Experimental Investigation on Compressive Strength and Permeability of Pervious Concrete Pavement (PCP) with Alternative Mixes

Pala Gireesh Kumar, Abhirami Priyanka Pathivada, and Velugoti Sasi Jyothshima Himaja

Abstract Sustainability has a monopolizing proportion over decades and the augmentation to the world of sustainable technology extends itself implying in various fields of transportation sectors like pavements. The present paper substantially explicates the concept of sustainable pervious concrete pavement (PCP) technology, meticulously analyzed for the behavioral dependency of PCP with constituent materials transposed. It clinched an optimum possible mix for PCP with all the aspects correlated. On top of the aforesaid, the properties such as void ratio, water-cement ratio, compressive strength, permeability, etc., were supervised for multifarious conditions, for the enhancement of the life span of the pavement. In furtherance with the priors, the behavior with variability of PCP's behavior was toiled along with the inclusion of admixtures. In the fullness of time, this paper bestows PCP at an intensified rate and endows results of all the aforementioned properties with graphitized analysis and thereby, proffering the sustainability of a previous pavement in terms of design life and permeability that acts as a beneficiary to the stormwater management.

Keywords Pervious concrete pavement (PCP) · Compressive strength · Permeability · Water-cement ratio · Void content

1 Introduction

Over decades, science and inventions have routed way into the new era of computers and technology. The leading edge has grown with time and finally led to the intellectual world that is automated and controlled with systems. In accordance, the wealth and global economy witnessed plenty of hikes. With an urbane living and a polished lifestyle, the quantum of risk has also grown with time. The quarter of climate, environment, and atmosphere, aroused the need for a tremendous check of

P. G. Kumar · A. P. Pathivada (✉) · V. S. J. Himaja
Department of Civil Engineering, Shri Vishnu Engineering College for Women (Autonomous), Bhimavaram, West Godavari District 534202, India

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these factors. Analogically, extreme ends of great infrastructure, intelligent transport systems, automized maintenance techniques are witnessed in the course of civil engineering. With greater advancing aspects, the realm of sustainability needed prior enforcement. The term sustainability accords to the art perpetuating an eco-friendly environment within a sophisticated society at a balanced economical rate. In accordance, sustainability in terms of economy, infrastructure, and transportation steered intensively. In this regard, transportation has seen many revolutions and especially in the area of pavements. A lot of pavements with multiferous pros got introduced. Though pavement splits into rigid and flexible, we have come across the pavement of Hot Mix Asphalt, pavement of Fine or Coarse Grade Asphalt, pavement of Stone Mastic Asphalt, concrete pavement, composite pavement, pervious pavement, etc. Of all the available paving types, the one that juts above all is the pervious concrete pavement (PCP).

The appellation of pervious concrete pavement refers to the pavement being permeable. PCP embraces leading precedence for sustainability and has proven to be a better option regarding design life, maintenance, and eco-friendliness. The concept of stormwater management is one of the predominant factors that sympathizes with PCP and has proven to be one of the best alternatives for water conservation. The average annual precipitation is around 990 mm, and most of it is getting wasted and often seen stagnated in areas. In highly developed societies, roads are the most frequently occurring constructions, and with proper operational methods like the adoption of PCP, water can be conserved. In addition to stormwater management, PCP also assists in the lower urban heat island effect that eventually reduces variations due to temperature changes. Also, the emission of oxides of carbon and other gases is less in the case of PCP. Apart from the environmental considerations, PCP holds an advantage concerning economic aspects like lower utilization of cement content that leads to cut in pricing and easy maintenance is one among the economy factor. On top of all the aspects prevailing, the design life of PCP is accountable but, low strength is one of the backdrops that is dwindling the use of PCP as a replacement for existing paving methods. To emphasize PCP usage and to propose optimum mix design considerations, experimental works were carried upon various mixes with varying water-cement ratios along with void content. The results of admixtures inclusion are analyzed in this study along with the proposal of maintenance methods and remediation techniques.

2 Appraisal of Anterior Studies

Pavement being a capacious sector with a diversified area of study, PCP witnessed new research work proposals and advancements in various aspects. Few influencing facets of PCP are scrutinized thoroughly and presented in this paper.

Table 1 Previous studies of strength attribute of PCP

Author (Year)	Notable entries
Uma Maguesvari and Narasimha (2013)	Strength altered from 10 to 26 MPa with inclusion of fines and reduction in aggregate size [1]
Mageswari et al. (2016)	PCP exhibited compressive strength up to 15 MPa for cement to aggregate ratio of 1:10 with W/C ratio of 0.36 [2]
Divya Bhavana et al. (2017)	Zeolite inclusion by 10% inferred compressive strength of 9.15 MPa whereas, for conventional mix, it is noted to be 8.5 MPa for cement to aggregate ratio of 1:4 [3]
AlShareedah and Nassir (2020)	Inclusion of fibers of polypropylene showcased an increase of compressive strength by 25% and flexural strength by 37% [4]
Tijani et al. (2019)	PCP with Recycled aggregate exhibited 7% lower strength in comparison with granite PCP despite having greater permeability and void content [5]

2.1 Explication of Strength Attribute of PCP

Strength is one of the predominant characteristics that nearly define the worth of a pavement. It is considered as a deciding factor for paving a surface. Table 1 briefly explains the numerous studies carried out concerning the strength of the PCP mix.

2.2 Explication of Void Content and Permeability of PCP

PCP's usage is totally dependent on the percentage of void content that is maintained throughout its design life to incur permeability. More the void content, higher is the advantage of permeability. Table 2 explicates void content influence over PCP.

2.3 Explication of Aggregate Usage in PCP

The size of aggregate influences the attributes like strength, permeability, and infiltration rate. Under aggregates, the type of aggregates such as recycled aggregates or crushed aggregates implies the increment and decrement of PCP properties. Table 3 elucidates the predominant key factors from previous research.

Table 2 Permeability of PCP with regard to void content—notes from previous studies

Author (Year)	Notable entries
Jayasuriya and Kadurupokune (2008)	PCP exhibited a range of 60% lowered runoff when tested in the field which no other pavement type ever shown [6]
Kevern and Dan Sparks (2013)	It is identified that the cement slurry often led to decline of voids and eventually lowering permeability, therefore a good mix proportion is crucial for a good PCP [7]
Kamarul Zaman et al. (2019)	Cement to Aggregate ratio of 1: 8 showed an infiltration ranging between 1250 to 3250 L/m^2/min and 1:9 as 2300 to 2700 L/m^2/min [8]
Gagandeep et al. (2019)	Mix with no FA exhibited a flow rate of 820 in/ hr whereas a mix with 1 part of sand of C:A ratio 1:7 exhibited 950 in/h of flow rate [9]
Meng et al. (2019)	Placement of geogrids at variable depths exhibited 20% porosity and 640 in/h flow rate [10]

Table 3 Key observations concerning the aggregate usage in PCP

Author (Year)	Notable entries
Abd Halim et al. (2018)	CA of size 10 mm evaluated better results of permeability when compared to CA of 5 mm to 8 mm or low [11]
Yanya (2018)	Usage of recycled aggregate (RA) influenced the strength and permeability aspect. Inclusion of RA showcased rise in permeability and strength up to a point and started decreasing with increase in RA addition [12]
Ulloa-Mayorga et al. (2018)	Natural Aggregate exhibited better properties in comparison to RA but with increase in cement paste content, strength with RA is more than NA as the RA is able to absorb the slurry [13]
Galishnikova et al. (2020)	RA was replaced at a percentage of 0–100 which finally showed that at 50%, strength increment is noted [14]

2.4 Miscellaneous Study

Apart from the above-stated works, there are several studies on the aspects like maintenance methods of PCP involving pressure washing that restores around 80% of infiltration rate [15]. It is observed that a design life of 20 years can be achieved with proper maintenance [16] and the level of emission of greenhouse gases like carbon dioxide is less in PCP in comparison with other pavements [17]. An 8-year study revealed that a good PCP eventually dilutes harmful vehicular emissions with the installation of exhausts for air circulation [18]. Differential heating effects of PCP have proven to be one of the dominating traits that hold resistance to the urban heat island effect [19] thereby, ensuring a quality pavement that is environment friendly and easily maintained with minimal cost of maintenance [20].

Table 4 Properties of cement from the test results

Grade	OPC grade 43
Initial setting time	57 min
Final setting time	436 min
Standard consistency	31%
Specific gravity	3.21

3 Experiential Approach

The work is of two phases where casting cylinders for varying water-cement ratios and void content with cement & aggregate content kept constant comprises phase one. The cylinders are tested for 28 days of compressive strength and permeability. Of all the mixes of varying concerns, the mixes which yielded the maximum strength and permeability rate are considered for phase 2. The second phase apportions with the experimental approach based on the inclusion of admixture, Ground Granulated Blast-Furnace Slag (GGBS) in the mixes in varying percentages. Admixture is added to the mixes considered from phase 1 and then the cylinders are tested for compressive strength. Three specimens for each mix are cast in both the phases and the average of the three specimens is considered for every mix in every set. The tests are performed after 28 days for both phases.

3.1 Cataloging of Materials

As the constituent materials influence the pavement in terms of strength and other attributes, the detailing of the materials considered in the experimental program is stated vividly.

3.1.1 Cement

The cement utilized throughout the experimental work is ordinary Portland cement (OPC) of grade 43. The results of cement's specific gravity, standard consistency, and setting time are tabulated in Table 4.

3.1.2 Coarse Aggregates

The coarse aggregates (CA) used are of rounded type about 10 and 20 mm sizes, tested for various properties and the results are stated in Table 5.

Table 5 Results of the tests on CA

Specific gravity	2.73
Impact value of aggregates (%)	23
Aggregate abrasion value (%)	33

3.1.3 Water

Water that is free from visible impurities is used in the work. As casting, curing, and testing require a hefty amount of water, an easy source of availability is taken into consideration.

3.1.4 Ground Granulated Blast-Furnace Slag (GGBS)

GGBS is used as a source of admixture in the phase two of the experimental work. GGBS is purchased from iron manufacturing unit where it is usually produced as a by-product during the iron manufacturing. The specific gravity of the GGBS used is stated to be 2.85 by the manufacturing unit and the GGBS exercised in the work is in powder form.

3.2 Material Mixing and Casting of Cylinders

Constituent tests for the materials are carried out and considering all the test results, the materials are used for mixing. A mixed proportion of cement to coarse aggregate ratio 1:4 is adopted for the experimental work. Cylinders of diameter 150 and 300 mm long are cast throughout the work. To avoid initial hydration due to the outside temperature, it is made sure that the casting is done on a shady day. Also, no mechanical vibrators are employed in the process as over-vibration results in loss of voids and thus fails the objective work. The cylinders are cast with varying W/C ratios and void content percentages. The specimens are demoulded after 24 h and cured for 28 days before testing for compressive strength and permeability.

3.3 Phase 1 Approach

As aforementioned, phase 1 considers casting of cylinders with varying ratios of water-cement and void content. A total of 27 cylinders were cast in phase 1. Three sets of cylinders are cast with a W/C ratio of 0.3 for set 1, 0.35 for set 2, and 0.4 for set 3. The casted cylinders are tested for compressive strength as per IS 516-1959 clause 5 with a gradual load from 140 kg/cm^2/min increased without sudden shocks. In addition, the permeability is found using the constant head permeability method.

Table 6 Compressive strength and permeability values of set 1

Set 1 specimens	Cement content (kg/m^3)	CA content (kg/m^3)	W/C ratio	Void content (%)	Compressive strength (MPa)	Permeability (cm/s)
1a	330	1650	0.3	18	9.797	1.192
1b				20	8.908	1.299
1c				22	8.594	1.456

The permeability is calculated using the Eq. 1

$$K = \frac{QL}{Ah} \tag{1}$$

where,

K Permeability (cm/s).
Q Recorded discharge (cm^3/s).
L Length of the cylindrical specimen (cm).
A Area of Cross- Section of the cylindrical specimen (cm^2).
h Level height of constant head causing flow (cm).

3.3.1 Reported Values of Specimens with Water-Cement Ratio 0.3

The mix is designed for a W/C ratio of 0.3 where three levels of void content are maintained for three specimens each. The average of the three specimens of each mix is taken into account. The highest compressive strength of 9.797 MPa is recorded for the mix with 18% void content whereas highest permeability of 1.456 cm/sec is recorded for the mix with void content of 22%. Table 6 elucidates the mix details along with the test results obtained after 28 days for compressive strength and permeability of set 1.

3.3.2 Reported Values of Specimens with Water-Cement Ratio 0.35

The mix is designed for a W/C ratio of 0.35 with void content percentages maintained for three specimens. The average of specimens witnessed 11.546 MPa as highest compressive strength for the mix with 18% void content and 1.252 cm/sec as highest permeability for the mix with void content of 22%. Table 7 portrays the mix details of set 2.

Table 7 Compressive strength and permeability values of set 2

Set 2 specimens	Cement content (kg/m^3)	CA content (kg/m^3)	W/C ratio	Void content (%)	Compressive strength (MPa)	Permeability (cm/s)
2a	330	1650	0.35	18	11.546	0.795
2b				20	10.979	1.154
2c				22	9.940	1.252

Table 8 Compressive strength and permeability values of set 3

Set 3 specimens	Cement content (kg/m^3)	CA content (kg/m^3)	W/C ratio	Void content (%)	Compressive strength (MPa)	Permeability (cm/s)
3a	330	1650	0.4	18	14.2	0.629
3b				20	13.499	0.899
3c				22	12.287	1.130

3.3.3 Reported Values of Specimens with Water-Cement Ratio 0.4

A W/C ratio of 0.4 is used for the mixes in set 3 with the maintenance of void content differential for three specimens each. The experimental approach has seen the mix with 18% voids showcasing a high compressive strength of 14.2 MPa and 22% voids mix showing a high rate of permeability of 1.130 cm/sec which are the average values of three specimens. Table 8 manifests the mix details of set 3.

3.3.4 Analysis of Compressive Strength and Permeability Results from Phase 1 Approach

From the performed experimentation with varying void content percentages and W/C ratios, differential results are inscribed. The compressive strength from each mix of every set is represented graphically in Fig. 1 where it elucidates that the highest strength of 14.2 MPa is recorded for 18% void content at 0.4 W/C ratio. Likewise, the excessive permeability of 1.456 cm/sec is recorded 22% void content at 0.3 W/C ratio as shown in Fig. 2. It is evident that increase in W/C ratio enhances strength despite lowering permeability and vice versa.

3.4 Phase 2 Approach

From the experimental work performed and the graphical representation illustrated in 3.3.4, it is comprehensible that the mix 3a comprising of W/C ratio 0.4 with void

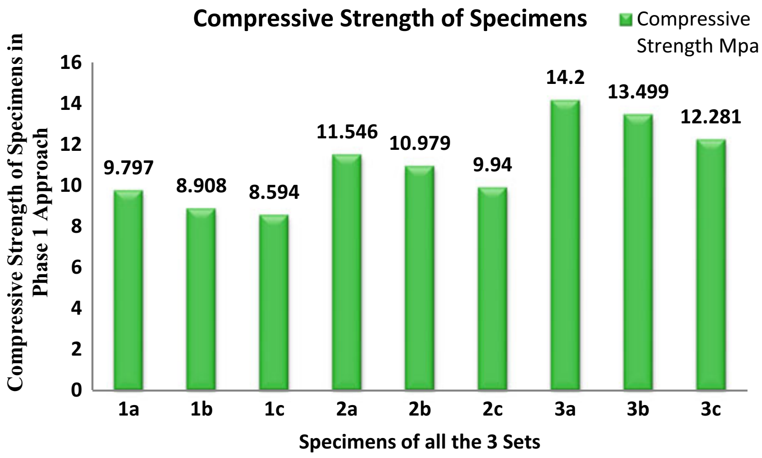

Fig. 1 Compressive strength of specimens in phase 1 approach

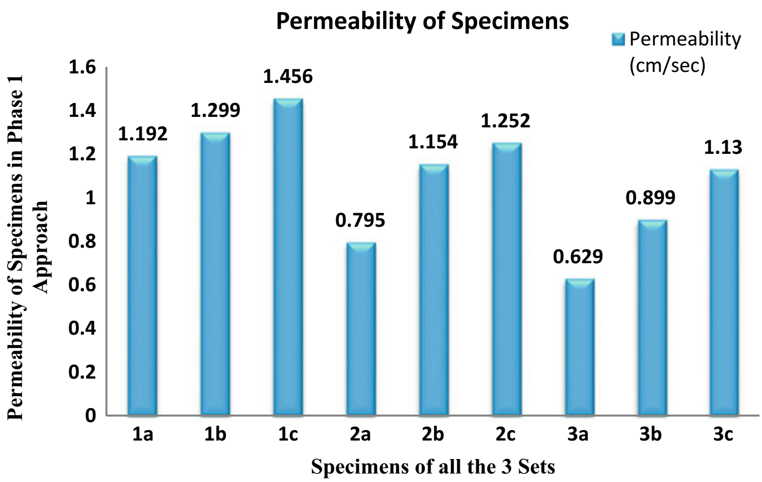

Fig. 2 Permeability of specimens in phase 1 approach

content 18% resulted in higher compressive strength of 14.2 MPa. Also, highest permeability of 1.456 cm/s is observed for mix 1c of 0.3 W/C ratio at 22% void content and thus, these two mixes are taken into consideration for phase two of the work where GGBS is added to the considered mixes in 10, 20, 30, and 50%.

Table 9 Compressive strength and permeability values of Mix 3a with the inclusion of GGBS

Set 4 specimens	GGBS inclusion (%)	Compressive strength (MPa)	Increment in strength with GGBS (%)	Permeability (cm/s)	Decline in permeability with GGBS (%)
4a	10	14.645	3.13	0.607	3.5
4b	20	15.140	6.62	0.590	6.2
4c	30	15.717	10.68	0.555	8.5
4d	50	15.790	11.19	0.534	12.1

Table 10 Compressive strength and permeability values of mix 1c with the inclusion of GGBS

Set 5 specimens	GGBS inclusion (%)	Compressive strength (MPa)	Increment in strength with GGBS (%)	Permeability (cm/s)	Decline in permeability with GGBS (%)
5a	10	8.872	3.24	1.409	3.26
5b	20	9.169	6.7	1.360	6.59
5c	30	9.494	10.47	1.324	9.1
5d	50	9.542	11.03	1.291	11.35

3.4.1 Results from the Addition of GGBS to Mix 3a

To elevate the compressive strength of the mix, GGBS is added in various percentages in powdered form. Cylinders are cast with the mix design of W/C ratio 0.4 and void content 18% inclusive of GGBS and are tested for compressive strength and permeability after 28 days. The results are tabulated in Table 9.

3.4.2 Results from the Addition of GGBS to Mix 1c

GGBS is added to the mix 1c in varying percentages of 10, 20, 30, and 50% where a W/C ratio of 0.3 and void content of 22% is used. The results of compressive strength and permeability are represented in Table 10.

3.4.3 Analysis of Compressive Strength & Permeability Results from Phase 2 Approach

With the inclusion of GGBS in various percentages, evident changes are observed in compressive strength as well as in permeability. With increase in inclusion of GGBS, the compressive strength in set 4 and set 5 have exhibited inclination in strength aspect whereas, a decline is observed in case of permeability. Figure 3 illustrates

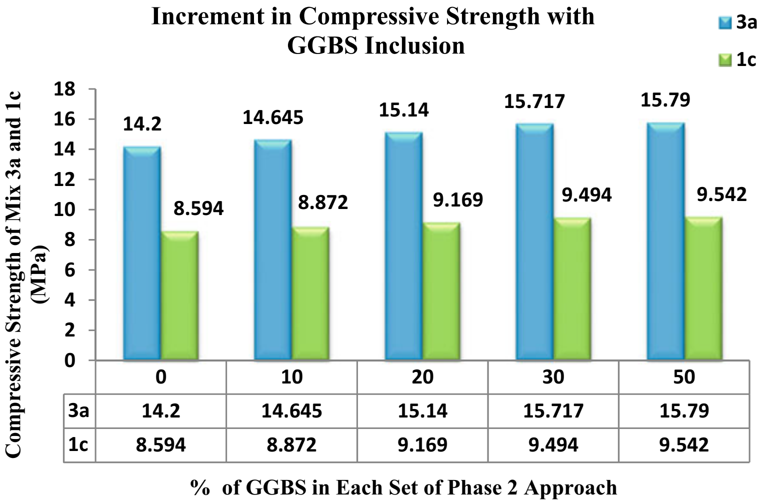

Fig. 3 Increment in compressive strength with GGBS inclusion

the incremental evidence recorded for compressive strength and Fig. 4 explicates the declination observed in permeability.

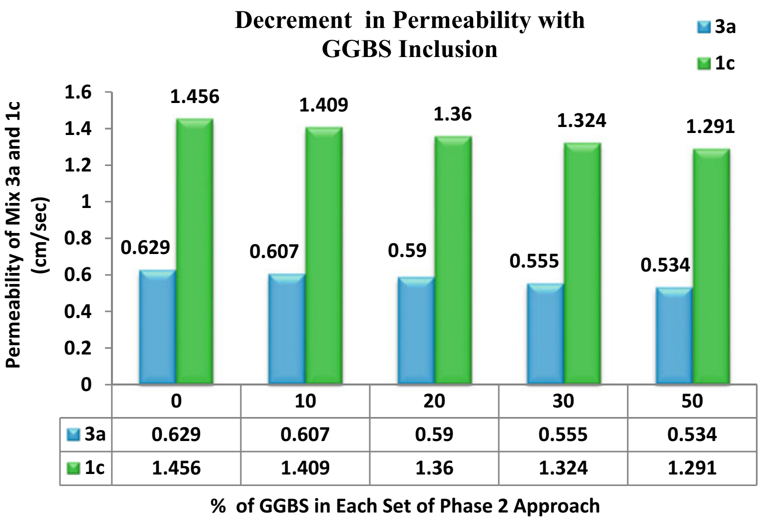

Fig. 4 Decrement in permeability with GGBS inclusion

4 Conclusions

From the performed experimental work, the results have cleared the way for the following conclusions,

- The compressive strength has witnessed an escalation with lower void content and a higher W/C ratio. However, the vice versa formulates the permeable behavior in the case of pervious concrete pavement. Thus, the extensive strength rate of 14.2 MPa is observed for a mix with a 0.4 W/C ratio where a void content of 18% is withheld. Despite a low permeability rate of 0.629 cm/s, it still falls under the optimal limitation to be used for paving of PCPs where rainfall intensity is of a lower level.
- In addition, the high permeability of 1.456 cm/s is recorded for a mix comprising a W/C ratio of 0.3 and void content of 22%. The compressive strength of 8.594 MPa makes it undesirable for heavy volume pavements whereas, it can be of high-performing paving material with heavy rainfall with low traffic volume.
- A mix with a W/C ratio of 3.5 and 20% void content resulted in the optimum values of compressive strength and permeability where the former reached is 10.979 MPa, and the latter is 1. 154 cm/s.
- As the strength of PCP falls short in numerous circumstances, the inclusion of Ground Granulated Blast- Furnace Slag has proven to be one of the predominant choices.
- The inclusion of GGBS has shown incredible results where 10% of GGBS increased the compressive strength of the mix by 3, 20% of GGBS resulted in an increment of 6.5, and 30% of GGBS unconcealed an increase by 10.5%.
- The incorporation of 50% GGBS has not succeeded in producing sufficient increment in strength and, therefore, it is not suggestible to go for 50% of GGBS. Similar results and approximate increment is achieved through 30% inclusion as well.
- All in all, with the addition of GGBS in the mix, a decline in permeability is witnessed. Despite the flaw of decrease, the permeability rate can be preserved with simple maintenance methods thereby making it sustainable.
- With the results and analysis carried out, pavement of pervious concrete proves to be the best replacement for conventional concrete pavement as it deals with.
- Stormwater management and the sustainable maintenance of PCP makes it predominant in the sector of pavements.

Therefore, a mix of Cement to Coarse Aggregate ratios of 1: 4 with the inclusion of GGBS at 30% for a W/C ratio of 4 and void content of 18% proves to act as an optimal design mix for PCPs.

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