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ENHANCEMENT OF PROPERTIES OF SUSTAINABLE POROUS CONCRETE THROUGH MIX DESIGN

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ABSTRACT

Porous concrete has an interconnected pore structure that freely allows the passage of water to flow through. This type of concrete can be applied for pavements of parking lots, sewage treatment plant sludge beds, swimming pool deck, bridge embankments and floors for zoo area and animal barns. It may also be used in applications requiring light-weight concrete. This paper presents an experimental program conducted with the objective of enhancing the engineering properties of porous concrete. Mixtures were designed based on cement paste / total aggregate ratio. Twelve mixes were cast and tested. The mixes were divided into 5 groups: group A had cement paste/aggregate ratios of 0.20, 0.30, and 0.40 for the three mixtures 1,2 and 3, respectively; group B used partial replacement of coarse aggregates by 8% and 12% sand; in group C cement was partially replaced by 8% and 12% silica; in group D cement was partially replaced by 12% and 20% fly ash and finally in group E fibrillated polypropylene fiber was added to the mix by 0%, 0.1% and 0.2% . For groups B, C, D and E the cement paste/aggregate ratios was 0.40, water / cement ratio was 0.27 for the mixes. A large number of test specimens were prepared to perform the required tests. Tests were carried out on fresh concrete to evaluate density, slump and compaction index. Tests conducted on hardened concrete were compressive strength, splitting tensile strength, flexure strength, permeability, as well as flow rate. The test results demonstrated the influence of mix proportions on the physical and mechanical strength of pervious concrete. Results indicated the possibility to produce porous concrete mixture with acceptable permeability and concrete strength through careful mix design.

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KEYWORDS: Porous concrete, Mix design, Permeability, Porosity, Sustainable concrete

1. INTRODUCTION

Porous concrete, also called pervious concrete, no fine concrete, gap graded concrete, is a special high porosity concrete used for applications that allows water to pass through. Porous concrete pavement is becoming a popular choice as pavement in low-volume road applications for storm water runoff collection and reuse, and is thus regarded as environmental friendly and sustainable construction system. Porous concrete has been used since 1970s in the United States in complex drainage systems and water retention areas. The most common applications include driveways, parking lots, sidewalks, streets and other low traffic volume areas [1-3]. Also, it is used for pavement, base course, noise absorbing and thermal insulation concrete and other civil engineering and architectural applications [4]. Also a special type of porous concrete was designed to be used in protective structures such as safety walls or storage for explosives [5]. Porous concrete is thus regarded an innovative approach to sustainable road pavement design and construction. However, from the construction management point of view, disadvantages include the need to closely apply quality management to pavement, mix design, and concrete placement. Also, another potential disadvantage with permeable concrete pavements is the ability to manage clogging issues like muddy water [6]. Due to this extended application, high strength and durability become the concern of porous concrete [7].

Compressive strength of pervious concrete mixtures has a wide range of 3.5 to 28 MPa, and flexural strength ranges between 1 MPa and 3.8 MPa, depending on the constituents and mix proportions. This makes pervious concrete suitable for a wide range of applications [1, 4].

The main problem of porous concrete is its low strength due to the high voids content. The strength of porous concrete is significantly affected by the porosity. The establishment of a quantitative relationship between porosity and concrete compressive strength was investigated and a model was suggested for prediction of compressive strength based on the material porosity [8]. A study was conducted in which mixtures of different pore structure features were proportioned and subjected to static compression tests. Larger aggregate sizes and increase in paste volume fractions resulted in increased compressive strength. In addition, the compressive response was found to be influenced by the pore sizes, their distributions, and spacing [9]. The strength, fracture toughness, and fatigue life of two types of pervious concrete, supplementary cementitious material modified porous concrete (SPC) and polymer- modified pervious concrete (PPC) were investigated. Results show that PPC demonstrated much higher fracture toughness and longer fatigue life than SPC at any stress level [5]. To strengthen the cement paste binder, various types of additives have been studied by several researchers. Many studies have been conducted in order to improve the conventional porous concrete. Even though various fundamental mixtures have been studied, the optimum condition to produce good porous concrete has still not been established.

This paper aims to produce porous concrete with desirable properties of high strength as well as acceptable porosity and permeability through carefully selected mix proportions. The present research investigates the effect of different parameters such as cement paste/ aggregate ratio and sand, silica, fly ash partially replacement ratio, and addition of polypropylene fibers on the physical and mechanical properties of porous concrete. The experimental program is described, and the experimental results are presented and discussed in the following sections.

2. EXPERIMENTAL PROGRAM

An experimental program was conducted in order to investigate the effect of different parameters on the physical and mechanical properties of porous concrete. The experimental work was conducted in the Materials Testing Laboratory at the Housing and Building Research Center. Twelve mixes were designed with different mix proportions, as listed in Table 1. Variables were the cement paste/ aggregate ratio, and sand, silica, fly ash partial replacement ratio, and addition of polypropylene fibers. For all the cast mixes, laboratory tests were made for compressive strength, splitting tensile strength, flexural strength, porosity and permeability.

3. MATERIALS AND MIX PROPORTIONS

The cement used for the experimental work was ordinary Portland Cement CEM type I 42.5 N, natural gravel was used as coarse aggregate passing 14 mm sieve and retained on 10 mm sieve. Siliceous sand was used as fine aggregate which was in the medium grading zone according to Egyptian code of practice [10]. The specific gravity and volumetric weight of the used sand were 2.6 and 15 kN/m³, respectively. Super plasticizer admixture type R 2004 from Sika was used 0.5% by weight of cement, and tap water was used for mixing. Silica fume, a by-product from manufacture of ferrous alloys, fly ash, and fibrillated polypropylene fiber were used in the mixes.

Twelve mixes were prepared and cast that were divided into 5 groups as shown in Table 1. Group A had cement paste/aggregate ratios of 0.20, 0.30, and 0.40 for the three mixtures 1, 2 and 3, respectively. For groups B, C, D and E the cement paste/aggregate ratios was 0.40, and the water / cement ratio was 0.27. Group B used partial replacement of coarse aggregates by 8% and 12% sand for the mixes 4 and 5, respectively; in group C cement was partially replaced by 8% and 12% silica for mixes 6 and 7, respectively; in group D cement was partially replaced by 12% and 20% fly ash for mixes 8 and 9, respectively; and finally in group E fibrillated polypropylene fiber was added to the mix by 0%, 0.1% and 0.2% for the three mixes 10,11 and 12, respectively.

Table 1: Proportions for all Porous Concrete Mixes

Mix No.	Cement content kg/m^3	Coarse agg. kg/m^3	Fine aggr. kg/m^3	Silica kg/m^3	Fly ash kg/m^3	poly-propylene %	Water content kg/m^3	Super plasticizer lt/m^3
Mix 1	335	2128	-	-	-	-	90.5	1.68
Mix 2	456	1934	-	-	-	-	123.3	2.3
Mix 3	558	1774	-	-	-	-	150.8	2.8
Mix 4	558	1632.08	141.92	-	-	-	150.8	2.8
Mix 5	558	1561.12	212.88	-	-	-	150.8	2.8
Mix 6	513.36	1774	-	44.64	-	-	150.8	2.8
Mix 7	491.04	1774	-	66.96	-	-	150.8	2.8
Mix 8	491.04	1774	-	-	66.96	-	150.8	2.8
Mix 9	446.40	1774	-	-	111.6	-	150.8	2.8
Mix 10	558	1561.12	212.88	-	-	0%	150.8	2.8
Mix 11	558	1561.12	212.88	-	-	0.1%	150.8	2.8
Mix 12	558	1561.12	212.88	-	-	0.2%	150.8	2.8

4. SPECIMENS PREPARATION

Constituents for all mixes were weighed according to the mix proportions shown in Table 1. Mixing was made in a pan-type mechanical mixer at room temperature, and the specimens were cast in clean standard steel moulds moistened with oil for easy removal. The moulds were filled with freshly mixed concrete in three layers of approximately equal height, each tapped 25 times by standard hammer. The specimens were removed from the moulds and kept in water until testing age. For each mix, three samples were cast for every test. The samples cast for the different tests are listed in Table 2, some of the cast specimens are shown in Fig. 1.

Standard cubes were cast for compressive strength tests and cylinders for splitting tensile strength with dimensions listed in Table 2. The cubes and cylinders were submerged in water and tested at two different ages; three specimens were tested after 7 days and the other three were tested after 28 days. For flexural strength the test samples were beams and for permeability testing a mould having dimensions (300 mm x 300 mm x 100 mm) with sides insulated was used. The prisms and beams were submerged in water and tested after 28 days.

Table 2: Laboratory Tests and Specimens

Test	Specification	Specimen		Testing day	Specimens no.	
		shape	Dimensions mm		each mix	total
Compression	ASTM C 39 [14]	cube	150 x 150 x 150	7	3	36
				28	3	36
Splitting tension	ASTM C 496 [15]	cylinder	150 x 300	7	3	27
				28	3	27
Flexural strength	ASTM C 78 [16]	beam	100 x 100 x 500	28	3	27
Permeability		prism	300 x 300 x 100	28	3	27
Porosity		cube	150 x 150 x 150	28	3	18
Specific gravity	C138 [11]	cylinder	150 x 300	Fresh concrete	1	12
	loose method			28	3	36
Slump	ASTM C143 [12]	cone	10 x 20 x 30	Fresh concrete	1	12
Compaction factor	ACI 211.3 [13]			Fresh concrete	1	12

Fig. 1: Some of the Cast Specimens

5. FRESH AND HARDENED CONCRETE TESTS

Tests were made on fresh concrete to check it is consistency and workability. Density was evaluated using cylinders of diameter 150 mm and height 300mm by two methods: the standard method in accordance to ASTM C138 [11], and the loose method where concrete was poured in the cylinder without any compaction. Slump tests and compact factor tests were performed according to ASTM C143 [12] and ACI standard 211.3[13], respectively, shown in Fig. 2.

Compression test was made on cubes after 7 days and 28 days from casting using the 2000 kN compression testing machine. An increasing compressive load is applied on the specimen until failure according to ASTM C 39 [14]. A cube positioned in the compression testing apparatus is shown in Fig. 3a. To evaluate tensile strength, splitting tensile test was performed as specified in ASTM C496 [15] for cylindrical samples 7 days and 28 days after casting, as shown in Fig.3b. Flexural tests were made in accordance with ASTM C 78 [16], shown in Fig. 3c, for beam specimens having dimensions (100 x 100 x 500) mm 28 days after casting, using Universal automatic testing machine 1000 kN.

a b c

Fig. 2: Tests on Fresh Concrete: a), b) Slump Test and c) Compacting Factor Test

a b c

Fig. 3: Tests on Hardened Concrete: a) Compression Test, b) Splitting Tensile and c) Flexure Test

Permeability (rate of flow) was measured using moulds having dimensions (300 x300 x100 mm), where the sides were insulated and the upper surface was exposed to water, as shown in Fig. 4. Water was poured on the top surface and collected from the lower surface. The rate of flow was calculated as the quantity of water collected in 30 seconds divided by the surface area exposed to water.

Porosity tests were made to estimate the amount of concrete pores and cavities expressed as a percentage of the total volume. Standard cube specimens of dimensions (150 x 150 x 150) mm were oven dried at 105oC for 24 hours and the specimens' dry weight (W1) is obtained. Then, the dried specimens are weighed in water and the weight under water (W2) is obtained, as shown in Fig. 5

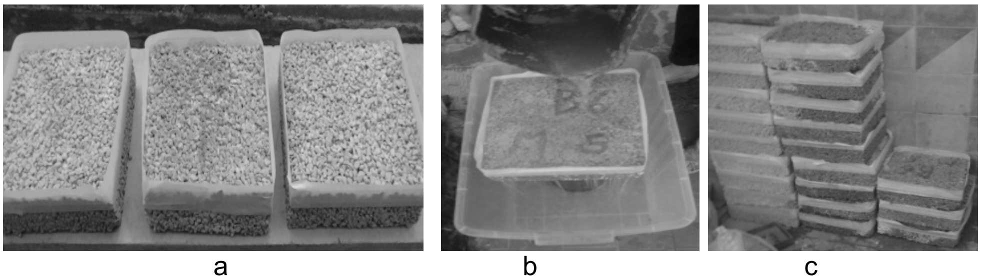

Fig. 4: Permeability Test: a) Specimen Preparation, b) Pouring Water on the Specimen and c) Specimens after the Test

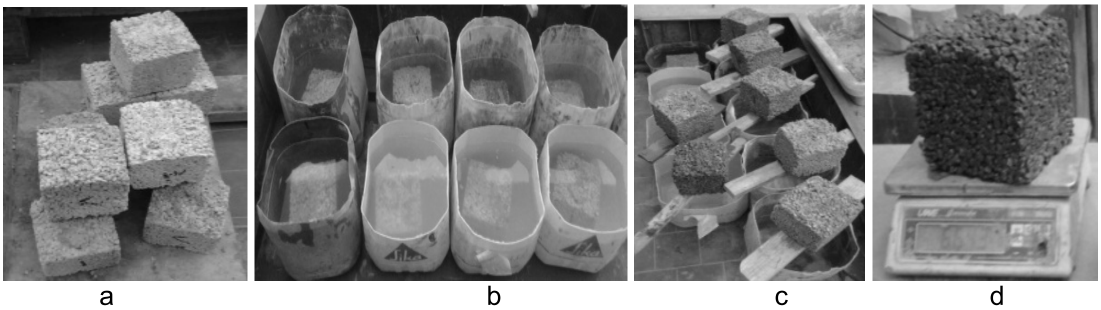

Fig. 5: Porosity Test: a) Oven-dried Specimens, b) Specimens Submerged in Water, c) Specimens After Removal from Water and d) Weighing of Specimens

6. EXPERIMENTAL RESULTS AND DISCUSSION

6.1 FRESH CONCRETE TEST RESULTS

The results of tests on fresh porous concrete for all mixes are presented in Table 3; the given values are the average of three tested specimens.

Results of slump test showed that increasing the cement paste /aggregate ratio improved the slump value and gave a more stiff mix. Slump was 100 mm for mixes 1and 2 having cement paste/aggregate ratios of 0.20 and 0.30, and improved to 30-40 mm for all the other mixes 3 to 12 having a higher cement paste/aggregate ratio 0.4. This yields a stiff mix of near to zero slump, as shown in Fig. 2b. The results also indicate that cement or aggregate replacement in the studied mixes had little influence on the slump.

The compaction factor results for all mixes were in the range of 77.85% to 83.55% as given in Table 3.This indicates that the mixes exhibited acceptable workability and cohesiveness. This could possibly be attributed to the use of appropriate quantity of super plasticizer to produce pervious concrete to fill the spaces of almost any size and shape without segregation or bleeding. These results are in agreement with those of other researchers [17].

Results for the density of fresh porous concrete are given in Table 3 as an average value for three specimens of each mix. The obtained results show that the standard density ranged from17.4 kN/m³ to 24.3 kN/m³, while the loose density had lower values ranging from 14.4 kN/m³ to 22.1 kN/m³. The common values for density of pervious concrete are in the range of 15 kN/m3 to 20kN/m3 [2]. The results fall in this range and are similar to those obtained by other researchers [18]. Comparison of the results of all mixes in Fig. 6 showed that increase in cement paste / aggregate ratio enhanced both the standard and loose densities. Keeping constant ratio of cement paste / aggregate, density increased for groups B (mixes 4 and 5) and group E (mixes 10, 11 and 12) containing sand and polypropylene fibers, respectively.

Table 3: Results for Tests on Fresh Concrete

Mix	Slump (mm)	Standard density (kN/m^3)	Loose density (kN/m^3)	Compaction factor (%)
M1	100	19.0	15.4	81.05
M2	100	19.2	15.1	79.9
M3	40	20.0	16.0	77.85
M4	40	23.3	18.8	80.6
M5	35	23.9	19.2	80.5
M6	35	21.1	16.6	78.6
M7	40	19.0	15.8	83.3
M8	30	17.9	14.8	82.7
M9	30	17.4	14.4	82.97
M10	33	24.1	22.1	82
M11	35	24.3	20.3	83.55
M12	35	22.2	15.8	83.05

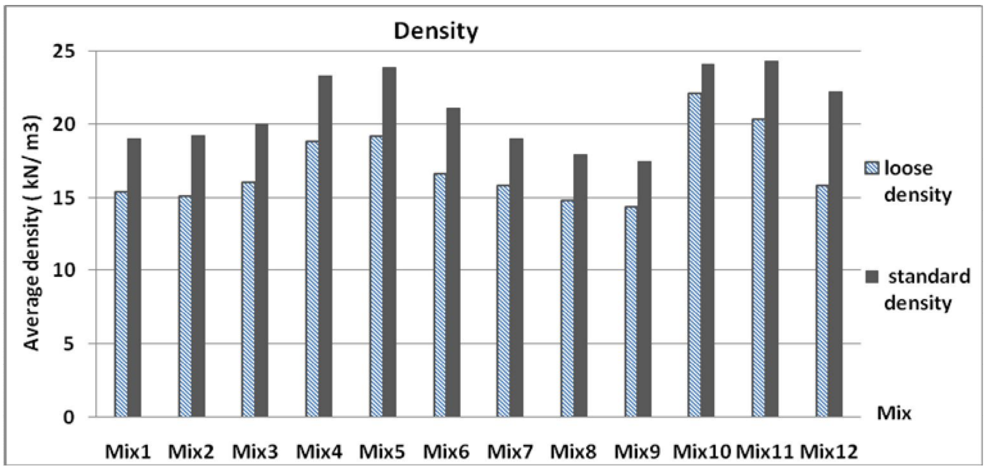

Fig. 6: Effect of Mix Proportions on Loose and Standard Densities

6.2 HARDENED CONCRETE TEST RESULTS

6.2.1 COMPRESSIVE, FLEXURAL AND SPLITTING TENSILE STRENGTHS

Compressive strength is evaluated from the results of compression tests performed on cube specimens 7 days and 28 days after casting by dividing the maximum load by the cube face area, from the equation

$$\sigma = \frac{P}{A} \quad (1)$$

Where σ is the compressive strength, P is the maximum compressive load and A is the area of the face of the cube.

Results of the splitting tensile tests on cylindrical samples at ages 7 and 28 days are used to calculate the maximum tensile strength using the equation.

$$\sigma_T = \frac{2P}{\pi DL} \quad (2)$$

Where σ_T is the tensile strength, P is the maximum load applied, D is the cylinder diameter and L is the length of the cylinder.

The results of the compressive, tensile and flexural strengths as average of three specimens of each of mix are plotted for the three mixes of Group A in Fig.7 and for all the mixes in Figs. 8 and 9. Results showed that the average 7-day and 28-day compressive strengths ranged from 3.2 to 31.8 MPa, and 4.2 to 37.5 MPa, respectively, for all mixes. Also, the average splitting tensile strength ranged from 0.22 to 2.0 and from 0.28 to 2.6 MPa for 7-days and 28-daysresults, respectively. The 28-days average flexural strength of the tested mixes ranged between 0.235 and 1.125 MPa. As expected, the 28 days compressive and splitting tensile strengths were higher than those of 7 days. The strength of porous concrete is increased with the age, due to the improved strength of the binder paste with time.

Results of group A where cement paste/aggregate ratios of 0.25, 0.35, and 0.40 were used for the three mixes 1, 2 and 3, respectively, show that compressive strength increases with the increase of cement content in the mix as shown in Fig. 7. Similar behavior is observed for the splitting tensile strength and flexural strength. The increase in cement paste provided more coating and increase of the contact area between neighboring aggregate particles, resulting in higher strength. These results are in agreement with the findings of previous research [18,19]. The proportions of mix 3 in group A was used as control mix for all other mixes thereafter.

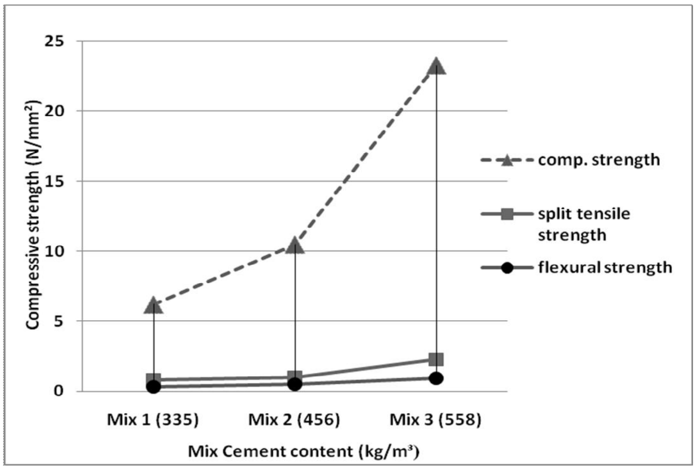

Fig. 7: Results for group A: 28-day Compressive, Splitting Tensile and Flexural Strengths

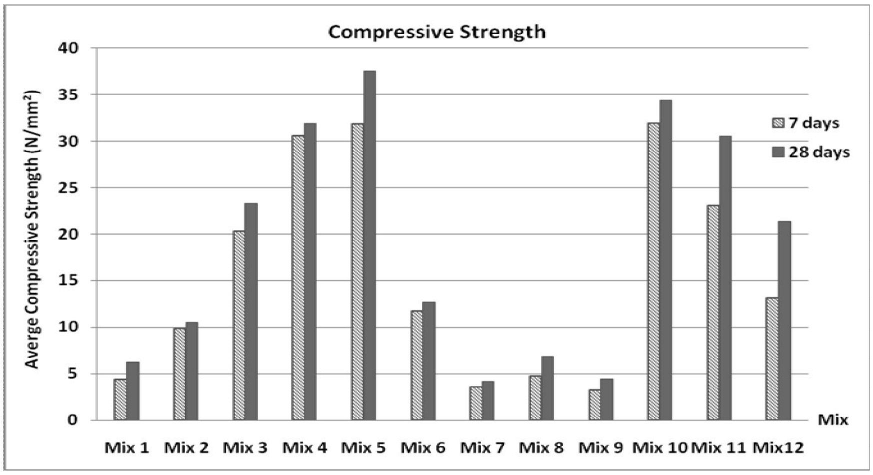

Fig. 8: Compressive Strength for all Mixes

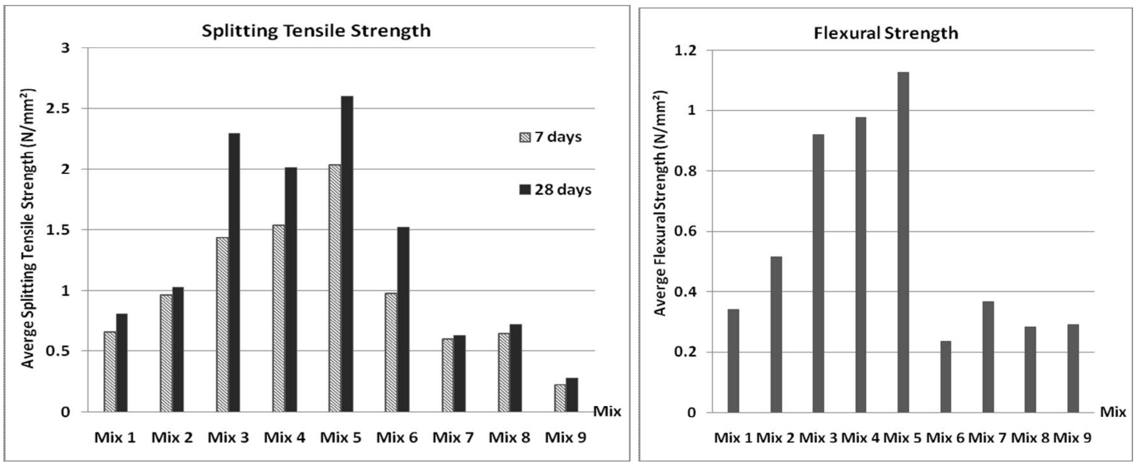

Fig. 9: Results of Splitting Tension Test and Flexural Test for the Mixes

Here, the cohesive agent, namely sand, and the cement hydration products co-mingle and create two interpenetrating matrices which work together, resulting in improved strength. In group C mixes 6 and 7, cement was partially replaced by silica while keeping the cement / aggregate ratio 0.4, causing decrease in 28-day mean compressive strength to be 12.7 and 4.2 MPa for 8% and 12% partial replacement of cement by silica, respectively. Similarly, in group D mixes 8 and 9, compressive strength decrease from. The same is observed in group D (mixes 8 and 9), where fly ash was used as partial replacement of cement. The 28-day compressive strength decreased to 6.83 MPa and 4.48 MPa for 12% and 20% partial replacement of cement by fly ash, respectively. The split tensile strength and flexural strength test results show the same tendency for all mixes. Finally, in group E, where fibrillated polypropylene fiber was added to concrete having the mix proportions of mix 5, the average 28-day compressive strength was as high as 34.4 MPa, 30.52 MPa and 21.35 MPa for 0%, 0.1% and 0.2% addition of polypropylene fibers in mixes 10, 11 and 12, respectively.

6.2.2 PERMEABILITY (FLOW RATE) AND POROSITY

Permeability is an important design parameter for pervious concrete since it is required to allow water to penetrate through it when applied as drainage layer in pavements. Permeability mainly depends upon the size of interconnected pores, which are present in porous concrete. Results of permeability and porosity of the various concrete mixes are given in Fig. 11. The water permeability coefficient is calculated using the formula

$$K = L \times \frac{Q}{A(l + h)} \quad (3)$$

Where K is the coefficient of water permeability (mm/s), Q is the amount of water (cc/s), A is the surface area (mm²), h= (h1-h2) water level, L is the thickness (mm).

The porosity is calculated as the difference between dry weight and weight under water according to the equation

$$P = \left(1 - \frac{W_2 - W_1}{\rho_w V}\right) 100 \ \% \quad (4)$$

Where P is the total porosity (%), W_2 is the weight under water (kg), W_1 is the oven dry weight (kg), V is the volume of sample (cm^3), ρ_w is the density of water at 21 °C (kg/cm^3)

Results show slight decrease in permeability with the increase in cement content in mixes 1, 2 and 3. This result agrees with other researchers findings [18]. Typical flow rate for water through pervious concrete is reported to be 120 lt/m2/min to 320 lt/m2/min [4]. Mixes 4 and 5 in which sand was used resulted in very low permeability values, about 55-70% less than all other mixes, although the porosity was high. The least water flow rate was observed for mix 5 with 12% coarse aggregate replacement with sand compared to all mixes. Similar result was obtained by other researchers and explained that sand yielded segmented and partly connected capillary pores [18]. It was recommended that use of sand as partial replacement of course aggregate should be limited to percentages less than 10% to achieve acceptable water permeability [18].Permeability decreases with increase in sand content used as partial replacement of coarse aggregates by 8% and 12% in group B. Results also indicate that permeability was independent of cement replacement by silica or fly ash, and is high enough to be accepted for porous concrete applications. The control porous concrete mix 3 and mix 9 with 20% fly ash cement replacement showed nearly the same water permeability.

The porosity of the tested mixes ranged from 16.71 % to 32.5 %, which are acceptable.

Mixes 1, 2 and 3 showed equal porosity percent, indicating that increase of cement content or cement paste/aggregate ratio had slight effect on porosity. As expected, the inclusion of sand as partially replacement of coarse aggregate in mixes 4 and 5 reduced porosity substantially by approximately 25% in comparison to the control mix 3 in which sand was entirely absent. Also, results show that the porosity is not significantly affected by partial replacement of cement by silica or fly ash. The obtained results agree with those in the literature [20].

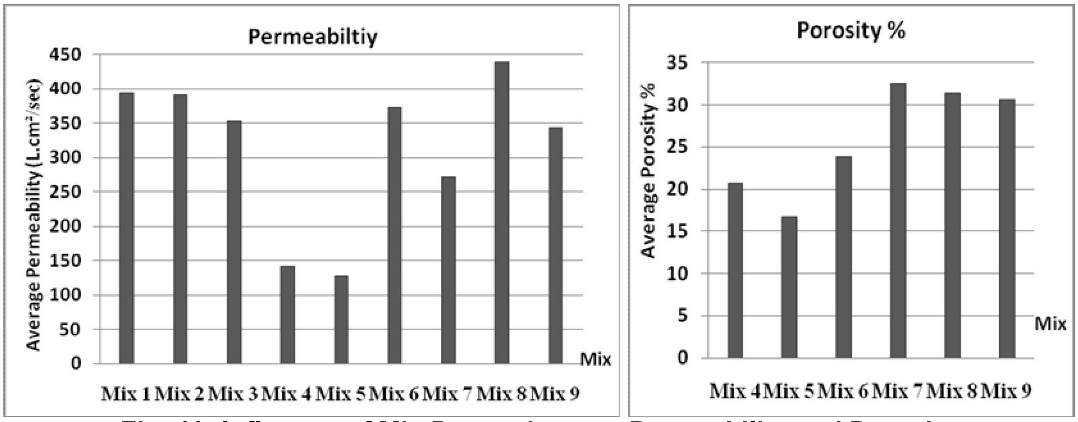

Fig. 10: Influence of Mix Proportions on Permeability and Porosity

7. CONCLUSIONS

In this research work an experimental program was conducted aiming to enhance the properties of sustainable porous concrete through mix design. Pervious concrete mixtures were prepared with different mix proportions. The studied variables were the cement paste/aggregate ratios, partial replacement of coarse aggregates with sand, partial replacement of cement with silica and fly ash, as well as addition of fibrillated polypropylene fiber to the mix. Laboratory tests were made on fresh and hardened concrete to investigate the influence of the studied variables on the physical and mechanical properties of pervious concrete and enable selection of the optimum mix achieving the desired properties.

Based on the experimental results obtained from this study, the following conclusions can be drawn:

1. All the studied mix proportions produced porous concrete with standard density of 17.4 - 24.3 kN/m³ and loose density 14.4 - 22.1 kN/m³, which are within the common values for pervious concrete.
2. The standard compaction test gave higher values for density than loose compaction density.
3. All the mixes yielded compaction factors that were in the range of 71% to 83.55%, which is acceptable.

4. The average values for compressive strength and splitting tensile strength obtained from samples tested 28 days after casting were higher than those obtained from tests 7 days after casting, as is expected.

5. The 28-days compressive strength of all the tested mixes was within the generally acceptable range.

6. Increasing the cement paste/aggregate ratio resulted in significant increase of compressive strength from, splitting tensile strength and flexural strength. The 28-day compressive strength increased from 6.2 MPa to 23.3 MPa for cement aggregate ratios 0.25 and 0.40.

7. The partial replacement of coarse aggregate by sand increased the compressive strength, splitting tensile and flexural strength. Yet considerable decrease in porosity and permeability were obtained.

8. Cement partial replacement by silica decreased the 28-day compressive strength to 12.7 and 4.2 MPa (i.e. decrease by 45 and 80%compared to the control mix) for 8% and 12% silica replacement, respectively.

9. Cement partial replacement by fly ash decreased the 28-day compressive strength to 6.8 and 4.5 MPa (i.e. decrease by 70 and 80%compared to the control mix) for 12% and 20% fly ash replacement, respectively.

10. The effective porosity ranged from 17% to 33% for the tested mixes,

11. The results show that the porosity slightly increased mixes with partial replacement of cement by silica and was nearly not affected by the partial replacement of cement by fly ash.

12. The concrete mixes with higher porosity showed high water permeability and low compressive, splitting tensile and flexural strength. The results verify the generally accepted rule that porosity and compressive strength are inversely related.

13. The lowest water permeability was observed for the porous concrete with 12% coarse aggregate replaced with sand.

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