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Experimental Investigation on Mechanical and Durability Properties of Pervious Concrete

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Abstract: *The term pervious concrete designates a near-zero-slump, open-graded material involving of Portland cement, coarse aggregate, little or no fine aggregate, admixtures, and water. The amalgamation of these ingredients will produce a hardened material with associated pores, ranging in size from 2 to 8 mm, which allows water to pass through simply.*

The pervious concrete is produced by using conventional cementitious materials, aggregates, and water. This concrete is tested for its properties, such as porosity, water absorption, soundness test, compressive strength, water permeability, split tensile strength, and flexural strength. The most important property of pervious concrete is its water permeability. According to American Concrete Institute (ACI), they provide some guidelines for mix design of pervious concrete in ACI 522R. This project was aimed to develop and test three design mixes according to ACI 522R of pervious concrete to identify the appropriate mix which would provide the maximum compressive strength with an acceptable permeability rate.

OPC 53 grade cement, coarse aggregate of size 20 mm, fine aggregate as 5%, 10% and 20% replacement of coarse aggregate were the materials used in this project. Based on the results, a design mix having 10% fine aggregate with a compressive strength of 5.23 MPa @ 28 days with a maximum coefficient of permeability of 3.12 cm/sec , having porosity of 16.14% was identified as the optimum.

Keywords*— Pervious Concrete, Mix Design, Compressive Strength, Split Tensile Strength, Flexure Strength, Permeability, Porosity, Density, Soundness and Water Absorption*

1. INTRODUCTION

1.1 Background

Conventional normal weight Portland cement concrete floor is normally used for sidewalk construction. The impervious nature of the concrete sidewalks leads to the increased runoff into the draining system, over-burdening the system and creating excessive surging in built-up areas. Pervious concrete is fetching significantly popular during recent decades, because of its potential assistance in solving environmental issues. Pervious concrete is a kind of concrete with significantly high water permeability compared to normal concrete. This has been mostly developed for draining water from the ground surface, so that storm water runoff is condensed and the groundwater is recharged.

Pervious concrete has been urbanized in the United States in order to meet US Environmental Protection Agency (EPA) storm-water regulation necessities. In 2003, the world's Portland Cement production reached 1.9 billion tonnes. The most populated countries on the planet, namely China and India, produced 41.9% and 5.2% respectively of the world's cement outcome. Therefore we need to reduce the consumption of cement too. Through, mix design mentioned in this paper we can reduce cement content nearly 50% when compared to conventional concrete.

In, Australia pervious concrete has been developed for key performance with regards to water sanitation urban design which seeks to enhance required water quality and amount in urban area. Pervious concrete blocks have recently been used as one of the permeable paving systems.

1.2 Objectives

The main objectives of this project were to:

a) Investigate the performance characteristics of the pervious concrete.
b) Determine the effect of fine aggregate extent on the hardened properties of the pervious concrete.

2. MATERIALS AND METHODOLOGY

2.1 Materials

a) Ordinary Portland cement

Ordinary Portland cement as per Indian specifications IS 8112:1889 was used for this investigation. Panyam cement having grade 53, OPC was used in this project. The properties of Panyam cement which is used in this project were tabulated in the next section.

b) Aggregates

Aggregates are procured locally for the casting work of concrete specimens. The aggregates were tested for their properties in accordance with the IS standards. Locally available river sand is used as a fine aggregate for concrete. Tests for fine aggregate and coarse aggregate were conducted as per IS: 383-1970. Also the physical properties of locally available coarse aggregates of size 12mm are shown below.

TABLE 1
Physical properties of materials

S.no.	Property	Value	Range
1	Specific gravity of cement	3.29	~ 3.15
2	Specific gravity of coarse aggregate (20mm)	2.96	2.5 - 3.0
3	Specific gravity of fine aggregate	2.78	2.5 to 3.0
4	Water absorption of coarse aggregate (%)	0.3	0.1 to 2.0
5	Unit weight of coarse aggregate (kg/m^3)	1822.9	1600 to 1870

c) Water

Water plays important role in concrete preparation as it is actively participates in chemical reaction with cement. Pure portable water was used for the preparation of concrete mixture.

d) Mix design

For the designing of pervious concrete mixture proportion there were no IS code recommendations. According to ACI 522R, provide guidelines for the mix design of material proportioning of pervious concrete. According to mix design there we get three different proportions of fine aggregate to be used; they are 0%, 10%, 20%. Therefore three mix designs were established by keeping water-cement ratio constant.

Table 2
Designation of mixes

Mix no.	Cement Kg/m^3	Fine aggregate, %	Coarse aggregate Kg/m^3	Fine aggregate Kg/m^3	Water Lit./m^3	Density Kg/m^3	W/C %	A/C %
#1	157	0	1382	0	63	2099	0.4	8.8
#2	154	10	1298	130	62	2154.65	0.4	9.27
#3	150	20	1186	237.2	60	2140.5	0.4	9.48

Fig. 1: Pervious concrete specimens of cubes and cylinders

3. LABORATORY TESTS

The mechanical properties of pervious concrete such as compressive strength, split tensile strength, flexural strength and rebound hammer test and durability properties like water permeability, porosity, water absorption and soundness were determined according to their relevant ASTM standards.

3.1 Compressive strength test: (ASTM C39)

The compressive strength of concrete (150 mm × 150 mm × 150 mm) is tested by means of compressive testing machine according to ASTM C39. All proportions were tested after 7 and 28 days curing period at standard 20 ± 2°C. Along with this test a Non-Destructive Test (NDT) is also conducted called Rebound hammer test to the all mix proportions.

3.2 Split tensile strength test: (ASTM C496)

The splitting tensile strength tests were performed according to the Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens (ASTM C496). Split tensile strength test on concrete cylinder is a method to determine the tensile strength of concrete. Specimens of 150mm diameter × 300mm height were used for this test. The specimens were tested for 7 and 28 days.

3.3 Flexural strength test: (ASTM C78)

For each mix, totally twelve number of prism of size 150 x 150 x 700 mm were cast and tested using Flexural Testing Machine (FTM). The specimen was placed perpendicular to normal axis on the platform of the flexural testing machine. The load was applied gradually until the failure stage. The ultimate load was noted and calculated the flexural strength of corresponding specimen. The flexural strength test will be carried out on the specimens at the end of 7 days and 28 days of curing.

3.4 Permeability test: (ASTM D5084-03)

The procedure to be followed to conduct permeability test is as follows:

Firstly the specimens were wrapped up with the polythene sheet tightly so as to not escaping the water from the sides of specimen as shown in figure 3.1(a). Arrange the permeability setup on a flat platform, to maintain perfect heads of water. Place the cylindrical specimen in the PVC mould as shown in figure 3.1(c). Place the graduated PVC pipe of 150mm dia. in such a manner that the specimen should be surrounded by that PVC pipe. Priming should be done to release all air voids present in the specimen and that of setup too. Then pour the water in the graduated pipe until the water level reaches the final head (h_2). Then release the valve and start the timer at a time when the water level is at final head (h_2). Record the time taken by the water to reach the initial head (h_1).

Fig. 2(a)

Fig. 2(b)

Fig. 2(c)

Fig. 2: Falling head Permeability test for pervious concrete cylinders

The coefficient of permeability (k) was determined applying equation,

$$k = (al/At) * \text{In}(h_2/h_1)$$

Where:

k = coefficient of permeability, cm/sec
a = cross sectional area of the standpipe, cm^2
l = length of sample, cm
A = cross sectional area of specimen, cm^2
t = time in seconds from h_1 to h_2
h_1 & h_2 = initial and final water level respectively, cm.

3.5 Porosity: (ASTM C1754)

Ghafoori and Dutta, "expressed that the bulk of pores in porous concrete are shaped by the areas left between coarse aggregates and that they distinguished between porosity and air void content. In their analysis, the fraction of measureable voids migrated by fluids within their experiments was termed porosity and therefore the total of measureable voids between aggregates and entrained or entrapped air in the cement paste was termed air content. In different words, the porosity of porous concrete may be outlined differently. During this study, for clarity, the measureable voids are outlined because the effective porosity since this relates to permeability and also the overall air content is consequently outlined as total porosity.”

3.5.1 Effective Porosity:

The effective porosity was determined by testing the volume of water displaced by samples. The sample was firstly oven dried at 110°C for 24h and then immersed in water for up to 24h. By measuring the difference in the water level before and after immersing the sample, the volume of water repelled by the sample (V_d) can be readily determined. Subtracting V_d from the sample bulk volume (V_b) yields the volume of open pores. This volume was then expressed as a percentage as an effective porosity percentage:

$$\text{Effective porosity, } n = (V_b - V_d)/V_b \ 100\%.$$

$$\text{Then, void ratio, } e = \frac{n}{1-n} X \ 100 \ \%$$

3.6 Unit weight and water absorption tests:

The unit weight of the pervious concrete was measured according to ASTM C29 in oven-dry conditions, and water absorption was measured according to ASTM C830. The pervious concrete specimen was hardened, stripped, placed in the oven, and dried at 105 ± 5^{0}C until the weight was constant. Then the dry weight W_{dry} was measured, and the specimen volume V was calculated using the unit weight of concrete expression below:

$$\text{Unit weight} = \frac{W_{dry}}{V} \ Kg/cum$$

The oven dried specimen was immersed in 20 ± 5^{0}C water for 24 h, removed, wiped with a damping cloth immediately, and weighed to obtain the wet mass W_{wet}. The water absorption was calculated by the following equation:

$$\text{Water absorption (\%)} = \frac{W_{wet} - W_{dry}}{W_{dry}} X \ 100$$

3.7 Soundness test: (ASTM C1012)

The soundness of a typical pervious concrete is determined by the standard test method followed by ASTM C1012.

a) Preparation of solution (Sulfate Solution, Na_2SO_4):

Each litre of solution shall contain 50.0g of Na_2SO_4 dissolved in 900 ml of water, and shall be diluted with additional water to obtain 1.0 L of solution (5% by weight of water). Mix the solution on the day before use, cover, and store at 23.0 6 2.0°C (73.5 6 3.5°F). Determine the pH of the solution before use; reject the solution if the pH range is outside 6.0 to 8.0.

b) Preparation for test (dry-wet immersion cycles):

The cube specimens (150mm*150mm*150mm) were immersed in the sodium- sulfate solution (5% by weight) for 16 h; then the specimens were dried in an oven at a temperature of 60^{O}C for 12h, and underwent a natural cooling for 2 h. These two steps represented one drying–wetting cycle. The drying–wetting procedure is to be done for 10 cycles.

c) Calculation of change in weight:

The oven dry weight of the specimen is first recorded as W1 and then the oven dry weight of the specimen of last cycle i.e., 10th cycle is recorded as W2. In this manner the weight of the cubes of each three proportion is tabulated. The % change in weight of pervious concrete specimens is calculated with the following formula,

$$\Delta W = \frac{W1 - W2}{W1} \times 100 \ \%$$

Where,

ΔW= % change in weight,
W1= oven dry weight of cube before immersion,
W2= oven dry weight of cube after 10th cycle.

4. RESULTS AND DISCUSSION

4.1 Compressive strength:

Table III summarizes the compressive strengths of each cube specimen. The specimens were tested at the age of 7 days and 28 days for water cured pervious concrete. The compressive strengths develop with age.

Table 3
Compressive strength of pervious concrete

	Compressive strength (N/mm^2)	
Age of curing (days) →	**7**	**28**
Mix #1	2.4	2.97
Mix #2	4.53	5.23
Mix #3	7.56	7.75

In Table 3, the pervious concrete showed significantly lower strength. The pervious concrete had the maximum compressive strength of 7.75 MPa at 28 days which is having 20% fine aggregate. As expected, pervious concrete resulted in low compressive strength due to its higher porosity.

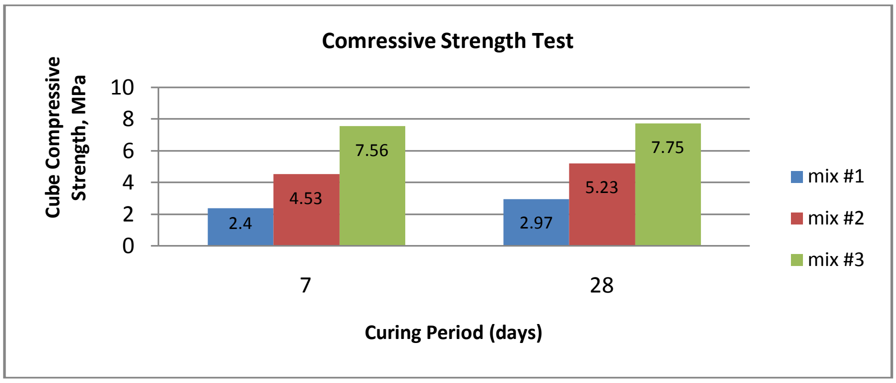


Fig. 3: Compressive strength Vs curing period

4.2 Rebound hammer test (N.D.T):

Table 4 summarizes the rebound hammer test of each cube specimen. The specimens were tested at the age of 7 days and 28 days for water cured pervious concrete. The compressive strength results of pervious concrete with respect to rebound hammer test are tabulated below with age.

Table 4

Compressive strength test results by rebound hammer

	Compressive strength (N/mm^2)	
Age of curing (days) →	**7**	**28**
Mix #1	25.5	13.73
Mix #2	24.5	16
Mix #3	26	27.46

By comparing compressive strength results of table 3 and table 4 i.e., destructive and non destructive tests conducted on test specimens, we can say that the strength of pervious concrete should not estimate with the non destructive techniques.

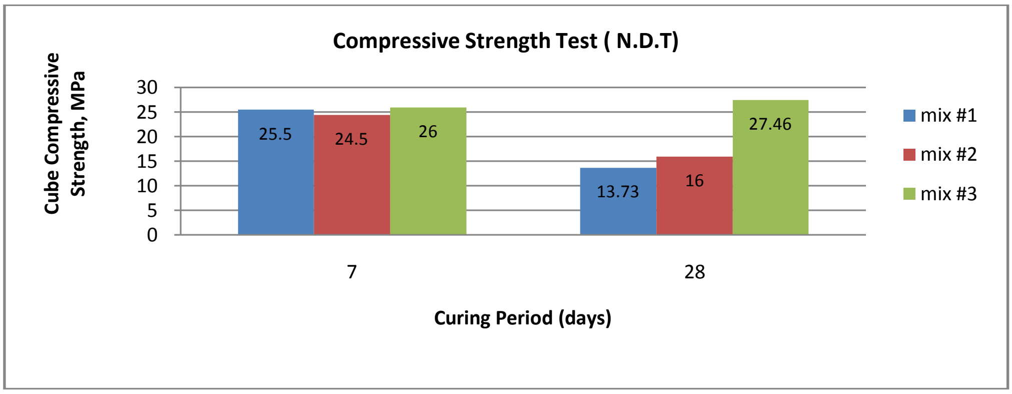


Fig. 5: Compressive strength (N.D.T) Vs curing period

This enormous change in the strength of destructive and non destructive tests was due to absence of fine aggregate. Because, due to lack of fine aggregate concrete specimens will have open pore structure at which the load will directly impose on coarse aggregate while the specimens were test with rebound hammer equipment i.e., the value showed on the rebound hammer reflects the strength of aggregates but not concrete.

4.3 Split tensile strength test:

Table 5 summarizes the splitting tensile strengths of each cylindrical specimen. The specimens were tested at the age of 7 days and 28 days for water cured pervious concrete. The splitting tensile strengths develop with the age.

Table 5
Split tensile strength test results

	Split tensile strength (N/mm^2)	
Age of curing (days) →	**7**	**28**
Mix #1	0.46	0.597
Mix #2	0.74	0.837
Mix #3	0.851	0.91

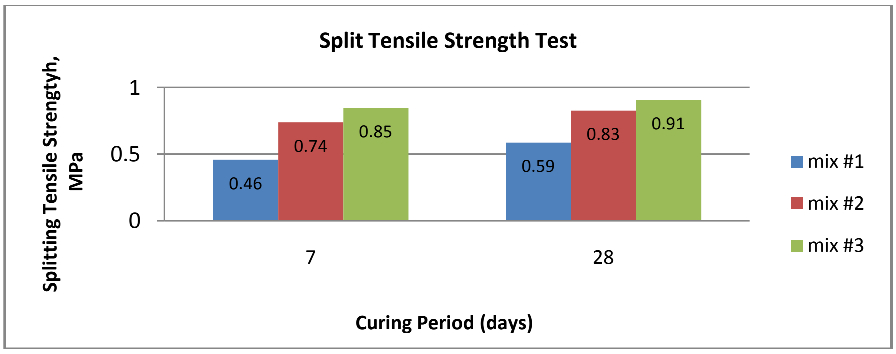


Fig. 6: Split Tensile Strength Vs Curing Period

In Table 5, the pervious concrete showed extensively lower tensile strength. The pervious concrete had the maximum tensile strength of 0.91 MPa at 28 days which is having 20% fine aggregate. Pervious concrete resulted in low tensile strength due to its higher porosity as which we observe in compressive strength results.

4.4 Flexural strength test:

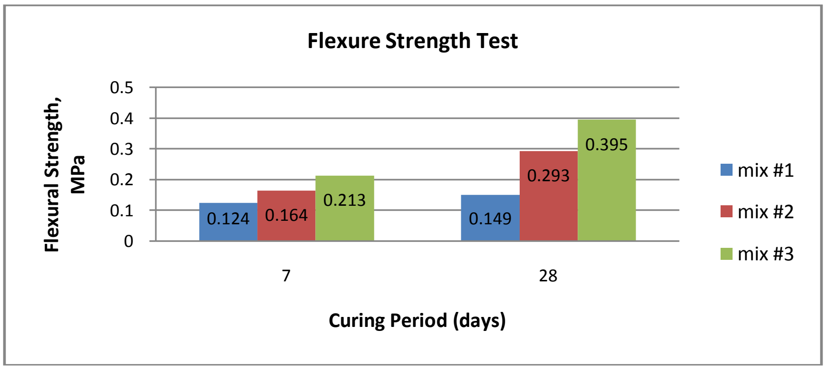
Table 6 summarises the flexure strength of each beam specimen. The specimens were tested at the age of 7 and 28 days for water cured pervious concrete. The flexure strengths develop with the age.

Table 6
Flexural strength of pervious concrete

	Flexural strength (N/mm^2)	
Age of curing (days) →	**7**	**28**
Mix #1	0.124	0.149
Mix #2	0.164	0.293
Mix #3	0.213	0.395

In Table 6, the pervious concrete showed inferior flexure strength at 7 days of curing. The pervious concrete had the maximum flexural strength of 0.395 MPa at 28 days which is having 20% fine aggregate. Pervious concrete resulted in low flexural strength due to its higher porosity as which we observe in previous test results. At 28 days of curing period the specimens showed good flexural strength when compared to 7 days curing.

Fig. 7
Flexure strength Vs curing period



4.5 Permeability test:

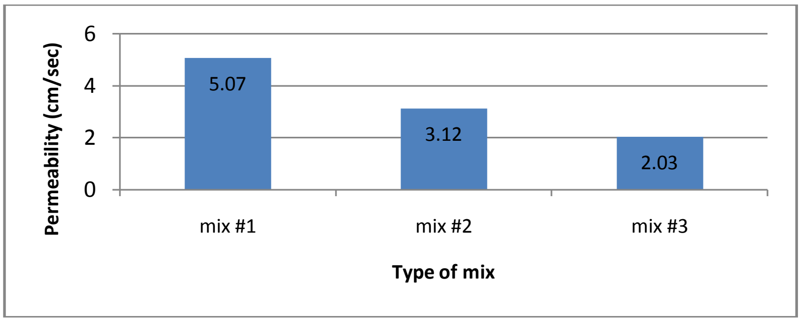
Table 7 summarizes the permeability of water through the pervious concrete. The specimens were tested at the age of 28 days for water cured pervious concrete.

Table 7
Falling head permeability test

Designation of mix	Permeability (cm/sec)
Mix #1	5.07
Mix #2	3.12
Mix #3	2.03

The permeability coefficient varied from 2.03 cm/s to 5.07 cm/s. This result is exciting because in comparison to the traditional pervious concrete (permeability coefficient usually under 1.5 cm/s), this typical mix of pervious concrete possessed more favorable water permeability even at much lower porosity. This excellent permeability could be attributed to the innovative physical structure, i.e., the top-bottom interconnected pore path, which also strengthens the concrete.

Fig. 8
Permeability Vs Amount of fine aggregate



4.6 Void ratio:

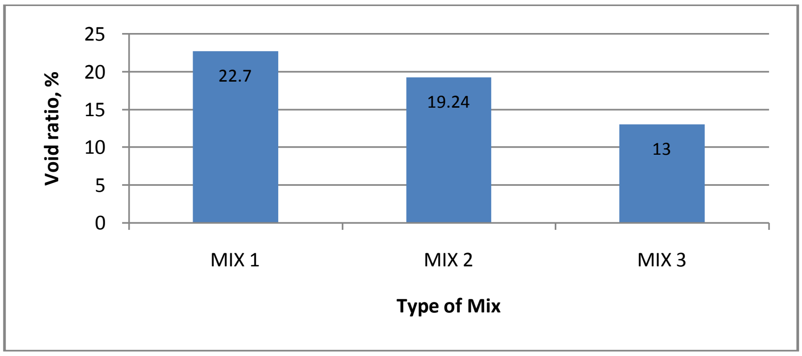
Table 4.6 shows the void content of the pervious concrete. The cubes were tested at the age of 28 days for water curing.

Table 8
Void ratio test results

Designation of mix	Void ratio (%)
Mix #1	22.7
Mix #2	19.24
Mix #3	13

From fig. 9, it can be noted that the range of the void content was between 13 and 23%. As the matter of fact the volume of voids decreases with the increment of fine aggregate content. The highest void content was obtained in mix #1. By decreasing the fine aggregate, the void content of mixtures will increase.

Fig. 9
Void ratio Vs Amount of fine aggregate



4.7 Density and water absorption:

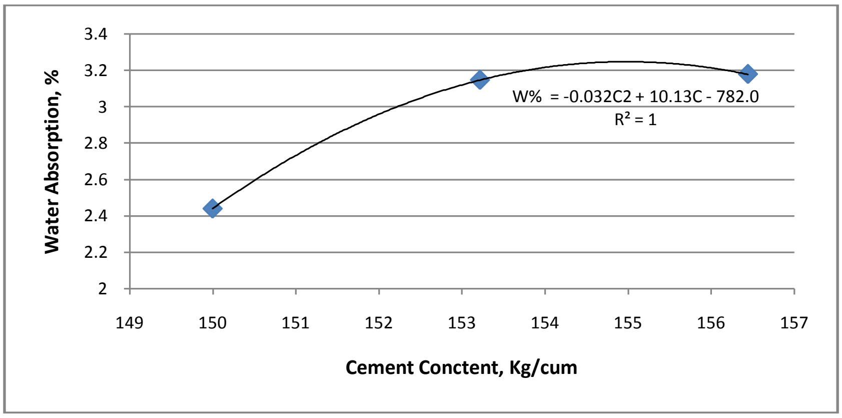
Table 9 summarizes the unit weight (or) density and the water absorption of the pervious concrete. The specimens were tested at the age of 28 days for water cured pervious concrete.

Table 9
Density and Water absorption

Designation of mix	Theoretical density, Kg/m^3	Density, Kg/m^3	Water absorption, %
Mix #1	2099	1919.11	3.18
Mix #2	2154.65	2154.37	3.149
Mix #3	2140.5	2133.33	2.44

From mix design stated in previous section, we calculate the density of the mixes having 3 different F.A percentages by theoretically and then by following experimental procedures, again we calculate the densities of same mixes which means by practical. From table 9 we can say that densities are almost equal which are calculated in both theoretical and practical methods. On the other hand water absorption of pervious concrete varies with irrespective of density of a mix.

Fig. 10
Cement content Vs Water absorption



From fig. 10, we can say that the absorption of water by the pervious concrete specimen increases with the cement content increases. From this it is evident that the main cause of decrement in water absorption is amount of cement which absorbs the water, as the cement content decreases the volume of paste need to be absorb the water will decreases eventually the water absorption will also decreases. Here in these design mixes the cement content decreases when the fine aggregate content increases, thereby we can state that water absorption is inversely proportional to the fine aggregate content.

4.8 Soundness test:

Table 4.8 shows the % change in weight or loss in weight of the pervious concrete specimens due to sulfate attack. The cubes were tested at the age of 28 days for water curing.

Table 10
% Weight loss due to sulfate attack

Designation of mix	Loss in weight (ΔW), %
Mix #1	4.90
Mix #2	3.50
Mix #3	3.14

From table 10, it is clear that the weight of concrete specimens is decreased with respect to cement content i.e., the more the cement content the greater will be the deterioration of strength/weight of concrete. In this project mix #1 has highest cement content (157 Kg/m^3) compare to the rest; due to this property the sulfate ions were reacts with the hardened cement paste to a great extent to form ettringite on the surface of concrete which leads to deteriorate the weight of concrete. Though mix #3 has lowest rate of weight decrement, it is not considerable due to having a least porosity nature which prevents our ultimate goal to provide a better porosity. So it is better to adopt the mix #2 having optimum cement content (154 Kg/m^3) with the better porosity rate and having good strength properties.

Fig. 11: Cube before sulfate attack

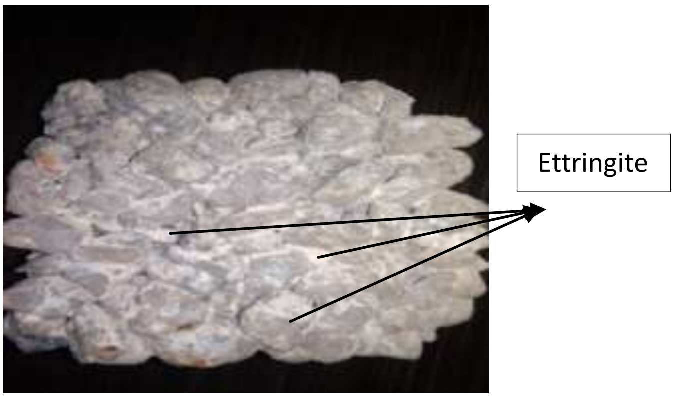
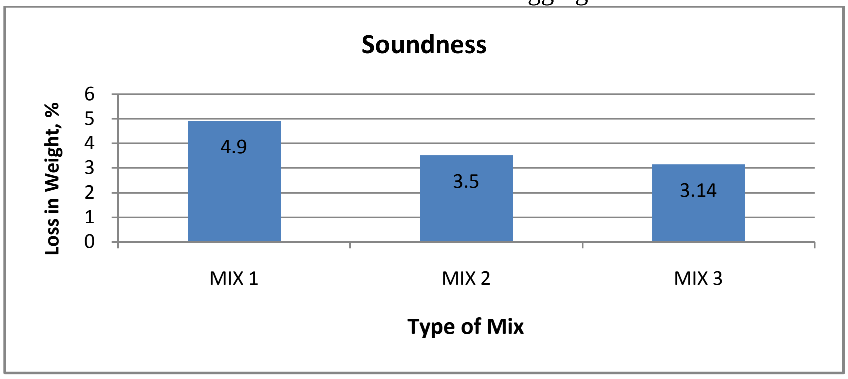


Fig. 12: Cube after sulfate attack

From fig. 11 & 12, it shows the variation of specimens that before and after immersion in the sodium sulfate solution respectively. From fig. 12, it is clearly seen that, after completion of 10 successive immersion (wet-dry) cycles, a white precipitate called as "Ettringite" is formed which directly reflects the disintegration of concrete.

Fig. 13

Soundness Vs Amount of fine aggregate



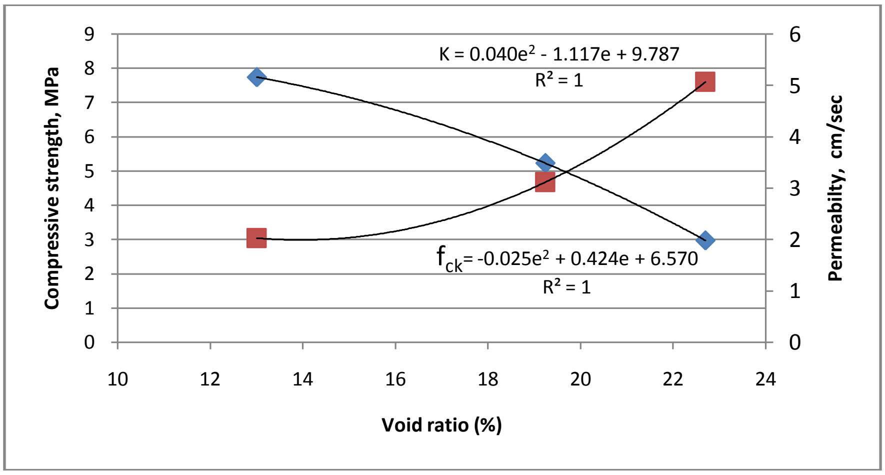
4.9 Relationship between Compressive strength, void ratio and permeability:

From fig. 14, it is clear that the compressive strength considerably decreases with the void ratio. Though the maximum compressive strength i.e., 7.75MPa is attained with the 20% F.A but it is undesirable due to its lowest void content i.e., 13% which doesn't serves our intended purpose, which to allow the water to pass through it effectively.

On the other hand the maximum void content i.e., 22.7% is achieved by using no F.A with a least compressive strength of 2.97MPa which deliberately cause the damage.

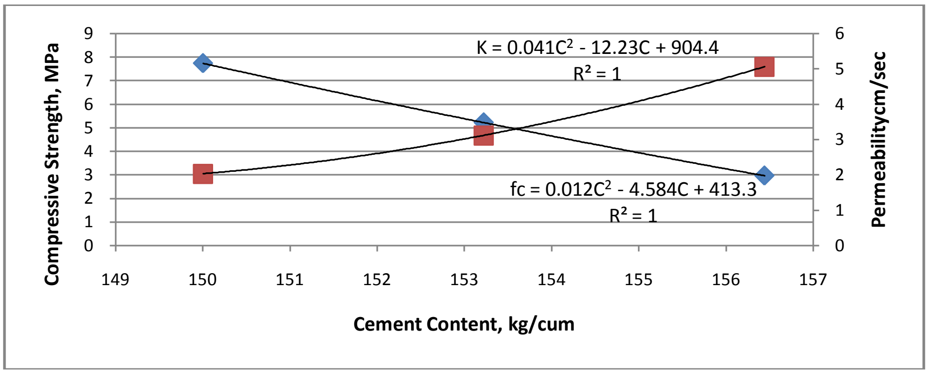
Fig. 14

Compressive strength and permeability Vs Void ratio



4.10 Relationship between compressive strength, cement content and permeability:

Fig. 15
Compressive strength and permeability Vs Cement content

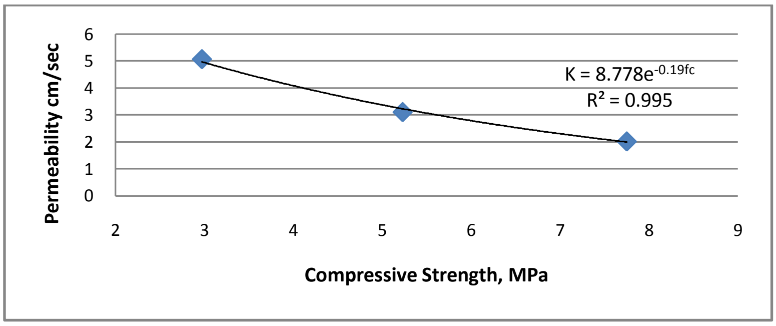


The above figure 15 shows that the variation of compressive strength and permeability when compared to cement content. From the design mixes the cement content decreases while we increase in fine aggregate content (mix 1 has cement content of 156.66 Kg/m^3, mix 2 has cement content of 153.22 Kg/m^3 and mix 3 has cement content of 150 Kg/m^3). As a matter of fact that while increase in cement content with the no change in water demand there should be an increase in compressive strength. Hence cement content is directly proportional to the compressive strength. But here in this project it is totally contrary because the compressive strength increase with a decrement in cement content by maintaining water cement ratio constant as 0.4.

From fig. 15 we can say that permeability decreases when cement content decreases. From table 2.2, it shows that cement content and aggregate-cement (A/C) ratio were inversely proportional to each other which reflect an increase in aggregate content happens with the decrease in cement content. From fig. 15 though the permeability rate increases with an increase in cement content but there occur the decrement in aggregate content which leads to increase in permeability rate.

4.11 Comparison of Compressive Strength and Permeability:

Fig. 16
Compressive strength Vs Permeability



From the above fig. 16 we compare the compressive strength with the permeability of three design mixes. In the science of concrete, it is clear that as the strength of concrete increases, the permeability will ultimately decreases. Strength of the concrete will directly relates to the aggregate-cement (A/C) ratio, therefore the concrete strength increases while there is an increase in aggregate-cement (A/C) ratio as a result there must be a decrement in permeability. As far as strength consideration we have to go for the mix which gives maximum strength, but here in case of pervious concrete we have to consider the permeability along with the strength. Therefore, the mix which would have good strength with the better permeability will finally be an optimum mix i.e., mix #2.

5. CONCLUSIONS

The mechanical and durability properties of pervious concrete made with different proportions of aggregate are examined. Based on the obtained results the following conclusions can be drawn:

1. Amongst the three mix proportions mix #3 has the highest compressive strength but taking the permeability into consideration mix #2 is the optimum mix for the compressive strength. Because though mix #3 has compressive strength of 7.75MPa, it has the lowest permeability (2.03cm/sec) character.
2. In the same manner of compressive strength, mix #2 is proved as the optimum mix for the split tensile strength and flexural strength through the experiments which we have shown in previous chapters.

3. Since the pervious concrete doesn't have smooth surface due to lack of fine aggregate, the non destructive test (Rebound Hammer Test) couldn't perform well because N.D.Ts require smooth surface. On comparing the compressive strength results of N.D.T with destructive type, it shows so much variation. Hence N.D tests are not preferable to estimate the strength of pervious concrete.
4. Water permeability is one of the important characteristics of pervious concrete, in this work mix #1 had shown the maximum permeability but the same mix have least strength amongst three mixes. So, mix #2 having the compressive strength of 5.23 MPa with the permeability of 3.12 cm/sec is concluded as the optimum mix.
5. As a typical range of void ratio for pervious concrete is 15-30%, in our experiments from obtaining results mix #2 having 19.24% of void ratio and strength of 5.23MPa is found to be optimum.
6. From the test results of density, we came to know that the densities obtaining from both theoretical and practical approaches are in similar manner. Though the mix #3 having density lower than the mix #2 and exhibit highest strength amongst three mixes, it will not considered as optimum because of its least porosity nature. Therefore mix #2 having density of 2155 Kg/m^3 is kept as optimum.
7. From water absorption test results, it is clear that, absorption of pervious concrete is greatly influenced by cement content. Amongst the three mixes, mix #2 having the water absorption of 3.15 % having the moderate cement content of 153.22 Kg/m^3 is kept as optimum.
8. A typical rigid pavement should not exceed the soundness of 12% when it is get contact with the sulfates. Therefore our results regarding soundness are in safe zone. From the obtained results of soundness and by observing strength parameters, mix #2 having soundness of 3.5% is kept as optimum.
9. By observing all above conclusions, we conclude that mix #2 having fine aggregate of 10% and A/C ratio of 9.27 with a density of 2154.65 Kg/m^3 is found as optimum.

References

[1] ACI Committee 522, report on pervious concrete, 522R-10, American Concrete Institute, Farmington Hills, MI, USA.
[2] Pervious concrete pavements, http:// www.perviouspavement.org, maintained by National Ready Mixed concrete Association (NRMCA).
[3] Manoj Chopra et al. Storm water Management Academy, University of Central Florida, Orlando, FL 32816
[4] K.S. Elango, V. Revathi, "Fal-G Binder Pervious Concrete", Dept. of Civil Engineering, K.S.R. College of Engineering, Tiruchengode, India
[5] Elnaz Khankhaje et al. "Properties of quiet pervious concrete containing oil palm kernel shell and cockleshell", Faculty of Civil Engineering, University Technology Malaysia, 81310 UTM Skudai, Johor Bahru, Malaysia
[6] Milena Rangelov et al., "Quality evaluation tests for pervious concrete pavements' placement", Washington State University, 2001 East Grimes Way, Pullman, WA 99164-5815, United States
[7] Hammad R. Khalid, et al., "Water purification characteristics of pervious concrete fabricated with CSA cement and bottom ash aggregates", Department of Civil and Environmental Engineering, Korea Advanced Institute of Science and Technology, Daehak-ro 291, Yuseong-gu, Daejeon 34141, Republic of Korea.
[8] Mohd Warid Hussin, "Properties of sustainable light-weight pervious concrete containing oil palm kernel shell as coarse aggregate", UTM Construction Research Centre (UTM CRC), Faculty of Civil Engineering, University Technology Malaysia, 81310 UTM Skudai, Johor Bahru, Malaysia.
[9] Di-tao Niu et. al., "Experiment study on the failure mechanism of dry-mix shotcrete under the combined actions of sulfate attack and drying–wetting cycles", School of Civil Engineering, Xi'an University of Architecture and Technology, Xi'an 710055, China.
[10] Nicholas A. Brake, "Flexural strength and fracture size effects of pervious concrete", Lamar University, United States.
[11] Anush K. Chandrappa, "Comprehensive investigation of permeability characteristics of pervious concrete: A hydrodynamic approach", Department of Civil Engineering, Indian Institute of Technology Kharagpur, West Bengal 721 302 India.
[12] Zhiquan Zhang, "Influence of crushing index on properties of recycled aggregates pervious concrete", School of Civil Engineering, Chang'an University, Xi'an 700061, PR China.
[13] Rui Zhong, Compression response of normal and high strength pervious concrete, Department of Civil and Environmental Engineering, University of Connecticut, 261 Glenbrook Road, United States.

