Pervious Concrete: An Overview and Experimental Study

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Abstract. The present climatic changes are occurring because of the various activities of the humans such as urbanization and increasing threat of green-house gas (GHG) emissions resulted in precipitation increase in many geographical areas. In view of this, OPC based pervious concrete (PC) was developed in order to enhance the sustainability of the urban drainage systems (UDS). No fines concrete also coined as OPC based pervious concrete (PC) which is a versatile material with high porosity content applicable in flat work applications which allows the water from various sources such as precipitation and other sources to flow through and in turn recharges the ground water levels. Apart from these aspects, PC can significantly decrease the solar radiation absorption and urban heat storing potential which leads to the protection of the environment as well as the health and safety of the human beings. Generally, no fines concrete generally consists of cementitious paste to overlay the coarse aggregate which relates the vanderwall bond between the coarse aggregate and the cement. However, PC requires periodical maintenance in order to prevent any sort of clogging within the voids by the vegetation and sediments. In the present investigation, the overview of PC as well as the experimentation to study the mechanical strength characteristics by the utilization of industrial waste exhausts materials like fly ash. The study conferred that addition of fly ash to pervious concrete significantly enhances the mechanical strength characteristics of PC. An equation is proposed to establish a correlation between split-tensile strength and flexural strength of PC and it is in good agreement with the previous studies.

Key words: Pervious Concrete, Coarse Aggregate, Industrial Waste Exhausts, Mechanical Strength Characteristics

1. Introduction

By the continuous urbanization and rapid growth in population, the increase in the OPC based pervious surfaces was observed. The percolation of runoff water from various sources was being disturbed, results in causing the increase in surface runoff which lead to flooding of human localities and erosion etc. Regarding this aspect, pervious or no fines concrete has the ability to pass the runoff water through it and recharge the ground water levels. Keeping in this in regard, extensive research was being done on pervious concrete for the storm water control measures. Such pavement systems with relative permeability can surely contribute to resolve the various problems in terms of drainage.
and decreasing the flash flooding risk which resulting from the rapid continuous urbanization development.

PC was a distinctive concrete type that was indicated by an interconnected pore structure and high porosity content usually in the range of 15-35% by volume. The utilization of PC can significantly reduce the risk of flooding, increase the ground water, decrease the storm water runoff, decrease no waste during the contact with tires of the vehicle and prevent the skidding and glaring aspect in the time of monsoon season by permitting the water to percolate freely from the pores [1, 2, and 3]. PC can be prepared at lower costs by which it can be contemplated across the major appealing suitable urban drainage systems. However, PC needs timely and scheduled maintenance in order to stop the clogging within the pores by the vegetation and sediments that might interchange its high permeability aspect. Further, PC may also undergo some sort of durability related issues like freeze-thaw cycles, abrasion that deteriorates the wider application aspect of PC.

While the constituent ingredients are same to that of normal PC contains no or little fine aggregate [2, 4]. It has wide range of applications and some major are low traffic pavement like parking lots, sidewalks, medians, high way shoulders etc., Different PC mixes with various aggregate sizes are investigated in the present study.

2. Materials

The mix ingredients of PC are similar to that of normal concrete. The porosity in PC was generated by excluding the fine aggregate content completely. The porosity of the PC was greatly influenced by the type of aggregate, gradation and size of the aggregate, binding volume of the paste [5]. The size of the pores in no fines concrete was also a significant influential factor as it affects the properties like sound absorption and permeability.

The gradation of aggregate in general utilized in PC was generally either size sized or graded between 9.5-19 mm coarse aggregate. PC that was prepared with lone sized aggregate consists of greater permeability, but possesses relatively lower strength development. Even though, 37.5 mm aggregate size was used to prepare PC, in general 20 mm aggregate was utilized. 25 mm lone sized aggregate was also utilized [2]. The utilization of lone sized aggregates was necessary in order to enable the packing of skeleton low enough to provide required open spaces in the matrix. Generally, a relatively uniform huge size of aggregate was generally recommended for having maximum rate of infiltration [5, 6]. Higher aggregate sizes produce larger voids and enhanced permeability aspect. However, the addition of little amounts of sand can also significantly enhance the strength aspect of PC on par with lone sized mixes. It was also furnished that the small fraction of particles with a diameter size less than D10 in the coarse aggregate can significantly affects the mechanical strength characteristic and hydraulic conductivity of the PC [7, 8]. When fine aggregate was utilized in PC, the paste volume should be rearranged in order to maintain the targeted pores content.

PC and SCM's are basically utilized in PC. However, literature reported that the utilization of SCM’s like fly ash and silica fume should be limited to 5-10% respectively so as to eliminate the problems like lower early strength and rapid drying. Trail mixes are very much required to know about the properties and applications of the PC. Densified silica fume was also utilized at a dosage of 5% as an
optimal replacement to enhance the bonding and strength characteristic of PC [9]. Other additions such as fibers and recycled/waste materials also significantly enhance the sustainability and decrease the overall carbon foot print of PC.

Depending on W/B ratio either HRWR or MRWR chemical admixtures should be used in PC so as to enable the ease of handling and in acquiring the in situ casting desired properties. Viscous modifying admixtures (VMA’s) are also used to enhance the stability by decreasing the time of discharge and improve the consolidation and placement [10]. Further, VMA’s are also utilized to prevent the paste to evacuate down and can increase the compression and flexural strength characteristics of PC [10]. Air entrained admixtures are used in PC in the cases of free-thaw, since it damages the PC.

3. Important Properties of PC

PC possess stiff consistency as determined by ‘0’ slump and hence it requires substantial effort of compaction in order to acquire the required mechanical strength characteristic, without considering the permeability properties that are completely based upon the void volume. By bonding of aggregate and cementitious paste, the hardened strength characteristics of PC are generated. There are various factors that affect the strength of PC that includes the cement content, W/B ratio, level of compaction of gradation of aggregate and quality of the aggregate. In order to optimize any optimal design mix, a relation between the permeability and strength was the major role. It was basically proven fact that the compressive strength of PC was related to the paste strength and void ratio and aggregate [2]. Further, it was also to be noted that the effort of compaction or technique will significantly influences the void content. The density of PC typically ranges in between 1600-200 kg/m$^3$ [19, 20], that was relatively less than that of normal grade concrete because of the significant higher volume of voids ranging from 15-35%. A typical correlation between the fresh density and void ratio of PC was shown in Fig.1 [15].

![Correlation: fresh density (F) & Void ratio (VR) [15]](image)

Past studies have identified various procedures in order to generate in-situ compaction technique so as to acquire pertinent results for lab specimens. The methods of compaction that includes vibration, tamping and utilization of proctor hammer [21], but till date, there was no standard type of procedure. PC mixes can develop the compressive strength within the range of 5-30 MPa, that typically ranges about 17 MPa, that was sustainable for a extensive application range like light traffic pavements [2, 4, 14]. Besides, the flexural strength of PC can be within the range of 1-3.5 MPa [4, 19]. Crouch et al., [17] suggested a correlation between the flexural and splitting tensile strength of PC which can be represented by eq.(1).

$$f_r = 0.083 f_{s}^{2/3} \quad ----eq(1)$$

Where $f_r$ = flexural strength of PC ; $f_{s}$ = splitting tensile strength of PC
At a constant amount of cement content, increasing the water to binder ratio from 0.28-0.4 in PC mixes enhances the compressive strength, since it provides a higher amount of paste volume in increased amounts required to summarize the aggregate for bonding the PC matrix. The excess paste clogs the open void structure of PC, by which the reduction in the void ratio and enhancing the compressive strength of the concrete mix [20, 22]. Contrarily, a very low water to binder ratio can tends to decrease in adhesion property between the particles of the aggregate and the placement problems. On par with ordinary concrete, the inclusion of SCM’s can significantly increase the hardened properties of PC. For instance, the pozzolanic reaction that was initiated by silica fume can significantly increase the compressive strength of the PC mixes. Further, the compressive strength of PC can also be enhanced if the cementitous binder content was increased. Small sized aggregate can be utilized to enhance the particle size of the aggregate per unit volume, and thus enhancing the cementitious paste binding area [7].

Research based on polymer modified PC pinnacles the utilization of polymer additives by which the mechanical strength characteristic of PC increases [21]. The emulsions of polymers can fill more pores, by which the strength of the pervious concrete enhances, but the aspect of permeability can be significantly decreased apparently. The inclusion of fibers as secondary reinforcement can also significantly enhances the tensile strength property of PC. Careful selection of fiber was an important aspect as the interaction depends on the type of fiber. However, metallic reinforcement like steel fibers are not suitable for PC as the open voided structure furnishes favorable conditions for corrosion. Fibers that are made of carbon, glass, natural or synthetic can be utilized to improve the performance of PC [12, 14]. Henceforth, the strength of PC can be simultaneously enhanced by compromising the aspects such as permeability and enhancing the paste properties and bond/interface between the aggregate and paste. The below furnished strategies can significantly enhance the strength of PC:
- Increased effort in compaction
- Incorporation of small extent of aggregate into the mix in order to fill up the some portion of voids.

High permeability and porosity properties are the most pertinent characteristics of PC as it consists of high void ratio within the range of 15 to 35%. The differences in permeability of PC may range between 81-730 L/min/m² based on the extent of compaction, void content, and type of materials and sub base rate of infiltration [6]. On par with the strength, the void ratio was directly linked to the permeability/infiltration rate of PC. The permeable void structure was acquired by various compaction techniques utilized to prepare that was type of material. Past research shows that an optimal void content of 15 to 25% provides desired strength and infiltration [11, 20].

The ASTM C 1701/M test methodology was utilized for testing infiltration of cast in-situ PC depending on the falling head permeability method in order to calculate the permeability coefficient (k) utilizing the Darcy’s law. A relationship between the permeability and void ratio of PC was furnished in Fig.2 [15]. The graphs shows a good relationship between the two properties with a determination coefficient ($R^2=0.82$). The non-linearity behaviour was assigned because of the infiltration rate dependency on the void percentage as well as their inter connectivity. Further, the permeability phenomena of PC are also interdependent on distribution of pore-sizes, roughness and their partitioning space [21]. Since a better correlation also exists in between the void ratio and fresh density(Fig.2), it can be recommended that the fresh density test may also acts a proper performance/quality control measure for the PC acceptance, that can be found out by ASTM C1688.
From regression analysis, an equation is proposed to obtain the correlation of void ratio and infiltration capacity rate for any lone sized coarse aggregate based PC and FPC

\[ K = 0.04 e^{0.15 \frac{VR}{eq(2)}} \]

Based upon the literature review findings, an experimental program was planned and executed. From the literature review findings, it was observed that the strength characteristics of lone sized aggregate are not under the desired limits and henceforth, a strategy has been made to incorporate fly ash which is a waste industrial exhaust material as a replacement to cement content in order to enhance the mechanical strength characteristic of PC.

4 Experimentation
4.1 Mix Proportioning

The design approach for PC was basically depends upon the prior selection of meticulously graded coarser aggregate and changing the paste volume until the desired characteristics are acquired. The optimal water content which should be utilized in PC basically depends majorly upon the physical and gradation characteristic of aggregates as well as the type of SCM’s. Typically the W/B ratio ranging from 0.27-0.43 and sometimes blended together with HRWR was basically selected for required workability [6]. The workability was supposed to be adequate when a handful of sample mixture was squeezed and released that results in a mixture which neither crumbles nor becomes void-free [6]. Same methodology was followed in the present study. Different mix proportions that are studied are specified in Table.1
Table.1 Mix Specifications of PC

| Authors     | Year | Cement (C) kg/m$^3$ | Coarse Aggregates (kg/m$^3$) | W/C ratio | Agg/C ratio | Water(W) |
|-------------|------|---------------------|-------------------------------|-----------|-------------|----------|
| Kabagire 7] | 2014 | 195-535             | 1500-1700                     | 0.30      | -           | -        |
| Salim [12]  | 2016 | 340                 | 1460                          | 0.32      | -           | 109      |
| Biligori [13]| 2016 | 321-487             | 1373-1692                     | 0.25-0.35 | 3-5         | 84-161   |
| Boutouil [14]| 2013 | 309                 | 1525                          | 0.3       | 4.9         | 93       |
| Sonebi [15] | 2010 | 315-415             | 1200-1400                     | 0.28-0.40 | 4-6         | 125-154  |
| Wang [16]   | 2009 | 180-380             | 1510-1820                     | 0.24-0.30 | 4.0-10      | 50-100   |
| Hewitt [17] | 2007 | 287-345             | 1542-1620                     | 0.30      | 4.5-5.6     | 87-105   |
| Dutta [18]  | 1995 | 300-413             | 1651-1800                     | 0.37-0.42 | 4-6         | 125-154  |
| Karawi [19] | 2020 | 310                 | 1725                          | 0.3       | 5           | 134      |
| Chockalingam [20]| 2019 | 326             | 1705                          | 0.31      | 5.3         | 132      |

A proper design mix for PC should contain a balanced material composition in order to establish the better properties like durability, strength and permeability. Mix design was done as per the specifications of National Ready Mixed Concrete Association (NRMCA, USA) [23]. The binder materials utilized in pervious concrete mixes are OPC based. Fly ash was utilized at various replacement levels to cement. The cement and fly ash fineness was 360 and 384 m$^2$/kg respectively. Three lone sized coarse aggregates varying from 4-6 mm, 10 to 12 mm and 13 to 20 mm are utilized in PC mixes. The naturally available aggregates are utilized as shown in Fig. 5. Coarse aggregate specific gravity was 2.65 for 10-12 mm and 2.25 for 13-20 mm aggregate respectively. The ratio of water absorption was 12 mm and 20 mm aggregates are 1.5% and 1% respectively. Fine aggregate was willfully excluded and the mix proportions for the present study are furnished in Table.2

Table: 2 Mix Proportions for PC

| Mix        | Cement (%) | Fly Ash (%) | Agg/Binder | Cement(kg/m$^3$) | Fly Ash(kg/m$^3$) | W/C ratio |
|------------|------------|-------------|------------|------------------|-------------------|-----------|
| PC6[M1]    | 100        | 0           | 3.00       | 270              | 0                 | 0.3       |
| PC12[M2]   | 100        | 0           | 3.00       | 270              | 0                 | 0.3       |
| PC20[M3]   | 100        | 0           | 5.70       | 320              | 0                 | 0.35      |
| FPC6[M4]   | 30         | 70          | 5.00       | 120              | 280               | 0.3       |
| FPC12[M5]  | 30         | 70          | 5.00       | 120              | 280               | 0.3       |
| FPC20[M6]  | 30         | 70          | 5.00       | 120              | 280               | 0.35      |
The aggregates are kept in saturated condition for 24 hours and taken out prior to 1 hour of casting. Batching is done keeping the aggregates in SSD condition. The W/B ratio adopted is 0.33 by weight and kept constant for all the mixes. All the mixes are in the specified range of workability. No HRWR was used in any of the mixes. The cast specimen’s sizes and the tests performed are specified in Table 3. The cast specimens are furnished in fig. 4, 5 and 6.

Table: 3 Tests conducted on PC mixes and their specifications

| S.No | Tests conducted          | Specimen size (mm) | Standards specification | Formula                  |
|------|-------------------------|--------------------|-------------------------|--------------------------|
| 1.   | Compressive Strength    | 150x150x150        | IS516:1959 [25]         | $f_{ck} = P/A$           |
| 2.   | Split-tensile Strength  | 150 x 300          | IS5816:1999 [26]        | $f_{exp} t = 2P/ \pi L$  |
| 3.   | Flexural Strength       | 100 x 100 x 500    | IS516:1959              | $f_{exp} s = MY/I$       |
| 4.   | Density(cube specimen)  | 150x150x150        | ASTM C 1688             | D = Cube Weight/Cube volume |
| 5.   | Void content (cube specimen) | 150x150x150 | ASTM C 1688             | Void content (%) = $(T-D)/T \times 100$ where, D = $(Mc-Mm)/Vm$ |

4.2 Preparation Process of Test Specimens

All the mixes are prepared by using a pan mixer in which the ingredients such as cement, coarse aggregate and fly ash are mixed in dry condition for few minutes and then the specified water content was added instantly. The mixing process was continued until a uniform appearance is found out. The fresh PC is tested for wet density and the concrete mix is transferred to standard steel molds of cube, cylinder and prism for hardened concrete testing. The past research had shown that the excessive vibration can cause segregation of PC. The specimens are demoulded after 1 day of casting and cured by covering them with straw and gunny bags. The test specimens are tested at the ages of 7 and 28 days to identify the mechanical strength characteristics as per the specifications of EN 12390-3 [24].

Fig. 3 furnishes an example for PC specimen. It was a blend of good standard aggregate which was covered with desired cementitious paste which tends to the development of disconnected and interconnected pores. A well balance between the disconnected and interconnected pores will tend to PC with desired strength and permeability.
Fig. 3 PC cube specimen

Fig. 4 Prepared PC beds for testing of infiltration capacity characteristic (1 x 1 m)  
(a) 4-6 mm  (b) 10-12 mm  (c) 13-20 mm

Fig. 5 Infiltration property of PC
4.3 Test Results and Discussion

Table 4 furnishes the tests carried out on PC as well as mechanical strength characteristic of PC mixes.

Table 4: Mechanical strength characteristic of PC

| Mix   | PC6 (M1) | PC12 (M2) | PC20 (M3) | FPC6 (M4) | FPC12 (M5) | FPC20 (M6) |
|-------|----------|-----------|-----------|-----------|-----------|-----------|
| Age (days) | 7 28 | 7 28 | 7 28 | 7 28 | 7 28 | 7 28 |
| Compressive Strength (MPa) | 9.8 15.9 | 6.7 10.4 | 5.8 10.6 | 10.3 19.6 | 8.91 15.43 | 6.9 14.2 |
| Split-tensile strength (MPa) | 1.8 2.4 | 0.8 1.5 | 0.9 2.4 | 2.2 2.8 | 1.2 1.7 | 1.4 2.7 |
| Flexural Strength (MPa) | 1.54 2.32 | 0.67 1.34 | 0.7 1.3 | 1.79 2.51 | 1.04 1.61 | 1.1 1.9 |
| Density (kg/m³) | - 2040 | - 1900 | - 1800 | - 2060 | - 2040 | - 1950 |
| Void Content (%) | - 22.7 | - 24 | - 27 | - 13.3 | - 16.8 | - 16.6 |
Fig. 7 (a, b, c) furnishes the impact of aggregate size and SCM i.e., fly ash with 7 and 28 days compressive strength of PC. With the addition of SCM in PC, the mechanical strength characteristics are found to be increased and the percentage increase is found to be 5.1%, 23.2% in compressive strength, 32.9%, 48.3% in split-tensile strength and 19%, 34% in flexural strength for 7 and 28 days of testing respectively. As per Wille et al., (2016) [12], the aggregate/cement ratio effects the PC strength by changing the void content. Further, with the decrease in size of coarse aggregate, the compressive strength of PC increases. The larger aggregate size enables less surface area for the cement paste bond that tends to show lower mechanical strength characteristics of the concrete.

From the test results, an equation is proposed to establish a correlation between split-tensile strength and flexural strength of PC and is represented by Fig. 8 and eq. (3)

\[ f_r = 0.009 f_{st}^{0.6898} \quad \text{eq. (3)} \]

Where \( f_r \) = flexural strength of PC; \( f_{st} \) = splitting tensile strength of PC

Eq. (2) shows a good agreement with the eq. (1) of Crouch et al., [17]. The inclusion of fly ash as a replacement to cement content in PC mixes has significantly enhanced the strength properties of PC.
5 Conclusions

Depending on the review of literature and experimental study performed, the furnished conclusions are drawn

1. Increasing the aggregate size and aggregate to cement ratio resulted in decrease of mechanical strength characteristic that in turn increased the void content of PC.
2. The loss of strength for mixes with 6, 12 and 20 mm aggregate are found to be in the range of 45-55% respectively when compared with those of 6 mm aggregate.
3. PC mixes along with SCM mixes with lower size aggregate and lower aggregate to cement ratio show superior mechanical strength characteristics than those mixes that are prepared with larger sized aggregates and higher aggregate to cement ratio.
4. The replacement of fly ash with cement resulted in considerable achievement of mechanical strength characteristics.

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