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Effect of aggregate gradation on the mechanical strengths and permeability properties of porous concrete

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Abstract

Porous concrete (PC) is a very popular construction material in developed countries and is now finding application in India in parking lots. In this investigation, an effort was made to study the various performances of PC in the laboratory. Different gradations of coarse aggregates namely 4.75–10 mm, 10–12.5 mm, and 12.5–16 mm are considered to characterize PC adopting conventional compaction by tamping rod, additional 5 and 10 compactions by proctor hammer. The effect of varying compaction and the coarse aggregate gradation is studied on axial compressive, flexural tensile, and splitting tensile strengths of PC. In addition, a simple method is proposed to determine the permeability of all PC mixes. The work was extended to know the influence of low-grade fly ash and GGBS as supplementary cementing materials (SCMs) on the strengths and permeability of PC. Though the strength of PC in the presence of SCMs has decreased, the permeability and the estimated porosity of all mixes decreased compared to the 100% cement counterpart. A wide range of PCs were developed to suit several combinations of mechanical strength, density, and permeability depending on the type of application leading to a sustainable solution. The simple test method proposed to determine the permeability of the PC gives satisfactory results.

Keywords: Porous concrete, Gradation of coarse aggregates, Degree of compaction, Permeability, Supplementary cementing materials, Fly ash; Slag

Introduction

Porous concrete (PC) or permeable concrete is a construction material with a high volume of interconnected voids. The first application of the PC was in 1852 [1] and is receiving renewed interest nowadays. The PC is a distinct mixture of cement, high-performance additives, and coarse aggregate (CA). This concrete mixture consists of a lower fraction of fine aggregates (FA) or no fine aggregates, creating a considerable amount of void content. The lower fraction FA or mortar content in PC leads to high porosity, which eventually leads to low-strength concrete. The highly permeable, interconnected voids in PC allow water to flow quickly through the concrete matrix [2, 3]. The flow of water through the voids aids in filtering water, thus hindering the penetrability of chemicals and hazardous contaminants entering the soil. The permeability coefficient of PC varies from 2 to 10 mm/s and porosity varies from 15 to 25% [4, 5]. Hence it is gaining attention as an eco-friendly, lightweight, and sustainable potential green material in the research and construction industry [6]. In addition to higher porosity, PC has energy-efficient properties like low thermal conductivity and higher sound insulation [4]. PC has been used in building road pavements, sidewalks, parks, and building exteriors due to its porous nature [7]. The higher permeability coefficient of PC also aids in enhancing groundwater potential and reducing storm-water runoff [8]. However, its usage in India is rather limited and is in the early stages of application.

Industrial byproducts such as fly ash (FA), ground granulated blast furnace slag (GGBS), and lightweight aggregates are used in the production of conventional, geopolymer, and PC [9–11]. In addition, many unconventional aggregates derived from vitrified, ceramic, and cinder wastes have strong potential in the production of low-strength concretes and PC [12]. The type, shape, and size of the coarse aggregates play a significant role, in the strength development [13]. The low FA content leads to the thin film coating on the aggregates that affect the compressive strength of the PC, which ranges from 2.8 to 28 MPa. The main aspect of PC is the volume of voids/porosity, size of voids, pore-network or interconnectivity of voids, and in-situ density of the fresh concrete. ASTM C1688 test method is used to find the fresh density (unit weight) of PC which 2200 ± 80 kg/m^3 is considered in the mix design.

Determining of permeability of a PC in a simple way is quite challenging. In this work, an attempt has been made to develop a simple and quick method to determine the permeability of the PC. In addition, several mechanical properties of PC, and permeability are also investigated to characterize its performance. Furthermore, the relative cost of the PC will be lower compared with the OPC. This is due to the absence of fine aggregates in the PC. The cost that is being spent for fine aggregates for 1 m^3 concrete production can be completely saved. With these objectives, current work is aimed at designing PC with varied fresh concrete density, mechanical properties, and permeability coefficient values. In practice generally, the fresh concrete density was varied by varying degrees of compaction. An in-house permeability apparatus was designed and built to measure the permeability coefficient of designed PC mixes. Industrial byproducts such as FA and GGBS are used as supplementary cementitious materials (SCM) at 50% replacement to ordinary Portland cement (OPC). Hard granite stones are used as CA whose sizes range between 4.75 and 16 mm in this work.

Experimental program

In this investigation, an effort was made to investigate the performance of PC in the laboratory. The influences of compaction and the coarse aggregate gradation were studied on the flexural, splitting tensile, and compressive strengths of PC. The permeability of PC is proposed by a simple test method and the results are quite satisfactory. An attempt was also made to utilize supplementary cementing materials as a replacement for cement.

Table 1 Preliminary test results on OPC 43 grade cement

Description	Test value	Requirement of OPC (As per IS:269–2015	Method of test
Normal consistency (in %)	29.5	No standard value	IS:4031 part 4, 1988 [15]
Setting time (in minutes)			
i) Initial setting time	135	Not less than 30	IS:4031 part 5, 1988 [16]
ii) Final setting time	245	Not more than 600	
Specific gravity (Le-Chatelier's flask)	3.14		IS:4031 part 11, 1988 [17]
Fineness, % (dry sieving)	6.2	Not more than 10	IS:4031 part 1, 1996 [18]
Fineness by Blain's air permeability method (m^2/kg)	275	Not less than 225	IS:4031 part 2, 1999 [19]
Soundness (Le Chatelier's method), mm	0.5	Not more than 10	IS:4031 part 3, 1988 [20]
Compression strength (MPa)			
3 days	25.48	23	IS:4031 part 6, 1988 [21]
7 days	37.67	33	
28 days	46.58	43	

Table 2 Typical mix proportion for PC

Ingredients	Quantity
Cementitious material	400 kg/m^3
Water/cementitious material ratio	0.35
Coarse aggregate	1400 kg/m^3
Water content	140 kg/m^3

Methods

The materials considered in the study were, water, coarse aggregates, class F FA with a specific gravity of 2.1, and GGBS with a specific gravity of 2.91, OPC of 43 Grade satisfying the requirements of IS 269-2013 [14]. Table 1 shows the properties of 43-grade OPC used in the current study is tabulated. The hard granite coarse aggregate in three gradations namely, 4.75 to 10 mm, 10 mm to 12.5 mm, and 12.5 mm to 16 were used with 95% of OPC, 70% of FA, and 60% of GGBS passing through a 90-µm sieve. The FA and GGBS are relatively low grade with low pozzolonicity used in this work. For the low pozzolonicity, the compressive strength at 28 days is found to be 61% when tested as per IS 3812 (Part 1):2003 [22]. For acceptance, the compressive strength should not be less than 80% of the strength of corresponding plain cement mortar cubes.

Mix proportions for PC

Different mix proportions are suggested by different investigators [2, 23]. The typical mix proportions for PC as suggested in ACI 522R10 [24] followed. The mix design employed is presented in Table 2. Suitable combinations of supplementary materials are used. Additional compaction by the modified Proctor hammer is was provided to modify the properties of concrete. Initially, the concrete is was compacted a with

Fig. 1 **a**–**c** Cube, cylindrical, and prism specimen for compressive, splitting tensile, and flexural tensile tests

Fig. 2 **a**–**c** Slump, stiffness, and appearance of PC

tamping rod and later compacted by giving 5 and 10 additional blows over an area of 100 × 100 mm. Generally, the PC water-cement ratio was found to vary from 0.24 to 0.42 and the aggregate-to-cement ratio varies from 3.97 to 6.50 [25]. In the present study, these values are 0.35 and 3.5 respectively.

Strength and permeability test procedure

Compressive, splitting tensile, flexural strengths, fresh concrete density, and coefficient of permeability are the main parameters considered in the study. Tests are conducted as per BIS standards. Figure 1a–c shows the cube, cylinder, and prism specimens used for the various tests. Figure 2a–c shows the nature of the slump, stiffness (which is the resistance to flow exhibited by very low slump or zero slump concrete), and surface quality of the PC. Figure 3a, b shows the nature of the compacted concrete in the cubes and cylinders. The compaction of concrete using a proctor hammer can be observed in Fig. 3c.

Only the permeability test is explained here as it is somewhat different. Conventional equipment is used for determining the permeability properties of conventional concrete, which is generally less than 0.01 mm/s. However, in the case of PC, leakage of water from the sides is an important concern when such equipment is used. With this large porous nature and high permeability, existing permeability testing devices are inefficient. In PC there exist large open pores and voids connected to the side wall at the surface, hence leakage from the side wall is a major concern. Hence, a modified permeability testing method for PC is developed. This device allows water to flow in a vertically downward direction and completely prevents the sidewall flow from the specimens, which can be observed in Fig. 4a, b. Just before the permeability test, the cylinders were removed from the curing tank and kept in laboratory condition for some time to ensure saturated and surface dry conditions. Initially, specimens were weighed, and then they were covered

Fig. 3 **a**–**c** PC cast in cubes, cylinders, and application of additional compaction using proctor hammer

Fig. 4 **a**, **b** PC preparation for permeability test

Table 3 Notations for different types of mixes with respect to the degree of compaction for all gradation of aggregates

Size of the aggregate (mm)	Type of compaction	Size of the aggregate (mm)	Type of compaction	Size of the aggregate (mm)	Type of compaction
4.75–10.00 (S-small)	NC NC + 5MH NC + 10MH	10.00–12.5 (M-medium)	NC NC + 5MH NC + 10MH	12.5–16.00 (L-large)	NC NC + 5MH NC + 10MH

with thin polyethylene sheets in 3 to 4 layers around the circular surface of cylindrical specimens to avoid the side-wall flow of the water while conducting the permeability test. The extra plastic sheet is intentionally left both at the top and bottom of the cylinder; which serves as an inlet and outlet for the water to pass through. Then the entire cylinder is sealed using cellophane tape as shown in Fig. 4a, b. The variable head permeability test is conducted and the time required for the water to flow from one level to another level is noted. First, the water is allowed to flow from the inlet of the cylinder by connecting it to the pipe of the variable head permeability cell. Later, the water is made to pass freely through the outlet. The pressure head between the inlet and the outlet of the cylinder is maintained constant, maintaining the free water flow through the PC. When the water is allowed to flow through the cylinder, the time required for the change in water level is noted.

Results and discussion

Strength tests

Three sizes of aggregates were considered for the present study. Whose size ranges from 4.75 to 10 mm (small-sized), 10 to 12.5 mm (medium-sized), and 12.5 to 16 mm (large-sized). Table 3 gives the different notations used for all gradations of the aggregates. The variation of compressive, flexural, and splitting tensile strengths with respect to the degree of compaction (number of blows) for all gradations of aggregate are shown in Fig. 5a–c. The mechanical strengths of PC were found to increase with the increase in the size of CA and degree of compaction.

The compressive strength range of PC is generally in the range of 3.5 to 28 MPa, which generally caters to a wide range of applications [4]. The variation of compressive strength at 7 days is slightly more which is about 70–80% of that at 28 days with

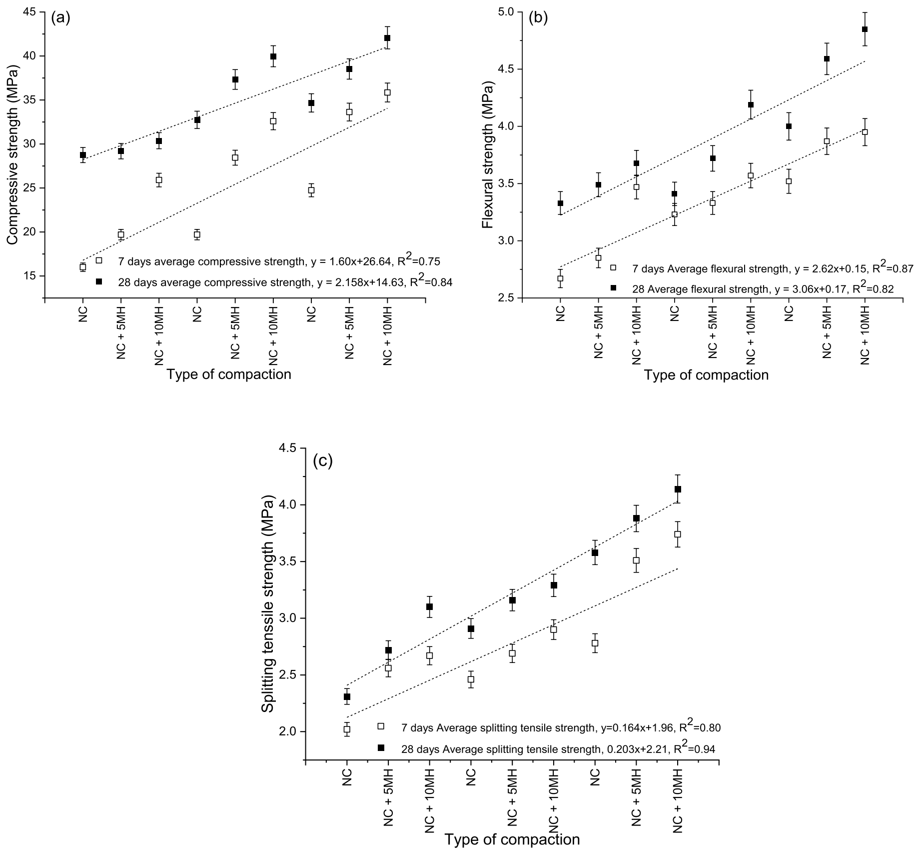

Fig. 5 **a** Variation of compressive strength with type of compaction. **b** Variation of flexural strength with type of compaction. **c** Variation of splitting tensile strength with type of compaction

respect to the type of compaction as shown in Fig. 5a. The increase in compressive strength at 7 days is more compared to 28 days. At average 7 days compressive strength was found to vary from 16 to 35.5 MPa and at 28 days compressive strength was found to vary from 28.74 to 42.07 MPa. The compressive strength also increases as the degree of compaction increases, i.e., from 5 to 10 blows. Average compressive strength was found to increase with the size of the aggregate and degree of compaction. The percentage of increase in 7 days strength was 61.9% for small-size aggregates, 65.4% for medium-size aggregates, and 44.9% for large-size aggregates with an increase in the degree of compaction. On the other hand, the percentage of increase in 28 days of strength was 5.7% for small-size aggregates, 22.1% for medium-sized aggregates, and 21.3% for large-sized aggregates with an increase in the degree of compaction.

The Increase in flexural strength was observed with an increase in the size of aggregates at 7 and 28 days as shown in Fig. 5b. The flexural strength varied from 2.67 to 3.95 MPa for 7 days and 3.33 to 4.85 MPa for 28 days with different types of compaction and size of aggregates. The variation of flexural strength was observed to be between 1 to 3.8 MPa [4]. An increase in flexural strength to an extent of 5 to 15% is noticed for 5 extra blows at 7 days and the strength further increases for 10 blows. At 7 days, the flexural strength is lower compared to 28 days. Average flexural strength was found to increase with the size of the aggregate and degree of compaction. The percentage increase in the 7 days of flexural strength was 30.0% for small-sized aggregates, 10.5% for medium-sized aggregates, and 12.2% for large-sized aggregates with an increase in the degree of compaction. On the other hand, the percentage increase in 28 days of flexural strength was 10.5% for small-sized aggregates, 22.9% for medium-sized aggregates, and 21.3% for large-sized aggregates with an increase in the degree of compaction.

The splitting tensile strength was also observed to increase as the size of aggregates increased from 4.75 to 16 mm and the type of compaction as shown in Fig. 5c. About 15 to 25% increase in splitting tensile strength has been observed for 5 additional blows at 7 days. However, at 28 days, a marginal increase in splitting tensile strength was observed. When 10 blows are applied, the increase in splitting tensile strength after 7 and 28 days of curing was found to be marginal in comparison with PC subjected to 5 blows. The percentage of increase in 7 days strength was 32.2% for small-sized aggregates, 17.9% for medium-sized aggregates, and 34.5% for large-sized aggregates with the increase in the degree of compaction. The percentage increase in 28 days' strength was 34.2% for small-size aggregates, 13.1% for medium-sized aggregates, and 15.6 % for large-sized aggregates with an increase in the degree of compaction. Seven-day splitting tensile strength was found to vary from 2.02 to 3.74 MPa and at 28 days it was found to vary from 2.31 to 4.14 MPa. From the above observations, it is clear that the behavior of PC is quite different from that of conventional concrete which contains sufficient fine aggregate (Sand) fraction as well. The rate of increase in strength mainly depends on the percentage of voids, the nature of the paste coating on the aggregates, and the distribution of the internal voids, which is again a function of shape, the texture of CA, and the degree of compaction.

Permeability of PC

The permeability of PC decreases as the size of the aggregate increases and further decreases as the degree of compaction increases as observed in Fig. 6. Permeability control is the main issue in PC which depends on the type of application and the nature of traffic, in addition to the intensity of rain prevailing in the region. Thus, to an extent of

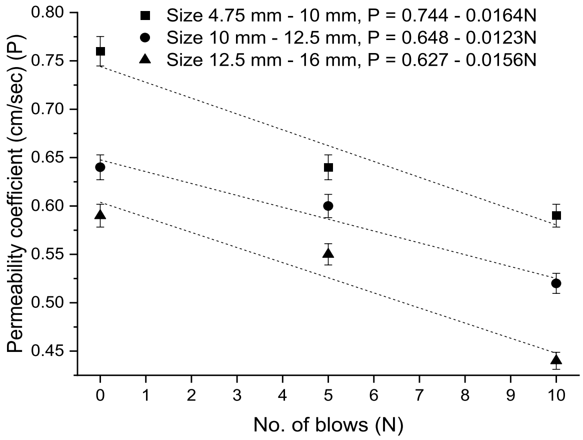

Fig. 6 Variation of permeability coefficient with respect to the degree of compaction

15 to 25% the permeability of PC can be reduced by increasing the aggregate size as well as increasing in degree of compaction, which results in reduced void content or porosity.

It is observed that the permeability of the PC and its aggregate counterpart is more or less comparable and it decreases to some extent as the cement content increases which occupies a certain volume of voids.

Thus, in the case of PC, some amount of voids are filled with cement, causing a slight reduction in permeability The variation of permeability with the type of compaction is given in Fig. 6. It is observed that for all sizes of aggregates, the permeability of PC decreases with the increase in the degree of compaction. Though the permeability decreases with an increase in the degree of compaction, the rate of decrease of the permeability coefficient is found to be comparable for all three grades of aggregates as seen in Fig. 6. Depending on the desired level of permeability required in the field, suitable aggregate size, and the number of blows can be varied. The mathematical models correlating the degree of compaction depending on the size of the aggregate are presented in Table 4.

Correlation between permeability and porosity for PC

The porosity of PC was estimated for different sizes of aggregate and for different compaction energy based on the exponential model proposed by Tho-In et al [8] (Eq. 1) and the linear model proposed by Bhutta et al. [26](Eq. 2).

$$k = 0.0447xe^{0.1388\Phi} \tag{1}$$

$$k = 0.2927\Phi - 4.97 \tag{2}$$

Where k is the permeability in mm/s and Φ is the porosity in percentage.

The results of the porosity are presented in Table 5, and it is observed that both models result in more or less the same porosity and the difference is negligible. As the degree of compaction increases, there is a small reduction in the porosity of the PC (2 to 5%). The reduction in porosity based on the exponential model is up to 5% compared to the linear model in which the reduction is up to 2%. From this observation, it can be concluded that the reduction in porosity as a function of the size of the aggregate and the degree of compaction is about 2–4%.

Effect of degree of compaction on permeability co-efficient and time of flow

The effect of the degree of compaction on the permeability coefficient is presented in Fig. 7a and from this, it is noticed that the permeability coefficient decreases as the degree of compaction increases. This is true for all sizes of aggregates, though the rate of

Table 4 Regression line between degree of compaction and permeability

Size of aggregate	Mathematical model
4.75 mm to 10 mm	$P = 0.744–0.01647N$, $R^2 = 0.939$
10 mm to 12.5 mm	$P = 0.648–0.0123N$, $R^2 = 0.967$
12.5 mm to 16 mm	$P = 0.627–0.0156N$, $R^2 = 0.942$

Note: P permeability in mm/sec, *N* number of blows

Table 5 Porosity for different permeability values

Size of aggregate	Type of compaction	Average permeability, cm/sec	Tho-In et al. Exponential model (2012)	Bhut et al. Linear Model (2012)
			Porosity, Φ (%)	
4.75 to 10 mm	NC	0.76	20.4	19.6
	NC + 5MH	0.64	19.2	19.2
	NC + 10MH	0.59	18.6	19.0
10 to 12.5 mm	NC	0.64	19.2	19.2
	NC + 5MH	0.60	18.7	19.0
	NC + 10MH	0.55	18.1	18.9
12.5 to 16 mm	NC	0.63	19.1	19.1
	NC + 5MH	0.52	17.7	18.8
	NC + 10MH	0.44	16.5	18.5

decrease is slightly lesser for 10 to 12.5 mm size aggregates. As noticed in Fig. 7b, as the degree of compaction increases, the time required for the discharge of a certain quantity of water, say 0.2 m^3 of water, increases, though the trend of decreases is different for different aggregate sizes. From Fig. 7a, b, it is observed that by changing the degree of compaction, the permeability characteristics of the PC can be modified depending on the design requirements of the PC. The time of discharge is calculated on a PC area of 1 m × 1 m and thickness of 0.3 m.

PC with supplementary cementitious materials

The effect of the low-grade cementitious material FA and GGBS has been studied on the mechanical properties and permeability of PC. The permeability of FA and GGBS-based PCs is less when compared with 100% cement-based PC. As the FA and GGBS are relatively coarser and less reactive, they may not contribute significantly to the mechanical properties. However, the micro-voids, porosity, and permeability will decrease to some extent. Thus, from the durability point of view, the PC containing SCMs performs better. Though the 7- and 28-day strengths of PC containing FA and GGBS are somewhat lesser than to compared OPC concrete, it is more than that required for PC for practical applications. Thus low-grade supplementary materials can be effectively used to produce medium-strength sustainable PC. In the present work, 50% of OPC is replaced by FA and GGBS to know the variation of various properties studied. The results of density, compressive, splitting tensile, flexural tensile strength, and permeability for PC containing 10–12.5 mm aggregates are presented in the subsequent sections.

Density for a different combination of mix

The density of PC increases as the degree of compaction increases from 5 to 10 blows compared with normal compaction with tamping. The density of PC containing FA and GGBS is relatively less by about 100–200 kg/m^3 compared with 100% cement PC. The variation of density for different geometry of specimens for the different supplementary mixes is presented in Fig. 8. The OPC represents 100% cement, OPC + Fly ash represents 50% cement and 50% FA and OPC + GGBS represents 50% cement, and 50%

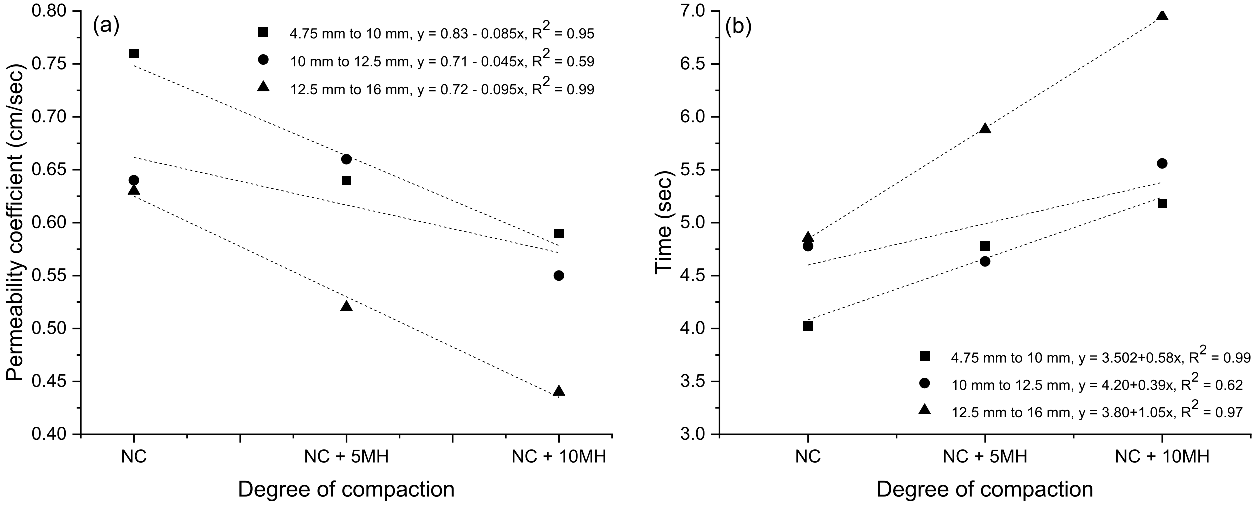

Fig. 7 **a** Effect of degree of compaction vs permeability coefficient for different gradation of aggregates. **b** Effect of degree of compaction vs time required to permeate 0.2 m^3 of water for different gradation of aggregates

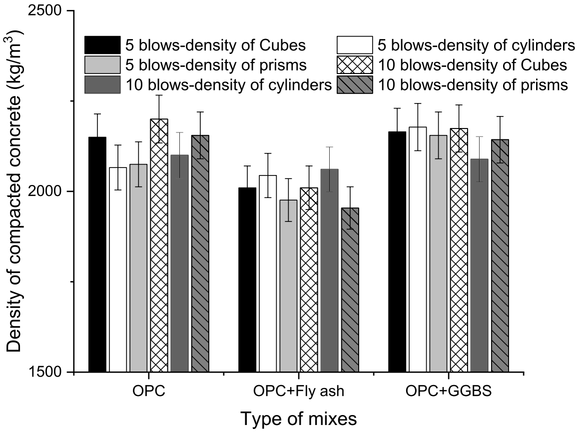

Fig. 8 Variation of average nominal density with type of mixes

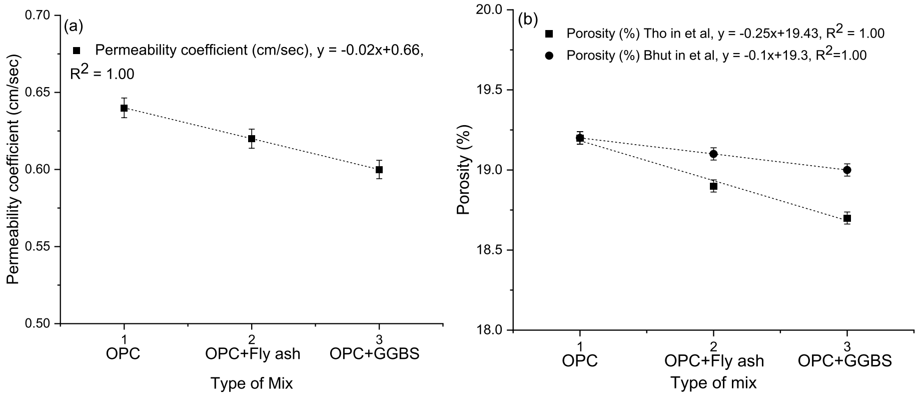

Fig. 9 **a** Variation of permeability coefficient with respect to different mixes. **b** Variation of porosity for different mixes based on models

GGBS. Within SCM, density was found to be the minimum for the OPC + Fly ash (by about 200 kg/m^3) combination. With the increase in the number of blows, the variation in the density of PC is marginal. The shape of the mould has an insignificant effect on the density of the PC. From the discussion, it is observed that the density of PC varied from 1900 to 2200 kg/m^3 depending on the mix combinations and the number of blows.

Effect of SCMs on the permeability of PC

The permeability of PC is studied for 10–12.5 mm aggregates under normal compaction. The effect of FA and GGBS on the permeability can be observed in Fig. 9a and the estimated porosity based on the mathematical models is presented in Fig. 9b. Though the fineness of SCM is relatively low compared with OPC, the product of hydration has resulted in denser microstructure leading to reduced permeability. As seen from Fig. 9a the reduction in permeability of PC in the presence of FA and GGBS is about 3 and 6% compared with 100% OPC. Similarly, the reduction in porosity of PC in the presence of FA and GGBS has decreased considerably to the extent of 2–5% as seen in Fig. 9b. Thus, the low-grade SCM can be effectively used to produce sustainable PCs having relatively low permeability.

Effect of pressure head on time of flow

The effect of the pressure head on the time of a flow is shown in Fig. 10. The effect of SCMs on the time of flow through PC as a function of the pressure head is presented in comparison to PC which contains 100% cement. From this, it is clear that the time of discharge is relatively less for any given pressure head in the case of PC which contains SCMs, which again indicates that SCMs reduce the rate of permeability marginally. The quality of the cementitious system surrounding the aggregates is relatively impermeable which adds to the performance of PC as the bond between the aggregates is denser compared to PC which contains 100% cement. However, the rate of discharge (time) is more or less comparable in all cases. The reduction in permeability of the paste is an indication of the better quality of the cementitious system in the presence of SCMs.

Effect of SCMs on strength properties of PC

The variation of compressive, splitting tensile, and flexural tensile strengths are presented in Fig. 11a–c. Flexural tensile strength is more compared with splitting tensile strength and the trend of variation is more or less similar to that found in normal concrete. As the quality of the FA is inferior, the strength at 7 and 28 days in the presence of SCM is substantially lower compared to the 100 % OPC counterpart. The 28-day compressive strength of FA-based PC is 14.89 MPa compared with 32.74 MPa of OPC counterpart. With the addition of low-grade SCMs, to the extent of 50% replacement, PC mixes having a strength of 15 to 30 MPa can be easily designed. With additional compaction, the compressive strength can be increased further as found in "Strength Tests" section, which is not tried in this case. Similarly, the variation of splitting and flexural tensile strength in the presence of SCM can be seen in Fig. 11b, c. The variation of splitting and flexural strengths will help in the design of PC pavements for parking lots depending on the variation of traffic load. The concrete strength used in the design of concrete pavements is based on AASHTO Test Method T-97 or ASTM C78. The flexural strength of concrete using a simple beam with third-point loading generally varies from 3 to 5 MPa. Usually, C30/37 strength class concrete is used to construct concrete

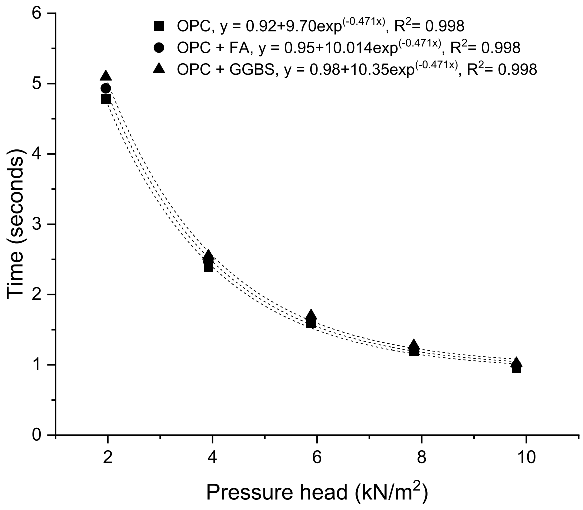

Fig. 10 Effect of varying pressure head of water vs time required to permeate 0.2 m^3 of water

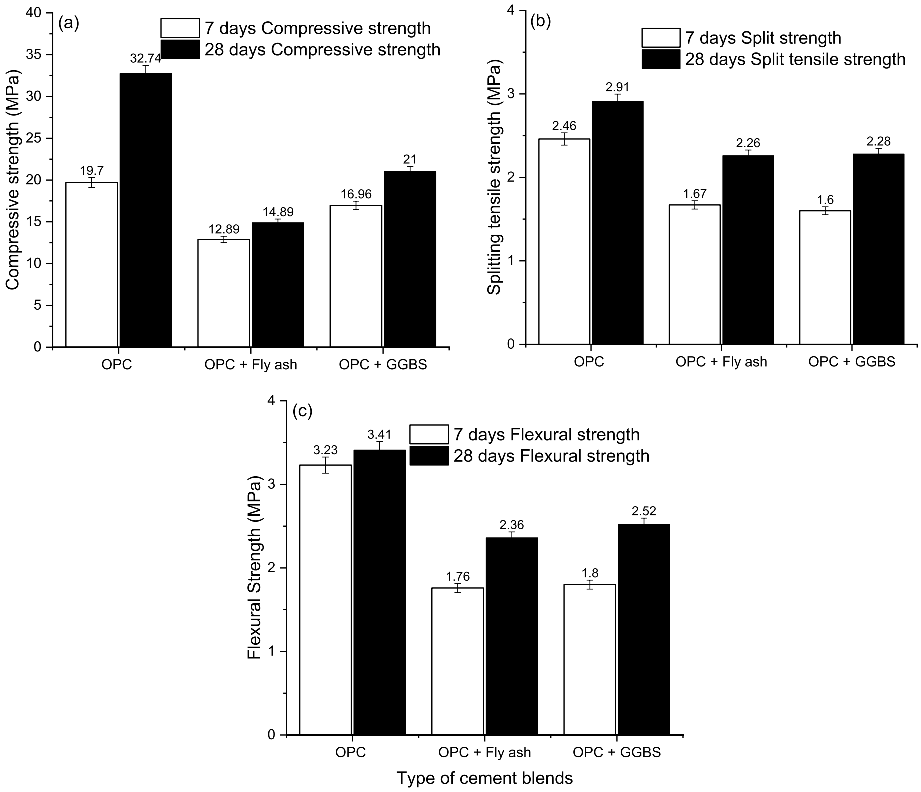

Fig. 11 Variation of mechanical properties. **a** Compressive strength vs type of cement blends. **b** Splitting tensile strength vs type of cement blends. **c** Flexural strength vs type of cement blends

pavements on a rigid, semi-rigid, or flexible base. Concrete with such a strength delivers essential design flexural and splitting tensile strengths between 4.5–5.4 MPa and 2.8–3.7 MPa, respectively [27].

Conclusions

Based on the analysis and discussion of the results presented in the previous sections, the following important conclusions can be drawn.

- The mechanical properties such as compressive, splitting tensile, and flexural strengths of PC increase due to additional compaction with the Proctor hammer leading to better PC. In the same way, the density of PCs increases substantially with the increase in compacting energy. However, higher compaction is a disadvantage because higher compaction results in a substantial reduction in the permeability and porosity of the PC.
- The gradation of aggregates also has a significant effect on these properties. For a given size of aggregates, a PC having any practical range of mechanical strengths, density, and permeability can be designed by controlling the degree of compaction.
- Use of supplementary cementing materials of low grade, though reduced the mechanical strengths, the permeability and porosity have decreased significantly which further enhances the durability of the PC.

- From the present study, it is observed that using cement alone and a combination of 50% of either fly ash or GGBS can produce PCs having average compressive strength in the range of 16 to 35.5 MPa and 28.74 to 42.07 MPa at 7 and 28 days respectively. With the addition of 50% low-grade FA and GGBS, the compressive strength has decreased to an extent of 50% and 33% respectively, which saved 50% of OPC, which is quite significant from the point of waste disposal and sustainability.
- The flexural tensile and splitting tensile strengths varied from 2.67 to 3.95 MPa and 2.02 to 3.74 MPa respectively at 7 days. Similarly, at 28 days, the corresponding variations are 3.33 to 4.85 MPa and 2.31 to 4.14 MPa respectively. These ranges of tensile strengths cover acceptable ranges of design tensile strengths for pavements.

Future research section

The research works on PC can be further explored by varying the parameters such as the shape of coarse aggregates for evaluating the permeability characteristics. In addition to this, exploring the permeability characteristics of geopolymer-based PC instead of Portland cement-based PC using manufactured aggregates which is emphasized in recent codes of practices could open up several potential research avenues in this field and also serve as a possible solution for the sustainability issues and reduces the carbon footprint.

Abbreviations

OPC	Ordinary Portland cement
PC	Porous concrete or permeable concrete
CA	Coarse aggregates
FA	Fly ash
GGBS	Ground granulated blast furnace slag
SCM	Supplementary cementitious materials

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Authors' contributions

MCN worked on conceptualization, formal analysis, investigation, methodology, project administration, and writing–original draft and was a major contributor in writing the manuscript. LSM worked on visualization, writing–review, and editing and was a major contributor to writing the manuscript. VRD worked on writing and editing and was a major contributor in writing the manuscript. VL worked on formal investigation, analysis, and writing and was a major contributor in writing the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials

Data shall be shared upon request.

Declarations

Competing interests

The authors declare that they have no competing interests.

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