generally occurred mainly in mixtures containing pozzolans. A unique behavior in property relations of pervious concrete was found, showing compressive strength to increase as w/cm increased, while porosity showed inverse proportionality with w/cm, both trends being contrary to the behavior of normal or conventional concrete. It was found that mixtures made with 6.7 or 9.5 mm granite stone gave porosity and permeability characteristics that were most suitable for hydrological applications. Similarly, incorporation of 20% FA, 30% or 50% GGBS in the mixtures gave the most appropriate mechanical and transport properties.

KEY WORDS: Pervious concrete; Compressive strength; Porosity; Permeability; Aggregates; Fly ash; Slag

1. INTRODUCTION

The global interest towards sustainability and use of environmentally friendly materials and scientific technologies has seen increased promotion of pervious concrete in the construction industry. Pervious concrete is a special form of concrete whose uniqueness lies in its hydrological properties. This type of concrete has been in existence since 1852 [1] but did not attain wide applicability in its early years and was mostly in oblivion until recent years when it has seen resurgence. The main engineering applications of interest responsible for this resurgence are associated with its use in storm water management and pollution control.

1.1 Pervious Concrete Applications

Also referred to as *permeable concrete* or *no-fines concrete*, this type of concrete is different from conventional concrete squarely due to complete absence of or presence of a fairly small amount of, fine aggregate in its mixtures. It therefore turns out to be porous to the extent of allowing free flow of water through the concrete. This hydrologic behaviour is controlled by permeability and porosity properties of the mixture.

As mentioned earlier, storm water management is the foremost application for which pervious concrete is predominantly used. Surface run-off is particularly a problem in urban areas and cities, due to densely built environment along with paved or concrete surfaces. Pervious concrete has been used in construction of parking lots, sidewalks, walkways and low volume roads in order to drain off stormwater hence reducing run-off, effectively recharging the ground water-table. This application is of benefit to the environment and is of particular interest to government agencies, municipal authorities, and also private property owners. Beyond the control of run-off, use of pervious concrete may result in significant pollution control benefits due to its ability to trap debris, motor oil or petroleum products and other contaminants that would normally be carried into rivers and waterways [2,3]. In the early ages of pervious concrete inception, it was also used in Europe as a structural material in building construction. The structural applications for which pervious concrete has been employed include its use in walls of two-story houses, use as infill panels and load-bearing walls for tall buildings of up to 10 storeys. Tennis et al.[2] lists an extensive range of construction applications for pervious concrete.

Quite interesting are also recent investigations [4,5] that have shown that pervious concretes contain water purification properties in which it acts as a filter to remove heavy metal concentrations giving prospects for its potential use for water treatment applications. Two forms of pervious concrete failures have been cited, being clogging and structural failures. Clogging results from accumulation of debris and contaminants both at surface and interior of the concrete, causing reduction in porosity and permeability and ultimately affecting its hydrologic performance. However, it has been argued that this is a maintenance issue and regular sweeping or vacuuming can restore porosity; pressure flushing is reported to restore 80 to 90% of its original permeability. Structural failures arise from load-bearing uses that may exceed its relatively low compressive strength of typically 2.8 to 28 MPa based on concrete cylinders [6], such as may occur from heavy traffic loads. Also, reports have indicated poor resistance of pervious concrete to freeze-thaw damage leading to failures. But investigations [3] have shown that proper mix design can result in improved performance against freeze-thaw attack.

1.2 Typical Mixtures and Properties

Suitable pervious concrete typically has 15 to 30% porosity, and pore sizes may range from 2 mm to 8 mm diameter. As previously mentioned, the compressive strength of concrete is quite low while permeability or drain rates of 120 to 700 litres/min/m^2 have been reported [2]. Small aggregate sizes of 6.5 to 13 mm are used, with 9.5 mm being most commonly employed along with cement contents of 270 to 400 kg/m^3 and water/cement ratios that may range from 0.25 to 0.40. The aggregate /cement ratio is typically 4 to 4.5. Due to low water/cementitious ratios typically used in pervious concrete, the mixtures are usually dry mixes with zero slump. For this reason, the use of superplasticizers in pervious concrete is necessary for achievement of workability. Normal cementitious materials including extenders (such as fly ash, slag, silica fume) may also be used.

It has been shown that the behaviour of pervious concrete is remarkably different from that of conventional concrete while its hydrologic properties are affected by mixture proportions. Kevern et al. [3] found a linear inverse relationship between compressive strength and porosity, but the permeability-porosity relation was reported to be non-linear, becoming exponential at porosity values exceeding 25%. Pervious concrete technology is not widespread in developing countries and further understanding of its diverse use is of interest. In the present experimental study, a wide range of variables are investigated in relation to their effects on mechanical and hydrologic properties of pervious concrete. The variables include water/cement ratio, use of different extenders of varied proportions, different aggregate types and sizes. The properties measured were the density and porosity of fresh pervious concrete; compressive strength and its development, and water permeability of hardened pervious concrete.

2. EXPERIMENTAL

2.1 Materials and Mixtures

A range of mix variables were applied to examine their influence on the properties of pervious concrete:

- Cementitious materials consisted of CEM I 52.5N with or without incorporation of extenders of 20, 30, 50% FA; 30 or 50% GGBS. Also used in the mixtures was CEM V/B 32.5R which typically contains a high volume of (at least 80%) FA/GGBS extenders [7-10].

Table 1: Varied mix ingredients and proportions: Gr = granite, Sh = shale, Dol = dolomite, w/cm = water/cementitious ratio, FA = fly ash, GGBS = ground granulated blast-furnace slag, SP = superplasticizer Chryso Fluid Premia 310

Mix No.	Stone size (mm) and type	Cementitious type	w/cm	SP (mls)
1	6.7 Gr	CEM I 52.5N	0.25	61
2	13.2 Gr	CEM I 52.5N	0.25	60
3	6.7 Sh	CEM I 52.5N	0.25	120
4	9.5 Dol	CEM I 52.5N	0.25	60
5	6.7 Gr	CEM I 52.5N	0.28	60
6	6.7 Sh	CEM I 52.5N	0.28	120
7	6.7 Gr	CEM I 52.5N	0.31	60
8	13.2 Gr	CEM I 52.5N	0.31	60
9	6.7 Sh	CEM I 52.5N	0.31	120
10	9.5 Dol	CEM I 52.5N	0.31	60
11	6.7 Gr	CEM I 52.5N	0.35	35
12	6.7 Sh	CEM I 52.5N	0.35	50
13	6.7 Gr	CEM I 52.5N	0.4	30
14	6.7 Sh	CEM I 52.5N	0.4	40
15	6.7 Gr	20% FA	0.25	60
16	6.7 Gr	30% FA	0.25	70
17	13.2 Gr	30% FA	0.25	30
18	6.7 Sh	30% FA	0.25	100
19	9.5 Dol	30% FA	0.25	45
20	6.7 Gr	50% FA	0.25	50
21	6.7 Gr	30% GGBS	0.25	35
22	6.7 Gr	50% GGBS	0.25	45
23	13.2 Gr	50% GGBS	0.25	30
24	6.7 Sh	50% GGBS	0.25	90
25	9.5 Dol	50% GGBS	0.25	40
26	6.7 Gr	CEM V	0.25	40
SMix1	9.5Gr	CEM I 52.5N	0.25	
SMix2	9.5Gr	CEM I 52.5N	0.30	
SMix3	9.5Gr	CEM I 52.5N	0.35	
SMix4	9.5Gr	CEM I 52.5N	0.40	

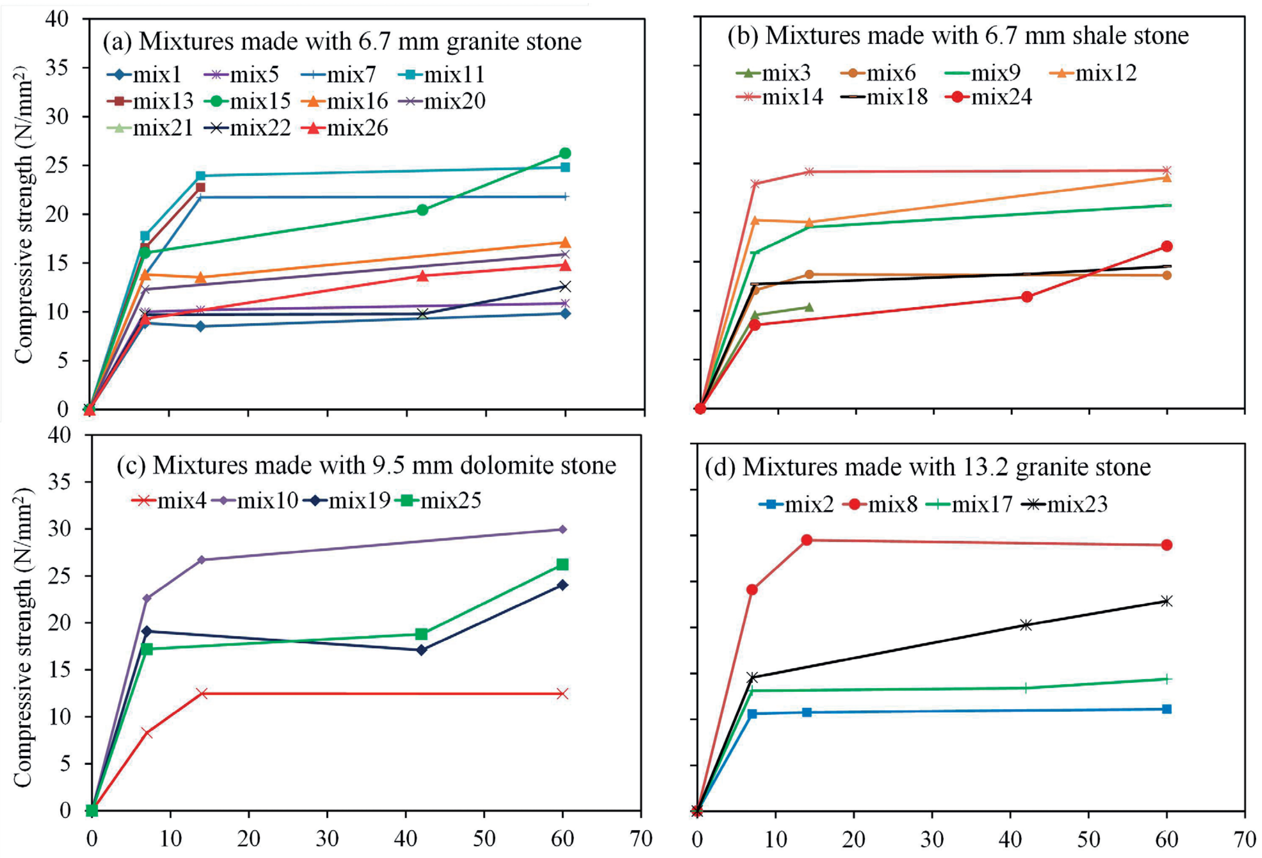

Figure 1a-d: Compressive strength gain in pervious concrete mixtures

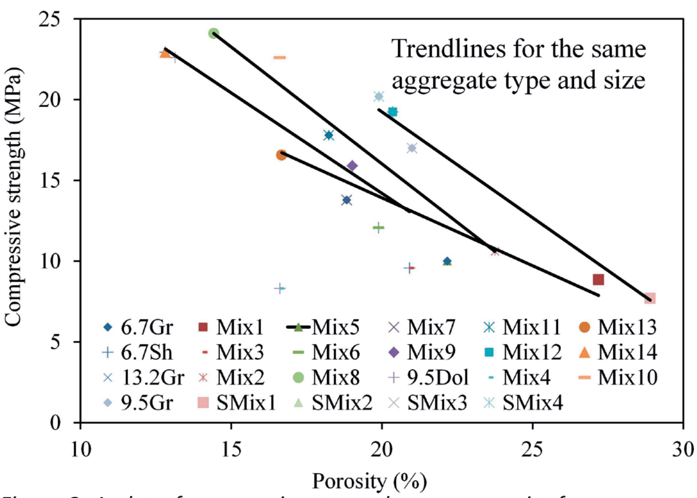

Figure 2: A plot of compressive strength versus porosity for aggregates of different types and sizes

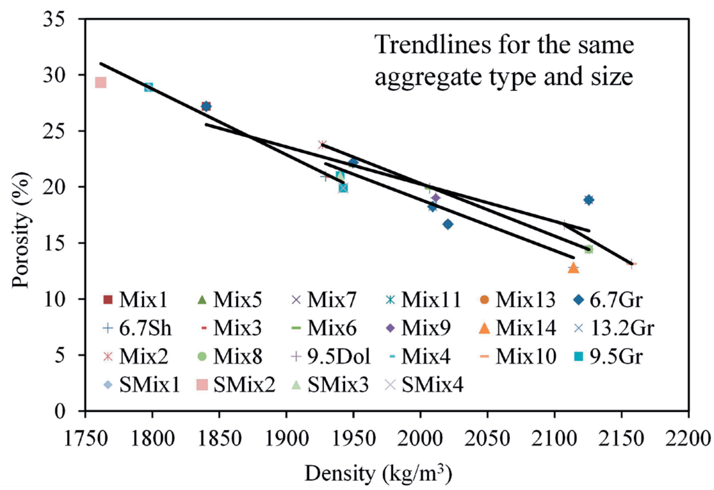

Figure 3: Plot of porosity versus density of pervious concrete mixtures for different aggregate types and sizes

- Three aggregate types of varied sizes were used comprising 6.7, 9.5, 13.2 mm granite; 6.7 mm shale, 9.5 mm dolomite. In all cases, single sized commercially available aggregates, satisfying the requirements of SANS 1083 [11] were used. They consisted of: (1) 6.7 mm single size stone with gradation of 100% passing sieve size 9.5 mm and 100% retained on 6.7 mm sieve, (2) 9.5 mm single size stone with gradation of 100% passing sieve size 13.2 mm and 100% retained on 9.5 mm sieve, and (3) 13.2 mm single size stone with gradation of 100% passing sieve size 19 mm and 100% retained on 13.2 mm sieve. The pervious concrete mixes were designed as 'no fines' mixtures [12]. Accordingly, fine aggregates were not used in mixes.

The w/cm ratios of the mixtures were varied from 0.25 to 0.40, while a cementitious content = 360 kg/m^3 and aggregate/cement ratio = 4.0 were maintained constant for all mixtures. It was found necessary to use a superplasticizer in all mixtures in order to achieve desirable workability. Table 1 gives the range of mixture variables used in the experiment.

2.2 Test Methods

A total of 30 mixtures were prepared. In each mix, twelve 100 mm cubes were cast and used for the various tests viz:- compressive strength tests at 7, 14, 42 and 60 days; density, porosity and permeability.

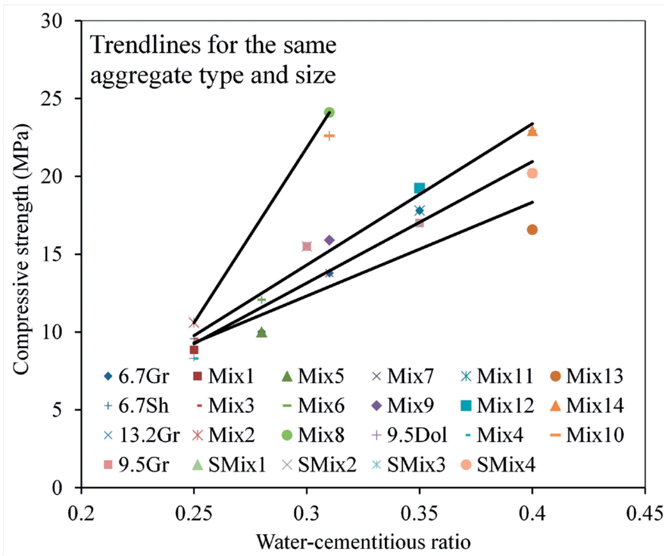

Figure 4: A plot of compressive strength versus water-cementitious ratio for different aggregate types and sizes

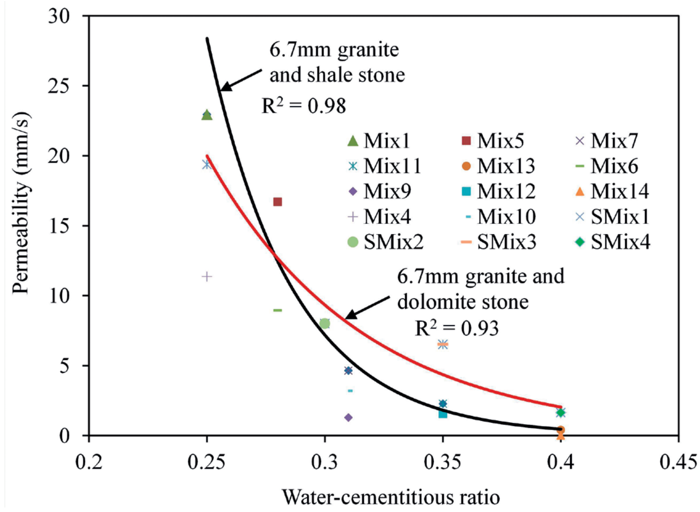

Figure 6: A plot of permeability against water-cementitious ratio for different aggregate types and sizes

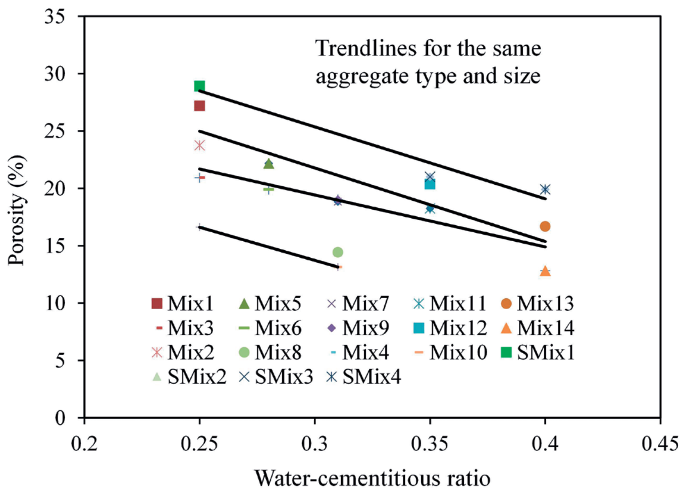

Figure 5: Plot of porosity versus the water-cementitious ratio for different aggregate types and sizes

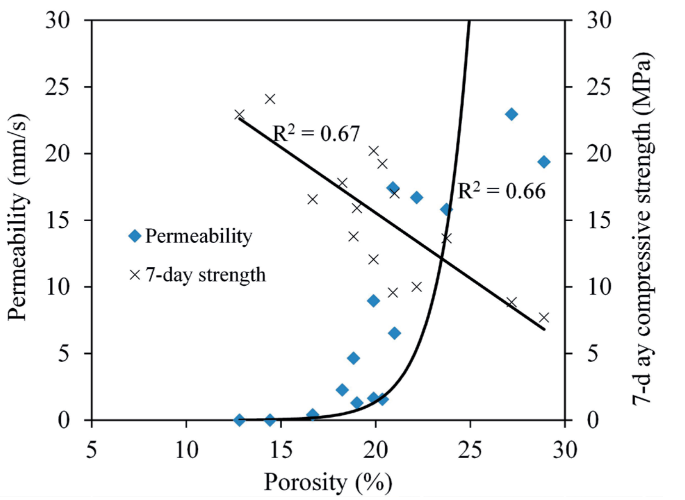

Figure 7: A dual plot of permeability and compressive strength versus porosity for various aggregate types and concrete mixtures

During casting of the cube samples, concrete was placed in moulds in two layers, each layer being rodded 10 times. The concrete-filled moulds were then placed on a vibrating table and vibrated for about 5 seconds to improve compaction and uniformity before finishing by trowelling. The cast samples were then covered with a plastic sheet for 24 hours, demoulded and stored under water at room temperature until the prescribed time periods of testing. Measurement of the density and porosity of fresh mixtures was conducted in accordance with ASTM C 1688 [13]. As prescribed by the test method, a cylindrical container 250 mm diameter x 200 mm height was filled with compacted concrete and weighed. Density was determined as the ratio of net weight of compacted concrete to volume of the container. Porosity or void content was determined as the percentage difference between theoretical density and density, the former being the total weight of all mix ingredients divided by their total absolute volume [13].

Water permeability was tested using drilled cores from cube samples. Tests were conducted after a 28-day curing period. The cores were 68 mm in diameter and 100 mm long. A falling head permeameter was constructed to test the specimens. The permeameter consisted of a 500 mm plexiglass tube with an inside diameter of 72 mm. The samples were wrapped in a membrane to prevent radial seepage and were placed inside the tube attached to the stand and fitted with an O-ring to ensure a water tight seal. The time taken for the water to drain over a given height of 150 cm was measured. The test was repeated three times on each sample. All samples were saturated in water for a minimum of 48 hours prior to permeability testing. Water permeability was calculated from the expression [14]:

$$k = \frac{aL}{At} LN\left(\frac{h_1}{h_2}\right)$$

Where:

k is permeability of specimen (m/s).

a is cross-sectional area of the tube (m^2).

L is thickness of specimen (m).

A is cross-sectional area of specimen (m^2).

t is time taken for water to drop from h_1 to h_2 (seconds).

h_1 is the top water level (m).

h_2 is the lower water level (m).

LN is the natural logarithm

3. RESULTS

3.1 Strength Gain with Age

Strength development in the porous concrete cube samples, monitored at ages of 7, 14, 42 and 60 days, is plotted in Figure 1a-d for mixes 1 to 26 of varied aggregate sizes, cement types and extenders, and varied w/cm of 0.25 to 0.40. Results indicate that compressive strength gain mostly occurs within the first 14 days, with only a slight strength increase between 7 and 14 days. Beyond 14 days, long-term strength gain is mainly realized in mixtures containing extenders such as seen in mixes 15 to 26. It therefore suffices to use 7 or 14 days compressive strength values to assess the mechanical properties of pervious concrete.

3.2 Mechanical Properties and Physical Properties

Results show that while some relationships between concrete properties follow recognized conventional behaviour, other characteristics of pervious concrete relate in an opposite trend to established understanding of normal concrete properties. Figures 2 and 3 respectively show that compressive strength decreases with increase in porosity, while porosity decreases with increase in density. These relations are well established norms in conventional concrete. However, the observations in Figures 4 and 5 showing compressive strength increasing with increase in w/cm, and porosity correspondingly decreasing with increase in w/cm are clearly the reverse of established trends in conventional concrete. These observed trends can be attributed to improvement in workability and compaction as the w/cm increases, in turn leading to lower porosity and higher compressive strength. This reverse behavior appears to be unique to pervious concrete and these results are consistent with findings in the literature including earlier work by the present authors[3,15-17]. An interesting feature in Figure 4 is the convergence whereby aggregates of different sizes and types tend to show similar strength behavior at lower w/cm ratios down to 0.25.

3.3 Relations between Transport Properties and Mix Proportions

The main hydrological properties of pervious concrete that are of interest concerning water flow, are the porosity and permeability characteristics. The permeability of pervious concrete is found to be non-linearly related to w/cm as shown in Figures 6. Figure 7 is a combined plot showing the dual relationships of porosity against permeability and against compressive strength, also similarly reported in the literature [3]. Note that the mixes used here are limited to concretes not containing FA and GGBS extenders. This was conducted in an attempt to isolate the general pattern of behavior without involving extender materials, since these are known to significantly impact the permeability characteristics in conventional concrete. The permeability results involving extenders are presented in Figure 9.

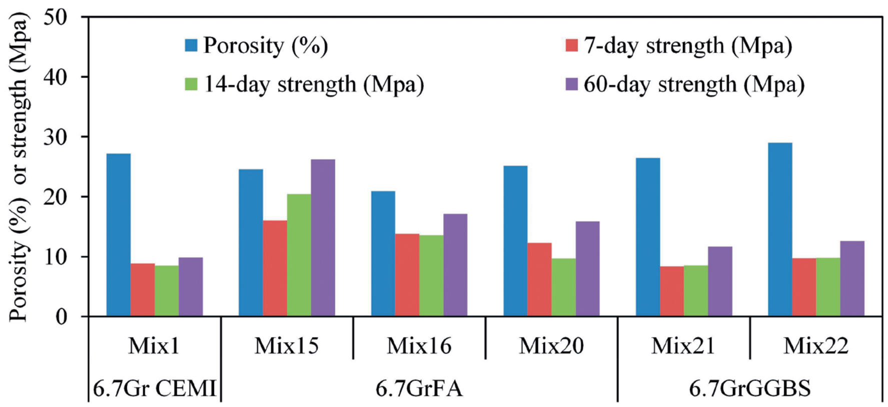

Figure 8: Influence of extenders on porosity and strength gain

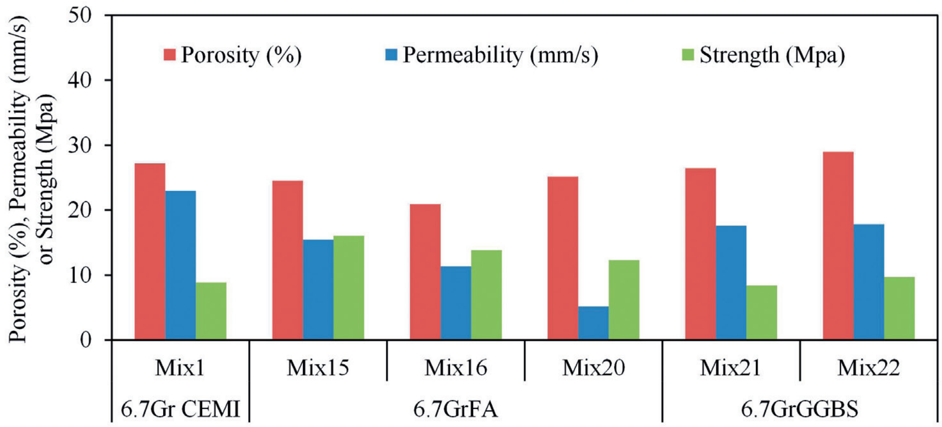

Figure 9: Comparison of compressive strength, porosity and permeability in mixes containing extenders

4. DISCUSSION OF RESULTS

4.1 The influence of Aggregate Types and Sizes

It may be recalled that three aggregates sizes of 6.7 mm, 9.5 mm and 13.2 mm were used in mixtures along with three aggregate types consisting of granite, shale and dolomite. Higher compressive strengths were exhibited by the higher aggregate sizes of 13.2 and 9.5 mm granite stone relative to their smaller size counterparts of 6.7 mm granite and shale types as seen in Figure 2. Shale stone generally gave lower porosities relative to its corresponding granite stone of the same size. These results are also evident in Figure 5 with porosities of the mixes decreasing in order of 9.5 mm granite > 6.7 mm granite > 6.7 mm shale stone. Over the range of w/cm = 0.25 to 0.40 used in the mixtures, the 9.5 mm granite stone gave the highest porosities of 20 to 30% (and corresponding lower densities) compared to 15 to 25% porosities for 6.7 mm granite while the 6.7 mm shale gave the lowest porosities of 13 to 21 %. For any given aggregate type, it is seen that porosities generally decrease as the aggregate size reduces. The aggregate types significantly affect porosity. In the results observed, granite aggregates give higher porosity than shale and dolomite aggregates.

It is also interesting to note in Figure 6 that granite aggregates always gave higher permeability relative to the shale aggregate. However, the relative influence of the different granite stone sizes appeared to depend on the mixture design, with mixes of w/c = 0.25 to 0.27 showing the permeability of 6.7 mm granite to be higher than that of the 9.5 mm granite stone while the reverse appears to be true for mixes of w/c = 0.27 to 0.40. Either way, the aggregate sizes of 6.7 or 9.5 mm granite stone are evidently most suited to produce appropriate permeability and porosity properties for water transport in a pervious concrete system, in comparison to the other aggregate types.

4.2 The Influence of Cement Extenders

Extenders were incorporated into concrete mixtures in proportions of 20, 30, 50%FA or 30, 50%GGBS. These particular mixes were made at a w/cm of 0.25.

4.2.1 Effect of the Extenders on Porosity and Compressive Strength

It can be seen in Figure 8 that the porosities of all the mixtures generally lay between 20 to 30% with the fly ash mixes showing slightly lower porosity values of 20 to 25%, while GGBS mixes were higher than 25% and similar to porosity of the control mix. However, the FA mixes gave generally higher strengths at all ages compared to the control or GGBS mixes. The mix 15 containing 20% FA appears to show better overall results with higher strengths and porosities relative to the mixtures containing 30 or 50%FA. The strength of the 20% FA mix is also greater than strengths of the GGBS mixes. The strength gain in the 20% FA mix

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is quite steady and relatively higher than the corresponding strength increase in the other FA mixes or GGBS mixes. Infact the strength gain in the GGBS mixes between 7 days and 60 days is relatively small and subdued compared to the corresponding gains in the FA mixes 15 to 20.

4.2.2 Effect of Extenders on Permeability

The influence of FA and GGBS extenders on permeability of the pervious concrete mixes can be seen in Figure 9. It is interesting to see that the results of 30 or 50% GGBS mixes were similar to the values of the control mix with slightly higher permeability for the latter.

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However, the behavior of FA mixes was widely different with mixes containing higher proportions of the extender showing a significant decrease in permeability and strength, in proportion to the amount of the extender incorporated into the mix. The 20%, 30% and 50% FA mixes had permeability values of 15, 11 and 5 mm/s compared to about 17 mm/s for the GGBS mixes and 23 mm/s for the control mix.

5. CONCLUSIONS

In the foregone investigation, the influence of various mix proportions on the mechanical and transport properties of pervious concrete were examined. The following conclusions have been reached:

1. Pervious concrete exhibits some unique properties that contradict the relationships known in conventional concrete by exhibiting strength increase and porosity decrease as the w/cm ratio increases.
2. Permeability shows an exponential relationship with porosity. Permeability becomes continuous at porosity values exceeding 20%. On the other hand, compressive strength shows an inverse linear relationship with porosity.
3. Aggregate types and sizes significantly influence the transport properties of pervious concrete. The 9.5 mm granite stone gives higher porosities of 20 to 30% relative to the 6.7 mm granite or shale stone.
4. Concerning the permeability and porosity properties, the 6.7 mm and 9.5 mm granite stone aggregates were found to produce pervious concrete mixtures of the most suitable hydrologic characteristics.
5. Incorporation of FA into the mixtures in proportions of 20 to 50% leads to a corresponding decrease in strength and permeability values of the mixes. In contrast, mixes containing 30 or 50% GGBS showed only slight changes to the porosity and permeability results, and gave similar results as the control mix. Mixtures containing 20% FA, 30 or 50%GGBS appear to be the most appropriate proportions for achievement of suitable hydrologic properties.

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