Journal of Asian Concrete Federation
Vol. 8, No. 2, pp. 1-7, Dec 2022
ISSN 2465-7964 / eISSN 2465-7972
DOI http://dx.doi.org/10.18702/acf.2022.12.8.2.1

Technical Paper

Effect of fine aggregates on the strength and hydraulic properties of pervious concrete

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(Received September 09, 2022; Revised October 10, 2022; Accepted November 08, 2022; Published December 31, 2022)

Abstract: In this study, the effect of inclusion of fine aggregates on the strength and hydraulic properties of pervious concrete have been investigated. A total of three mixes were casted using three different proportions of fine aggregates at a constant water to cement ratio and powder to aggregate ratio of 0.35 and 0.16 respectively. The partial inclusion of Natural Fine Aggregates (NFA) in place of Natural Coarse Aggregates (NCA) was done in the proportion of 0%, 10% and 20% respectively. The influence of NFA was investigated by performing workability, permeability and compressive strength at different curing periods. It was observed from the results that incorporation fine aggregates in pervious concrete up to 20% increases the compressive strength values significantly. A maximum increment of 17% in compressive strength was seen at 20% of NFA at 28 days of curing. Moreover, it was observed from the microstructure observations that a dense and layered calcium-silicate- hydrate (C-S-H) was seen for mix M20. It was further investigated from energy dispersive x-ray spectrometer that 50-60% of volume was occupied by C-S-H gel for mix M20.

Keywords: Pervious concrete, Workability, Permeability, Compressive strength, Scanning Electron Microscope.

1. Introduction

Both the rigid cement concrete and the flexible asphalt pavement wearing courses operate as heat storage materials during the day and provides warmness back into the air at night, instigating the Urban Heat Island (UHI) effect [1,2]. Urban residents experience heat stress due to UHI's 2–12 0C increase in the ambient temperature, which increases energy use for cooling and Carbon dioxide emissions into the atmosphere [3–5]. Researchers from different regions have been working to investigate and evolve cutting-edge pervious pavement materials and top construction practices, which could possibly help address the aforesaid apprehensions, in order to lessen the effects of impermeable pavement systems on the environment [6,7] Designing and constructing pervious concrete pavement structures is one strategy for resolving issues brought on by high impact development. A unique type of concrete used for roads is called pervious concrete, and it is made by omitting the fine aggregates found in regular concrete in order to ensure that the material has interconnecting macropores (1.5-8 mm) throughout it [8–10]. In addition to improving vehicle safety, pervious concrete also reduces glare and skidding by averting standing runoff on highway surfaces [9,11,12].

The absence of fines forms an open void structure, letting runoff to penetrate from the surface down through the interconnected cavities. Therefore, it is an unusual type of concrete having higher percentage of micro and macro cavities through which runoff can effortlessly diffused to the lower strata of ground [13,14]. Thereby recharging the root zone area of vegetation and supplementing the prevailing municipal drainage system by draining of the stormwater [15,16]. Moreover, the porous structure permits the air sandwiched between the tyre and the pavement to escape, the pervious concrete pavement could be used to cut the road noise [17–20]. Nevertheless, due to higher pore volume of pervious concrete, the compressive strength range significantly decreases which limits the applications of pervious concrete as pavement material. Therefore, to overcome this prominent loss in compressive strength, different techniques have been used by different researchers. K. Ćosić et al. [21] used lower coarse aggregate proportions, such as 4 to 8 mm, and discovered that adding more finer aggregates to pervious concrete enhances density, which greatly boosts the material's compressive and flexural strengths. The impact of aggregate size and

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type on the compressive strength and hydraulic characteristics of pervious concrete was investigated by Jinlin Huang et al [22]. The study found that pervious concrete created with dolerite aggregate has more compressive strength and permeability than pervious concrete made with granite aggregate. Additionally, dolerite aggregates of 5 to 10 mm in size were found to have the highest permeability and porosity at a w/c of 0.25. When the crushing index of aggregates increased from 9% to 37%, Zhiquan Zhang et al [23] discovered that the compressive strength, flexural strength, and elasticity modulus of the aggregates reduced by 36%, 28%, and 21%, respectively.

Based on the detailed literature, it was observed that limited investigations were available on inclusion of fine aggregates in pervious concrete. Therefore, the present study focused on developing the pervious concrete with three proportions of Natural Fine Aggregates (NFA). The workability of pervious concrete was assessed through slump cone test, mechanical strength was assessed through compressive strength test, and hydraulic conductivity was evaluated through falling head permeability apparatus using Darcy equation at 7 and 28 days respectively. Moreover, microstructure of pervious concrete was analyzed through Energy Dispersive X-ray spectrometer (EDX) and a Scanning Electron Microscope (SEM).

2. Experimental Program

2.1 Materials

Ordinary Portland cement (43 grade) was the primary binder in all the pervious concrete mixes as per IS: 8112 [24]. The control mix used in this investigation was made with 0% of NFA, 100% CFA, and 100% OPC. In the next mixes 10% NFA, 90% CFA, and OPC and 20% NFA, 80% CFA and 100% OPC respectively. The particle size distribution of OPC was found and is revealed in Fig. 1. The different physical properties and chemical compositions of OPC are presented in Table - 1 and Table - 2 respectively. The fine aggregates (2.36 mm) having fineness modulus 2.65 and coarse aggregates (4.75 – 10 mm) having fineness modulus 6.15 were used in all the mixes. All the aggregates were used in the saturated dry surface condition which was achieved by pre-soaking the aggregates for 24 hours prior to casting.

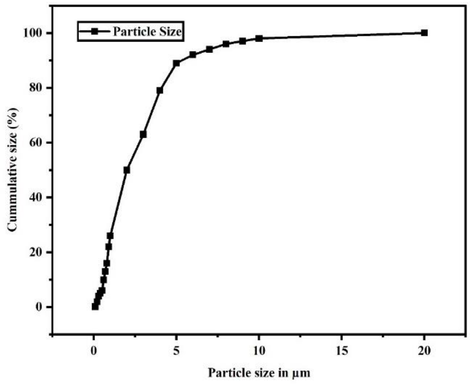

Fig. 1: Particle size distribution of OPC

Table - 1. Physical properties of OPC

S. No	Property	Test Value
1	Specific gravity	3.15
2	Initial setting time(min)	40 minutes
3	Final setting time(min)	240 minutes
4	Compressive Strength (MPa)	
	(a) 3 days	20.6
	(b) 7 days	34.2
	(c) 28 days	52.9

Table - 2. Chemical composition of OPC

Component	Cao	SiO_2	Al_2O_3	Fe_2O_3	MgO	Na_2O	P_2O_5	TiO_2	K_2O	MnO
Amount (%)	51.01	32.68	8.60	0.85	0.82	0.52	0.27	0.23	0.20	0.04

2.2 Mix design proportions

The mix proportions of various pervious concrete mixes are shown in Table 3. The basic mix proportions for the control mix were as per the literature which meets the requirements of ACI 522R-10 [25]. Three different aggregate grade proportions were used as 0:40:40:20 (X), 10:40:40:10 (Y) and 20:40:40:0 (Z) to cast all the three mixes using tilting drum mixer. A constant powder to aggregate ratio (p/a) and Water to Cement ratio (w/c) of 0.16 and 0.35 were used for all the pervious concrete mixes. Two types of specimens were used, 150 mm sized cubes for the compressive strength and cylinders 100 mm diameter and 200 mm length were used for permeability purposes.

2.3 Test methods

After 24 hours of casting, all the specimen were demoulded and placed in curing tank for 7, 28, 56, and 120 days at 20 - 25 °C temperature as shown in Fig. 2. For every reading calculation, three specimens were tested. All the testing procedures were conferred in following sub-sections.

Fig. 2: Pervious concrete samples in curing tank

2.3.1 Workability

The workability of pervious concrete was assessed through slump cone test in fresh state conferred to [26] as shown in Fig. 3. The conical mould is filled in three steps and at each step 25 blows of tamping is performed to get the compacted mould. After filling and leveling the mould completely the mould is lifted carefully in vertical direction after few seconds. The slump is calculated as the disturbed height due to self-weight as compared to initial height of slump mould (300 mm).

Fig. 3: 'Workability of pervious concrete

2.3.2 Water Permeability

The permeability of pervious concrete was evaluated through falling head permeameter after 7 and 28 days conferred to IS: 2720 (Part 17) -1986 [27] as shown in Fig. 4. The cylindrical sample is prepared by wrapping the outer girth of sample with transparent adhesive tape to ensure the unidirectional flow of water. After preparing the sample, it is installed into to collar of permeameter and clamps are tightened so that no leakage of water is seen. Switch of the water motor is turned on and water head tank is filled up to the upper head of 90 cm. Initially the valve (V) on the bottom horizontal limb of permeameter is kept on to ensure that sample gets saturated and no free air is present inside the sample. As the sample gets fully saturated the valve 'V' is kept in off position and head is again maintained at 90 cm. A transparent water pipe of small diameter and paper inch tape is also installed on the head tank for the purpose of piezometer and head reading respectively. After maintaining the upper head valve 'V' is opened and time of head fall from 90 cm to 30 cm is noted on stopwatch. Finally, the Eq. (1) is used to calculate the permeability of pervious concrete.

$$K = (A_1/A_2)\ \frac{L}{t}\ \ln(h_1/h_2) \quad \ldots\ldots\ldots\ldots (1)$$

where, K is permeability or hydraulic conductivity, A_1 is cross-sectional area of the head pipe, A_2 is cross-sectional area of the specimen, L is length of the specimen and 't' is time required for water to travel from top head h_1 to bottom head h_2.

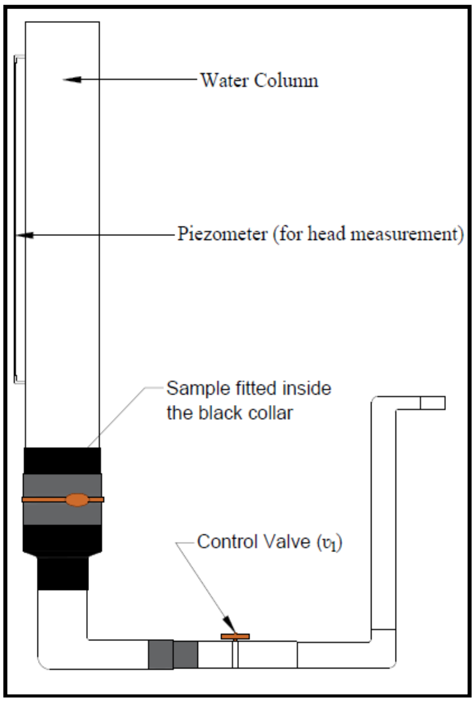

Fig. 4: Falling head permeameter

2.3.3 Compressive strength test

The compressive strength of pervious concrete was evaluated through Compressive Testing Machine (CTM) as shown in Fig. 5 conferred to IS 516 at the curing periods of 7, 28, 56, and 120 days [28]. The average compressive strength of three specimens were stated as final compressive strength of pervious concrete using Eq. (2).

$$f_c = P/A \quad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Where, fc is compressive strength in MPa, P is load taken by specimen up to first crack in kN and A is the area of specimen in mm^2.

2.3.4 Microstructure

The microstructure features of pervious concrete were studied using an Energy Dispersive X-ray spectrometer (EDX) and a SEM. The voltage was fixed at 15 KV for all the testing to improve the picture resolution of SEM images.

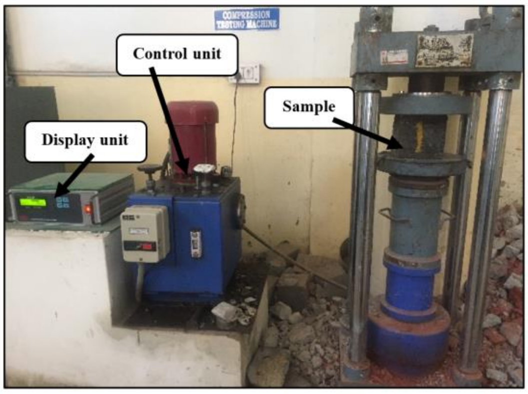

Fig. 5: Compression testing machine

3. Experimental Results and Discussion

3.1 Workability

The workability results through slump cone test of all the mixes of pervious concrete can be visually seen from Fig. 6. Trend in workability of various mixes show that with increasing the NFA percentages from 0% - 20%, workability of pervious concrete increases significantly. It can be seen from the results that slump of control mix, i, e mix M0 in which percentage of NFA was 0% was observed as zero. After that for mix M10, in which the NFA percentage was 10%, a slump of 60 mm was seen, however slump in pervious concrete may not be true slump alike in conventional concrete. Therefore, with increasing the fine aggregate percentages in pervious concrete, ball bearing effect of aggregates increases due to large surface area of smaller aggregates due to which workability of pervious concrete increases. A maximum workability of 120 mm was seen for mix M20, in which NCA was replaced with 20% of NFA. The finer aggregate content with cement paste provides more flowability as more water is adsorbed which decreases the viscosity of pervious concrete. Moreover, more adsorbed water later on helps in gaining the strength during C-S-H formation in hydration process.

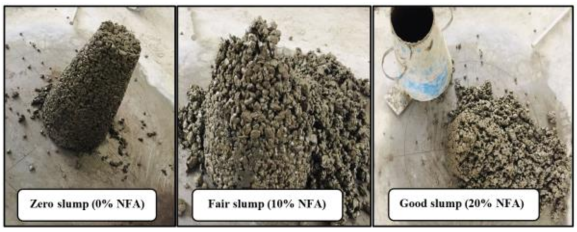

Fig. 6: Slump results of pervious concrete

3.2 Permeability

The permeability of pervious concrete made with three series of aggregate proportions at 7, 28, and 56 days are shown in Fig. 7. Trend of results shows that permeability of pervious concrete decreases significantly with inclusion of NFA in reference to control mix. it can be seen from the results that permeability for mix M10 decreased by 22%, 20%, and 22.5% at 7, 28, and 56 days as compared to permeability of control mix. Therefore, with 10% inclusion of NFA in mix M10, a significant decrease in permeability shows that refinement of pore has been occurred. Moreover, the permeability of pervious concrete for same mix at different curing ages changes marginally due to its dependance on several factors such as pore volume, pore density and tortuosity. However, for mix M20 in which percentage of NFA was 20%, a prominent reduction in permeability was seen at 7, 28, and 56 days of curing age. It was detected from the results that permeability reduces by 23%, 24%, and 25% in reference to control mix, M0. This significant decline in permeability was due to development in density of matrix due to which pore size of pervious concrete decreases and tortuosity increases.

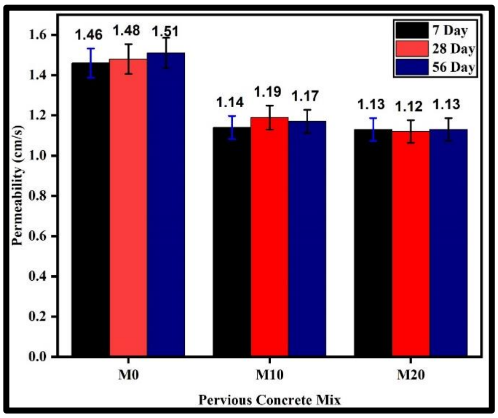

Fig. 7: Permeability of pervious concrete

3.3 Compressive Strength

Compressive strength of pervious concrete mixes has been evaluated to study the effect of NFA inclusion at different percentages at 7, 28, 56, and 120 days. The effect of replacement of NCA with NFA at different levels show that a quantified development in compressive strength has been observed as shown in Fig. 8. Trends in compressive strength presented in Fig. 8show that compressive strength magnifies significantly at all the curing periods with increasing the NFA content related to reference mix of pervious concrete. For example, in the pervious concrete mix M10, made with Y series proportion of aggregates having 10% NFA, the increment in compressive strength at the curing ages of 7, 28, 56, and 120 days was observed as 1%, 15%, 10%, and 14.9% relative to control mix. It was observed from the results that a maximum development of 15% was observed at 28 days as compared to control mix, however with increasing the curing age from 28 to 120 days, development in compressive strength partially decreases. Moreover, while comparing the development of compressive strength from 7 to 28 days, it was seen that mix M10 gains 53% compressive strength which is 8% more when compared to development of compressive strength in control mix. The development in compressive strength is due to the increment in paste matrix density, thereby strengthens the interfacial transition between paste and aggregate. Therefore, aggregate size directly affects the compressive strength of pervious concrete. Thus, inclusion of fine aggregates in the pervious concrete mix densifies the microstructure that can be seen from Fig. 9(a) in which dense and layered calcium-silicate-hydrate (C-S-H) gel formation is clearly observed. It was further confirmed from the mapping technique of EDS as shown in Fig. 10 that 50-60% of the volume of hydrated matrix was taken by C-S-H alone.

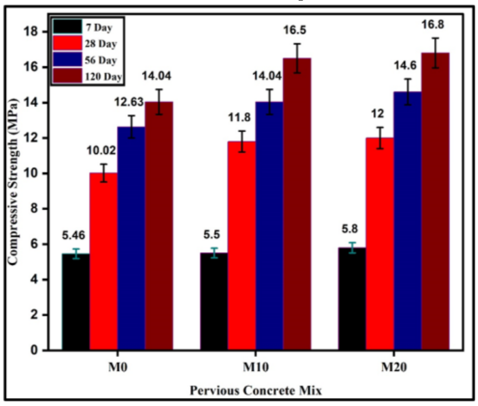

Fig. 8: Compressive strength of pervious concrete

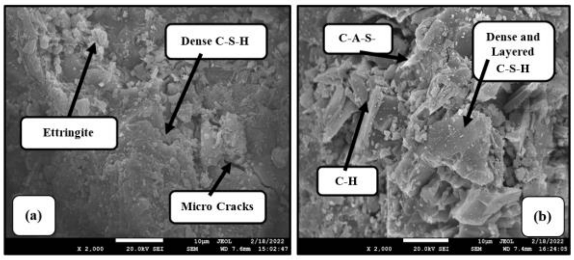

Fig. 9: Microstructure of mix M10 and M20 of pervious concrete

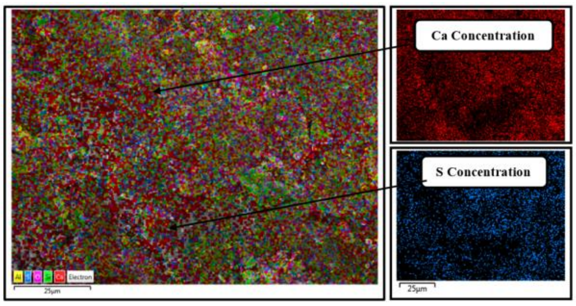

Fig. 10: EDS mapping of pervious concrete

Moreover, for mix M20 made with aggregate proportion series of Z in which 20% NFA was used in place of NCA. it was observed from the results that an increment of 6%, 16.5%, 13.4% and 16.4% was seen at 7, 28, 56 and 120 days of curing period as related to reference mix, which is significant. However, the development in compressive strength for mix M20 is more as compared to mix M10 at all the curing ages. Therefore, inclusion of more NFA in pervious concrete shows more development in compressive strength due to higher matrix density. The microstructure as presented in Fig. 9(b) shows more accumulates C-S-H and C-H gels. However, a few percentages of needle shaped crystals known as ettringite (calcium trisulfoaluminate) are also present which later on gets unstable and converts into monosulfoaluminates, a hexagonal plate structure also called as calcium aluminate hydrates (C-A-S-H) and imparts some more strength to concrete.

4. Conclusion

The present study was performed to evaluate the effect of fine aggregate on the properties of pervious concrete. The different conclusions drawn from this study were summarized as.

1. A significant development in compressive strength of pervious concrete was observed when NCA was replaced with NFA. However, a maximum increment of 17% in compressive strength was seen at 28 days at 20% inclusion of NFA.
2. It was observed from the results that permeability of pervious concrete diminishes with increasing percentage of fine aggregates. However, a workable range of permeability (1.12-1.51cm/s) was seen for all the mixes of this study.
3. A dense and layered C-S-H gel was observed for pervious concrete mix when replacement of NCA was maximum.

Conflicts of Interest

The authors affirm that they have no known financial or interpersonal conflicts that would have appeared to have an impact on the research presented in this study.

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