



Environmental Performance and Resource Efficiency of Pervious Concrete for Sustainable Pavement Systems

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Abstract

Pervious, or porous, concrete has been growing in acceptance as a promising solution to decrease the quantity of impermeable surface area associated with pavements or sidewalks, lower puddling, and delay stormwater draining surface high flow rates. As important as these benefits are for surface runoff mitigation, there are concerns about the capability of pervious concrete mixes to provide enough structural support and longevity for the expected span life of the sidewalks. The composition of pervious concrete creates limitations to its mechanical compressive strength and challenges in its continuous maintenance to achieve the required service life. The performance of pervious concrete pavements is relevant to their regional location and applications. Twelve various pervious concrete mix designs that include commercially available mixes as well as laboratory-designed mixes were investigated in this study. Results showed that mechanical performance is strongly dependent on binder content and aggregate angularity. Mixtures with crushed limestone significantly outperformed those with rounded river gravel in all tests. While compressive strength was within the ACI 522R range, existing ACI 318 relationships for predicting tensile and flexural strength from compressive strength were found to overestimate pervious concrete mechanical properties and are therefore not applicable. Furthermore, no clear correlation was observed between elastic modulus and void ratio, indicating that stiffness is governed more by paste quality and aggregate characteristics than porosity alone. Vibration and placement methods affect mechanical properties.

Keywords

Pervious, porous, concrete, Mix, Design, compression strength, tension, flexural strength, Splitting, Stress, Tensile, elastic modulus, cement, mechanical properties, sidewalk, pavement, aggregate.

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Introduction

Pervious concrete was first introduced in Europe during the nineteenth century and was subsequently adopted in residential construction in Scotland and England during the 1920s. Pervious concrete is a permeable material with a high interconnected porosity, usually ranging between (15-35) %, which allows water to pass through it. It is often built with an underlying stone reservoir that temporarily stores surface runoff before it infiltrates deep into the subsoil. There are many benefits to employing pervious concrete in paving sidewalks. Effectiveness for stormwater management is one of the most important benefits; reduce

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puddling reducing storm water runoff. It can also remove pollutants, thus enhancing water quality. Some previous research has measured high removal rates of total suspended solids (TSS), oil, metals, and fat, as well as moderate removal rates for phosphorus, from using pervious concrete [1,2]. They can also reduce the use of melting chemicals, and while they do not remove chlorides, the reduction of melting chemical use is an efficient technique for reducing chloride contamination [3]. However, pervious concrete may experience clogging over time in the absence of periodic vacuuming and regular maintenance. There have been many studies, articles, reports, and presentations focused on the application, properties, and performance of pervious concrete. Research conducted by Dong et al. [4] shows that the use of smaller aggregate sizes, polypropylene fibers, and latex can enhance abrasion resistance when assessed using ASTM C944[5]. B. Izevbekhai and Akkari [6] found that pervious concrete exhibited lower thermal gradients compared to conventional Portland Cement Concrete pavement. They also further indicated that pervious concrete provides superior sound absorption compared to conventional Portland Cement Concrete pavements and that freeze-thaw cycles can be enhanced with reduced clogging. Multiple factors that are responsible for reduced performance of the pervious concrete were determined. Inadequate construction practices altered the target pore distribution and substantially lowered the permeability of the pervious concrete sections, progressively leading to a gradual loss of perviousness in surfaces. Often, pervious concrete is constructed in the absence of control joints and permitted to crack randomly [7]. ACI522 [8,9] defines pervious concrete as a zero-slump, open-graded material consisting of hydraulic cement, graded coarse aggregate, low or no fine aggregate, desirable admixtures, and water, designed to allow stormwater to drain through its interconnected void structure. According to ACI Committee 522 [8,9], its effective application as a pavement system requires strict specifications for materials, mixture proportions, design, installation, and curing to ensure adequate permeability and structural performance. As a result, both the long-term durability and practical drainage water capacity of pervious concrete pavements requires those specifications to be followed. Singh and Gupta [10] found that the addition of relatively replaced aggregate reduces strength properties including compressive and tensile stress for pervious concrete, as it has more porous structure and accompanies weak interfacial transition zone compared with normal concrete, while by adding silica fume into the mix design, not only mechanical properties are altered by a pozzolanic reaction but also pore refinement strongly takes place resulting in drastic improvement. The use of recycled aggregate increased the permeability whereas incorporation of silica fume decreased it, with an optimum level of silica fume substitution resulting in a stronger concrete via more balanced improvement to strength and hydraulic conductivity. Li et al. The work of [11] showed that an additional synergistic incorporation of nano-silica and fly ash can significantly improve the compressive strength of pervious concrete, where nano-silica enhances early-age hydration and densifies the interfacial transition zone by filling nanoscale voids and providing pozzolanic formation of further C-S-H gel. Microstructural analysis demonstrates that the dual use maintained necessary permeability and enhanced compactness of the matrix, despite an inherent drawback of increased fly ash content over time with respect to strength. AlShareedah and Nassiri [12] comprehensively reviewed that incorporating industrial waste materials such as fly ash, silica fume, slag, and recycled concrete aggregates in porous concrete can improve sustainability while generally maintaining adequate permeability and mechanical performance when replacement quantities are optimized. They concluded that the main challenge in mixture design is balancing the trade-off between porosity-driven permeability and strength durability, which is strongly governed by aggregate gradation in the mix, binder content (gel), and type of waste supplementary cementitious materials. Zhu et al. A novel high-strength pervious concrete was pioneered by [13], who proposed an ultra-high performance paste to bind the aggregate, resulting in significantly higher compressive strength and still acceptable permeability despite lower overall porosity. Mulugeta and Hareru [14] observed that replacing part of the normal aggregate with waste plastic in pervious concrete resulted in lower compressive strength and density, however functional permeability and workability can be maintained up to a certain replacement level that makes this route a worthwhile sustainable waste recycling alternative. Saboo et al. As established in [15], aggregate gradation directly controls pore size, connectivity and porosity of pervious concrete; well-graded mixes improve compressive strength but reduce permeability compared to uniform single-sized coarse aggregates. Zhang et al. In one example [16], it was demonstrated that pervious concrete prepared with recycled concrete aggregate (RCA) and a geopolymer binder showed similar mechanical and hydraulic

performance compared to similar normal cement-based pervious concrete, while also dramatically reducing carbon footprint and embodied energy.

The objective of this research is to provide general recommendations for pervious concrete mixture design and construction for sidewalks. Test for chemical composition were performed on some various kind of porous concrete. The purpose is to create consistent regulations and standards for use in case a permeable sidewalk installation is pursued. While the increase in pavement use of pervious concrete will ultimately lead to added confidence in its design and performance, there remain many data gaps and limited field experience with this system.

Research Significance

The main objective of this study is the use of pervious concrete for pavement for sidewalks. Porous concrete is widely promoted as a sustainable solution for stormwater management and urban heat island mitigation. Porous concrete would create a pervious surface and allow for a larger drainage surface to be considered. The structural design of porous concrete is still limited due to a lack of reliable guidelines and mechanical property data. For instance, existing design codes based on empirical formulas developed for normal concrete (e.g., ACI318) constitute the basis of current design practice, but they may not be applicable to very porous concrete. To achieve this primary goal of the study, we will perform the following tasks: 1. Study the effects of major factors affecting the quality of porous concrete implementation in sidewalks. These include structural performance to meet normal expected sidewalk strength. 2. Identify the potential mix designs with reasonable content for each case scenario and propose the best formulation based on visual observation of the laboratory results with respect to mechanical properties and durability performance of test specimens prepared using different mix designs. 3. By providing a comprehensive dataset on twelve mixtures made with local materials, this work offers essential guidance for material selection. It contributes to the development of specific predictive models for pervious concrete pavements.

Material Properties And Mix Design

In previous studies [17,18,19], the ingredients employed in the mix design for pervious concrete pavements normally contain coarse aggregates (10 mm and 6 mm), Portland Cement Type I or Type II, water, including or not small amounts of fine aggregates, slag, fly ash, water reducers in medium and high range (HRWR or MRWR), viscosity modifiers (VMA), hydration stabilizers (HSA), and air entrainment (AE). Typically, the mix designs for pervious concrete contain one size of local coarse aggregates mixed with cement Type I and water. The addition of air-entraining and water-reducing admixtures is also recommended. Fine aggregate and fly ash are used in some mixes. Commonly, the void content ranges from 15% to 25%, and infiltration rates are approximately between 6350 mm/hr and 32000 mm/hr. Mixtures employed for High durability have a typical fine aggregate content between 5% and 10% for high strength and durability. Latex-based admixtures have been employed to improve the cement paste tensile strength. The mixtures investigated in this research exhibited relatively high porosity (15%-35%) and low strength, while European mixtures demonstrated lower porosity (15%-20%) and higher strength [20].

In this investigation, twelve mix designs using two coarse-aggregate sizes, cement with variable content, and variable water-cement (W/C) ratios and admixtures were evaluated for structural properties. These factors significantly influence the short- and long-term performance of pervious concrete. Table. (1) shows a summary of the different mixes experienced in this research. Several factors were taken into account for the formulation of a suitable mix design, including aggregate size and type, the w/c ratios, cement content, and aggregate content. When preparing pervious concrete specimens, more important considerations were made to ensure the correct application of vibration. Preparation of trial mixes to study the effect of vibration. The analysis of the results found that vibration is a significant factor influencing the properties of porous concrete mixtures. A moderate degree of vibration is needed as excessive vibration can result in segregation of the paste while inadequate vibration leads to a raised void content and lower paste coverage around the aggregates so that the overall cohesiveness and strength of pervious concrete suffers. Based on the vibration evaluation, recommendations will be offered on the laboratory vibration of porous concrete mixes. The mixes PRC-1 included sand, while mixes PRC-7 and PRC-8 contained slag and fly ash, respectively. The

addition of sand will give Mix PRC-1 a greater flexural and compressive strength. Therefore, only small amounts of sand may affect the porosity of a hardened mix. This study employs two size aggregates; 6 mm stones (+12.5) and 10 mm stones (+19), which are comprised of crushed stones and river gravel according to the mix design. Due to the Type I Portland cement with or without fly ash and slag. The rest of the mixes had variable aggregate content, w/c ratios, and sizes. Mixes PRC-10 and PRC-11 contained round river aggregate type. Mixes PRC-2, PRC-3, and PRC-9 were provided from local concrete suppliers. Due to the distinct geometric shape of the river gravel, the mixes using river gravel show different performance compared to crushed stone mixes. Their flowability, placement, consistency, hydrological properties, physical properties, and long-term performance were tested and compared to other mixes with crushed stone. To permit lower W/C ratios, the mid-range water-reducing admixtures (MRWR) are added in the mix designs. A hydration stabilizer is added to enhance workability and facilitate simplicity of placement. The air-entraining admixture was used to enhance the freeze-thaw resistance of the prisms. In the PRC-5 mix, the viscosity modifier is added. Due to the absence of fine aggregate (sand) in pervious concrete mixes, these mixes tend to be difficult to mix and hydrate with reasonable uniformity. Viscosity modifiers serve as lubricants for the mix and make placement easier. Slag and fly ash were added in PRC-7 and PRC-8, respectively, to compare durability and workability.

Table (1). Mix design proportions of selected porous concrete mixes

Series ID	Cement (Kg/m ³)	Coarse agg. Size 10 mm (Kg/m ³)	Coarse agg. Size 6 mm (Kg/m ³)	Sand (kg/m ³)	Fly ash (kg/m ³)	Slag (kg/m ³)	Water (kg/m ³)	w/c ratio	MRWR (SP) (liter/m ³)	HS (liter/m ³)	VM A (liter/m ³)	AE (%)
PRC-1WV	397	1421	---	133	---	---	124	0.33	---	---	---	---
PRC-1NV	377	1441	---	133	---	---	124	0.33	---	---	---	---
PRC-2	512	1441	---	---	---	---	140	0.27	---	---	---	---
PRC-3	356	1681		-	-	-	96	0.27	2.5	2.5	---	1
PRC-4	368	1601	-	-			100	0.27	2.5	2.5	---	1
PRC-5	368	1601	-	-			100	0.27	2.5	2.5	2.6	1
PRC-6	368	818	818	-	-	-	100	0.27	2.5	2.5	---	1
PRC-7	311	1483			33		100	0.29	2.5	2.5	---	1
PRC-8	276	1483				92	100	0.27	2.5	2.5	---	1
PRC-9	297	---	1601				98	0.33	-	-	---	1
PRC-10 (gravel)	356	1601					107	0.30	-	-	---	1
PRC-11	356	---	1601				107	0.30	-	-	---	1

(grave l)												
MRWR= Mid Range Water Reducing Admixture					HS = Hydration Stabilizer							
AE - Air Entrainment		VMA= Viscosity Modifier										

MECHANICAL PROPERTIES

Compressive strength represents a fundamental mechanical parameter for evaluating the allowable bearing strength of pervious concrete. Beyond that, it can indicate other mechanical properties, including elastic modulus, tensile strength, and flexural strength. Since ASTM has not established a dedicated procedure for evaluating the compressive strength of pervious concrete, ASTM C39/C39M [21], which specifies the testing procedure for cylindrical concrete specimens, will be adopted in this study. However, compressive strength should not be considered independently when evaluating the quality of pervious concrete. The measured strength should be examined together with other relevant criteria, particularly the specified void content and density of the fresh mixture, which can be determined in accordance with ASTM C1688 [22]. Another essential mechanical property is flexural strength, which determines the pavements' resistance to flexural stresses induced by traffic loads and other applied loads. The reported flexural strength values for pervious concrete are typically in the range of ~1–4 MPa. Flexural strength data from laboratory tests of concrete show greater variability than comparable compressive strength measurements, so care should be exercised in choosing design values [7]. Similar to compressive strength, flexural performance is affected by several mixture and processing factors, including the degree of compaction, porosity, aggregate-to-cement (A/C) ratio, and W/C ratio. In pavement applications, the allowable load capacity is primarily governed by the flexural strength and pavement thickness, which can be calculated using the pavement design procedures recommended by AASHTO [23].

SAMPLING, DIMENSIONS AND TEST SETUP

All the concrete batches were mixed and produced in a controlled lab conditions inside civil engineering laboratory. Mixing operation was performed using 0.4 m³ mechanical drum mixer. The volumetric size of every process batch was approximately 0.4 m³, and the mixer had sufficient volumetric capacity as well as power to adequately blend all concrete types studied in this research. To prepare specimens, ASTM C192/C192M, Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory was followed with modifications to account for the special properties of pervious concrete. Proportions of materials for each mixture were decided either a day prior to mixing or on the same day when mixing was done. To prevent inconsistent blending and reduce the effort required for cleaning, the interior surface of the drum was sprayed with water before charging the mixer. The drum was raised about 15 degrees above horizontal and clamped in place prior to loading. In order to enforce homogeneity, half of the coarse aggregate was manually filled first, sand if required were then filled and compressed, after wards cement is poured, and finally packing in remaining half of the coarse aggregate. Do not load cement first. Cement has fine particles that stick to the walls of the drum and disrupt mixing uniformity and consistency; Once all dry components were in, the mixer was turned covered and ran without water for roughly 1 to 2 minutes. The dry blend, along with the already mixed and then poured cement and coarse aggregate submitted for visual inspection to confirm uniform distribution of that material before stopping the blender drum again and restarting it, this time uncovered. Liquid admixtures were added to the tumbling dry materials (previously mixed with pouring water). The mixer was subsequently closed and permitted to run for a period of three minutes. After this, a two-minute resting period was allowed followed by another two minutes of mixing for improved chemical interactivity among constituents. A familiar technique to that used for conventional concrete. Continuous monitoring of mix consistency was essential to ensure adequate workability. If the mixture appeared overly dry, a small, weighed quantity of water was incorporated, and this extra water was documented and used to correct the water-to-cement ratio. Figure (1) illustrates the different beam and cylinder specimens after casting. Table. (2) shows the number and dimensions for each specimen used in this experiment.



Fig. (1) Various types of specimens after casting

Table. (2) Number of specimens and size for each test

Test Type	Flexural Test	Compression Test	Splitting Tensile Test	Modulus of Elasticity Test
Dimensions (mm)	150X150X450	100X200	100X200	100X200
Mold Shape	Prisms	Cylinders	Cylinders	Cylinders
No. of samples for each Mix	3	3	3	3

The flexural strength, Compressive, and splitting tensile strength tests, as well as elastic modulus tests, were tested at 7 days and 28 days.

Compressive Strength

The compressive strength of the pervious concrete specimens was calculated following the procedure specified in ASTM C39/C39M [21]. For each mixture, three cylindrical specimens measuring 100×200 mm were prepared and tested at ages of 7 and 28 days using a 4500 kN Forney compression testing machine. Prior to testing, the cylinders were removed from the moisture-curing environment approximately 24 hr. in advance and allowed to dry. However, due to the relatively high interconnected void structure of pervious concrete, some specimens required an extended drying period to reach the desired dry condition. The ambient moisture level during testing also affects the drying time. Accordingly, selected specimens were removed from the curing rooms approximately 36 hr. before performing the test to ensure adequate drying and improve the reliability of the calculated strength. Following drying, the ends of the cylinders were prepared using molten sulfur capping at approximately 180°C . After full hardening of the sulfur layer, each specimen was centered between the loading platens of the Forney testing machine. Compression was applied at a rate of $1.2\text{--}2.2\text{ kN/s}$ immediately until failure and the load recorded in either 2 or 4 kN increments. Great care was taken to produce the capped surfaces as flat and specimens in the testing apparatus aligned because both can affect measured compressive strength significantly. Prior to sulfur capping, the upper surface of each cylinder was leveled using a heavy, flat 25 mm thick steel plate. The combination of surface leveling and sulfur capping was found to provide sufficiently uniform transfer and

distribution of the applied compressive load. A representative 100 × 200 mm cylindrical specimen positioned in the 4500 kN Forney testing machine is shown in Fig. (2).



Fig. (2) Compressive strength test on (100 X 200) mm sulfur-capped cylinder

The coefficient of variation (C.O.V.) is calculated using the equation:

$$\text{C. O. V}(\%) = \frac{\text{Average Peak Load}}{\text{Standard Deviation}}$$

Flexural Strength Tests

The calculation of flexural strength was performed following the procedures outlined in ASTM C78/C78M. For each testing age of 7 and 28 days, three prismatic beams with dimensions of 150 mm × 150 mm × 450 mm were subjected to flexure using an MTS Sintech 10/GL testing frame. The test configuration is illustrated in Fig. (3). Load data were recorded automatically through the MTS software, from which the maximum applied load, cracking moment, and modulus of rupture were obtained. To verify repeatability, three replicates were examined for every mixture proportion at both curing ages.



Fig. (3) Porous Concrete Beam Test Set-Up (150 × 150 × 450) mm

Splitting Tensile Strength Tests

The splitting tensile strength of the pervious concrete is determined according to ASTM C496/C496M [26]. As shown in Fig. (4). The specimens were tested horizontally between the loading platens at a rate near 1.2 kN/s, and long wooden strips were placed along the upper and lower contact surfaces of the cylinders during placement and testing to keep them vertically aligned in addition to preventing lateral movement or rolling. We did not apply end capping to the cylinder before performing the splitting tensile test (as would have been done on those specimens used for baring compressive strength). With the maximum load obtained by

each specimen just before failure, this value was used to calculate the splitting tensile strength. At each of the curing ages, for each mixture three replicate cylinders were tested to evaluate the consistency and repeatability of experimental measurements.



Fig. (4) Splitting tensile strength test of (100X200) mm porous concrete cylinder

Elastic Modulus Tests

Testing the elastic modulus was challenging and time-consuming. The tests were conducted in compliance with ASTM C469/C469M [27], using a compatible compressometer with two yokes used for (100X200) mm cylinders. For measuring the modulus of elasticity, only vertical deformation was measured throughout the tests. Maintaining a constant distance between the screws and the specimen, and keeping the top and bottom rings parallel to each other and to the horizontal surface are all key to obtaining accurate readings. After the compressometer is placed correctly onto the cylinder, the specimen must be centered on the bearing plate of the Forney compression machine. It is then loaded to 40% of its failure load and unloaded, and the cage distances on the opposite sides are then measured. As the specimen is loaded again, readings are taken at 2 to 4 kN intervals depending on the compressive strength of the cylinder. The loading rate is generally between 1.2 and 1.8 kN/s. Each specimen is tested first with the loading from one capped end, and then again with the load coming from the other capped end to ensure consistency of the test results. Fig. (5) shows the modulus test setup.



Fig. (5) Elastic modulus test of (100X200) mm sulfur-capped porous concrete cylinder

Test Results and Discussion

Compressive Strength Results

Fig. (5) demonstrates the development of compressive strength (f'_c) for all pervious concrete mixes investigated in this experiment at 7 and 28 days. Generally, the compressive strength appears to be directly correlated with the cement content of each mix, where the mixes with the most cement content have the highest compressive strengths, excluding PRC-1, which was the only mix containing fine sand. The results show a general trend of strength gain with age across all series, attributed to sustained cement hydration and pozzolanic reactions at later ages. The highest compressive strength (f'_c) at 28 days was recorded for mix PRC-2 with 23.5 MPa, while its 7-day strength was only 10.6 MPa, as listed in the Table. (3). This substantial increase (approx. 125% gain) this suggests a gradual but large increase in strength development and it may be related to the combination of different types of supplementary cementitious materials or type of admixture in this mix. The highest values of compressive strength measured at 7 days (13 to 13.7 MPa) and 28 days (15.6 to 16.2 MPa) were obtained from mixes PRC-1WV, PRC-1NV, and PRC-11 (gravel). This implies better early hydration and closer inter-particle bonding of these pervious concrete mixes. PRC-1WV and PRC-1NV having similar compressive strength values indicate that while the method of vibration (WV vs NV) is different, it appears to have a minimal influence on the compressive strength of the concrete. The lowest early compressive strengths, even at 28 days (7.7 to 9.1 MPa), were shown by the PRC-5, PRC-6, PRC-8 and PRC-9 mixes [3]. The decrease can be explained by the increased porosity, void content, or a reduced aggregate interlock already seen for pervious concrete at greater permeabilities. Of the 2 mixes of gravel aggregates, PRC-11 (for gravel) gave better performance than PRC-10 (gravel), giving compressive strength of 13.7 MPa and 16.0 MPa at days 7 and 28 respectively against a value of 10 MPa and 14.2 MPa from the same day for PRC-10. This shows that with respect to load-bearing capacity, aggregate gradation and mix proportioning are interrelated.

From ACI 522R [8,9], it is common to have pervious concrete compressive strengths from 2.8 to 28 MPa (400-4,000 psi). All mixes in this experiment were noted as falling within these parameters, confirming the applicability of mix designs for pervious pavement applications. Low-traffic roads and parking lots normally require concrete with a minimum strength of 14 MPa at 28 days compared to 3.5 MPa for walkways and pedestrian areas. Based on this, mixes PRC-1WV, PRC-1NV, PRC-2, PRC-3, PRC-10 (gravel) and PRC-11 (gravel) meet the requirement for light traffic applications, whereas mixes PRC-5, PRC-6, PRC-8 and PRC-9 are limited to pedestrian and non-structural applications. The results are consistent with previous studies. Neamitha and Supraja [28] reported 7-day and 28-day strengths of 8.5-14.2 MPa and 11.5-19.5 MPa for pervious concrete with various aggregate sizes. Similarly, Ali et al. [29] found compressive strengths of 6.8-16.3 MPa for gravel-based pervious mixes, which matches the performance of PRC-10 and PRC-11 in the current study.

Table. (3) Average of Compressive Strength Results at 7 and 28 days

Series ID	Compressive Strength f'_c (Mpa)		C.O.V(%)	
	7-days	28-days	7-days	28-days
PRC-1WV	13.5	16.2	5	2
PRC-1NV	13	15.6	6	3
PRC-2	10.6	23.5	4	5
PRC-3	11.5	14	16	17
PRC-4	10.8	13.7	17	12
PRC-5	6.8	7.7	6	18
PRC-6	7.3	8.9	7	10
PRC-7	10	13	9	16

PRC-8	6.5	9.1	11	15
PRC-9	6.5	8	5	2
PRC-10 (gravel)	10	14.2	11	2
PRC-11 (gravel)	13.7	16	3	3

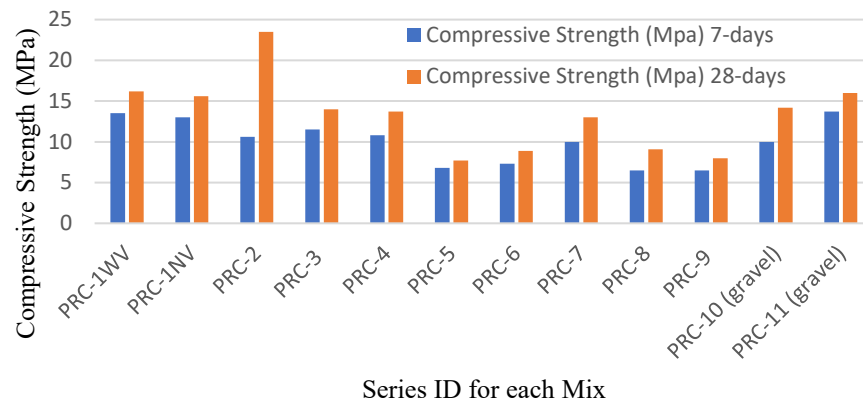


Fig. (5) 7 days and 28 days compressive strength of all mixes

Splitting-Tensile Strength

The splitting tensile strength was evaluated at 28 days of curing. The results for all mixtures and the associated coefficient of variation (C.O.V.) are summarized in Table 4. In general, the variation of the tensile strength follows a consistent response to that observed for compressive strength (f'_c). The maximum reported tensile resistance was for mix PRC-2 (2.20 MPa), followed by PRC-11-gravel (1.95 MPa) and PRC-1WV (1.92 MPa). This sequence is consistent with the compressive strength hierarchy, where PRC-2 also exhibited the maximum load-carrying capacity. Conversely, the lowest tensile capacities were observed in mixes PRC-9 (1.10 MPa) and PRC-5 (1.20 MPa), which also demonstrated the lowest compressive strengths, indicating that the quality of the inter-particle cementitious bond governs both failure modes. The measured values, ranging from 1.1 to 2.2 MPa, are well within the typical range reported for pervious concrete in ACI 522R (1 – 3 MPa). The ratio of splitting tensile strength to compressive strength at 28 days was found to be between 10% and 18%, which is higher than that of conventional concrete about (8-12%) due to the nature of the failure plane that is forced to propagate through the aggregate-paste interface rather than through the aggregates. A significant aspect of the current results is the low dispersion. The coefficient of variation (C.O.V) for the splitting tensile test ranged from 2% to 10%, with an average of 4.8%. This is considerably lower and more stable than that obtained from the compressive strength tests. This improvement in repeatability can be attributed to the more stable testing configuration and the better control over the loading rate (0.02-0.05 MPa/s) in the splitting test, which minimized eccentric loading and local crushing effects that are common in the compression test of highly porous specimens. The only exception was PRC-6, which showed a C.O.V. of 10%, potentially due to heterogeneous void distribution within the specimens.

Table. (4) Reported Average splitting tensile strength of all mixes

Series ID	Average Splitting Tensile Strength (Mpa)	C.O.V (%)
PRC-1WV	1.92	3
PRC-1NV	1.73	4
PRC-2	2.2	2
PRC-3	1.64	4
PRC-4	1.9	2
PRC-5	1.2	5
PRC-6	1.4	10
PRC-7	1.5	7
PRC-8	1.5	7
PRC-9	1.1	5
PRC-10 (gravel)	1.73	3
PRC-11 (gravel)	1.95	6

Flexural Strength (Modulus of Rupture)

The flexural performance of pervious concrete was investigated using a third-point loading configuration as per ASTM C78 [25]; see Fig. (3). Beam specimens were tested at both 7 and 28 days of curing. The modulus of rupture (f_r) results and their corresponding coefficients of variation (C.O.V.) are presented in Table 5 and illustrated in Fig. (6). Compared to the compressive and splitting tensile tests, the flexural test results showed notably less scatter and higher consistency. The coefficient of variation (C.O.V) for all mixtures at both ages was consistently below 10%, with values ranging from 3% to 10%. This improved repeatability can be attributed to the larger failure surface in the flexural test, which averages the local heterogeneity of the void structure, and to the elimination of capping-related stress concentrations inherent in compression testing. As shown in Fig. (6), all mixes demonstrated a modest strength gain between 7 and 28 days, typically in the range of 5% to 15%, except for PRC-3 and PRC-5, which showed higher development of 50% and 55%, respectively. Mix PRC-2 had the highest 28-day flexural strength of 2.86 MPa, followed by PRC-1WV (2.70 MPa), whereas mix PRC-9 exhibited the lowest strength (1.06 MPa). In agreement with this trend, compressive strength behavior indicate that both dense paste and enhanced aggregate interlock are directly responsible for flexural capacity improvement. Table. (6) shows a comparison between compressive strength (f_c'), flexural strength (f_r), and splitting tensile strength (f_t) at 28 days. The value of f_r/f_c' ranged between 0.12 to 0.18 while averaging as 0.15 throughout the study. This ratio is substantially higher than the values commonly reported for traditional concrete (0.10 to 0.12), suggesting that pervious concrete has a relatively higher flexural strength at a specific compressive strength. The last column of Table. (6) compares the experimental modulus of rupture (f_r) values with the empirical relationship provided by ACI 318 [30] predicts normal-weight concrete, $f_r = 0.62\sqrt{f_c'}$. According to the ACI prediction, all pervious concrete mixtures tested had a modest modulus of rupture. For a flexural strength of pervious concrete, the conventional ACI correlation overestimates the strength in the range from 25% to 45%. This divergence is expected due to their high porosity and the lack of fine aggregates, which fundamentally change the distribution of stresses and modes of crack propagation. To date, neither ACI 522R nor ASTM has established a standardized (f_c'), (f_r)

correlation for pervious concrete, emphasizing the need for a specific predictive model for this type of concrete material.

Table. (5) Flexural strength (modulus of rupture) at 7 and 28 days

Series ID	Flexural Strength f_r (Mpa)		C.O.V(%)	
	7-days	28-days	7-days	28-days
PRC-1WV	2.46	2.7	5	3
PRC-1NV	2.3	2.55	8	4
PRC-2	2.62	2.86	3	7
PRC-3	1.6	2.4	10	8
PRC-4	2.3	2.5	4	7
PRC-5	0.9	1.4	7	7
PRC-6	1.21	1.5	8	8
PRC-7	1.32	1.64	3	4
PRC-8	1.3	1.51	6	3
PRC-9	0.95	1.06	4	6
PRC-10 (gravel)	1.7	1.8	8	3
PRC-11 (gravel)	1.95	2	5	3

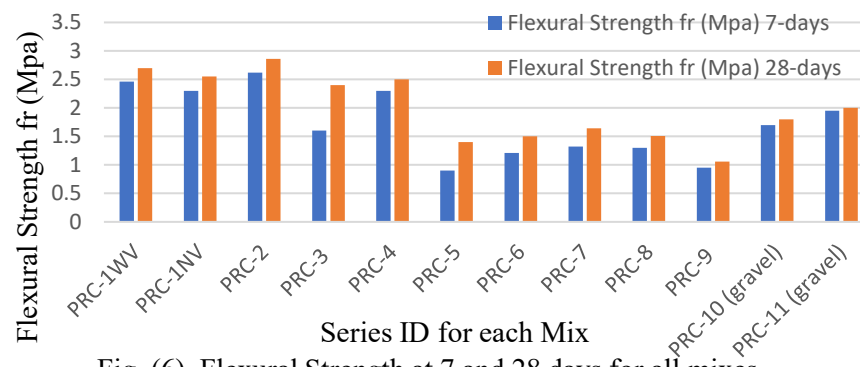


Fig. (6). Flexural Strength at 7 and 28 days for all mixes

Table. (6) Relationship between f_t , f'_c , and f_r at 28 days, and comparison with ACI prediction of f_r in terms of f'_c

Series ID	f'_c (Mpa)	f_r (Mpa)	f_t (Mpa)	f_r/f'_c	ACI formula $f_r = 0.62\sqrt{f'_c}$
PRC-1WV	16.2	2.7	1.92	0.17	2.50
PRC-1NV	15.6	2.55	1.73	0.16	2.45
PRC-2	23.5	2.86	2.2	0.12	3.01

PRC-3	14	2.4	1.64	0.17	2.32
PRC-4	13.7	2.5	1.9	0.18	2.29
PRC-5	7.7	1.4	1.2	0.18	1.72
PRC-6	8.9	1.5	1.4	0.17	1.85
PRC-7	13	1.64	1.5	0.13	2.24
PRC-8	9.1	1.51	1.5	0.17	1.87
PRC-9	8	1.06	1.1	0.13	1.75
PRC-10 (gravel)	14.2	1.8	1.73	0.13	2.34
PRC-11 (gravel)	16	2	1.95	0.13	2.48

Modulus of Elasticity

The static modulus of elasticity (E) showed considerable scatter among the considered mixtures. The values of the modulus of elasticity (E) at 28 days, as summarized in Table (7), ranged from 4,700 MPa to 18,200 MPa. This range is in general agreement with previous work conducted at the University of Minnesota, where (E) values for pervious concrete were reported to be between 13,800 MPa and 20,700 MPa. In the present study, the majority of the mixtures demonstrated a modulus equal to or greater than 12,300 MPa, except for PRC-1WV (8,400 MPa), PRC-1NV (7,360 MPa), PRC-8 (7,860 MPa), PRC-10-gravel (4,700 MPa), and PRC-11-gravel (5,760 MPa). The (E) has shown a high scatter due to the fact that it is influenced by many mix design parameters jointly. The variations in w/c ratio, binder content and type of aggregate used in this investigation program contribute directly to this dispersion because elastic modulus of concrete is a function of the stiffnesses of the components mixed to make it which are paste characteristics, aggregate properties and the total void content. Aggregate type showed significant effect as mixtures PRC-10 and PRC-11 used 6 mm and 10 mm rounded river gravel as a replacement of crushed limestone. These lowest moduli (60-70% lower than the crushed aggregate mixtures average) are attributed to the weaker bond between gel and the smooth coated aggregate, as well as hardware interlock loss with rounded particles. In contrast; PRC-2 (18200 MPa), PRC-7 (17680 MPa), PRC-3 (16830 MPa) and PRC-4 (16020 MPa); recorded the highest values of the elastic moduli as found in Table 7. These mixtures were characterized by the highest cementitious contents among all mixes, with the exception of PRC-7, where 15% of cement was replaced by fly ash. In principle, the modulus of elasticity of pervious concrete is governed by the volumetric fraction of voids, the stiffness of the aggregate skeleton, and the quality of the hardened cement paste. For this composite, void content is anticipated to be the dominant factor. To examine this dependency, the relationship between E and void ratio is plotted in Fig. (7). As depicted in Fig. (7), the results show a scattered distribution with no statistically significant correlation between elastic modulus and void ratio. Although it is theoretically expected that E, should decrease with increasing porosity due to the reduction in effective load-bearing cross-section, this trend was not observed. This random behavior suggests that within the tested void ratio range of 22-36%, other factors such as cement paste thickness, compaction heterogeneity, and especially aggregate type, had a more pronounced influence on the stiffness than void content alone. Similar inconsistent E vs. void ratio trends have been reported in the literature for highly porous cementitious systems.

Table. (7) Reported Modulus of Elasticity for all Mixes

Series ID	Elastic Modulus (E) (Mpa)
PRC-1WV	8400

PRC-1NV	7360
PRC-2	18200
PRC-3	16830
PRC-4	16020
PRC-5	12300
PRC-6	14000
PRC-7	17680
PRC-8	7860
PRC-9	13170
PRC-10 (gravel)	4700
PRC-11 (gravel)	5760

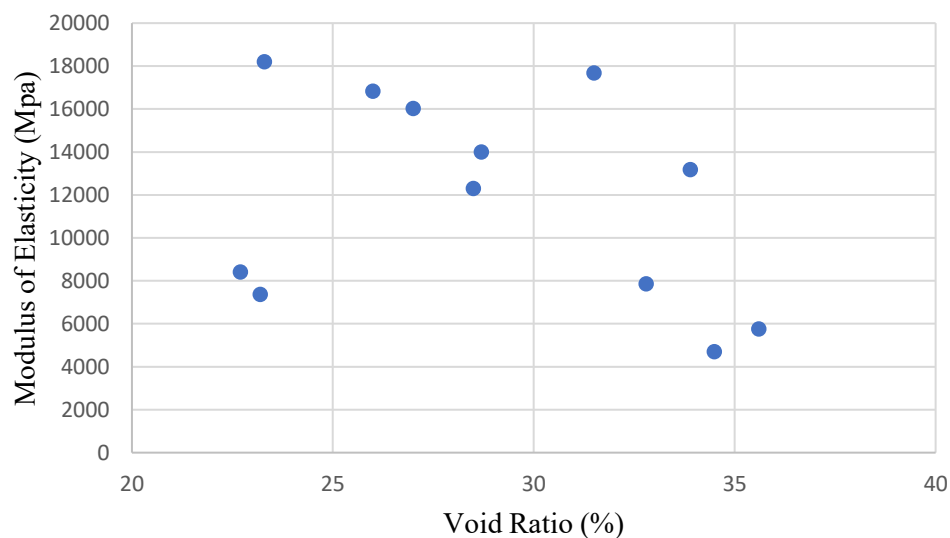


Fig. (7) Elastic Modulus (E) (Mpa) vs. Void Ratio (%) for each Mix

Conclusions

The present study focuses on evaluating the mechanical properties of twelve pervious concrete mix designs with varying w/c ratios, cement contents, and aggregate types, the presence of sand, fly ash, or slag, and admixtures for use in sidewalks. Based on the experimental data obtained at 7 and 28 days, the following findings were established:

1. In terms of workability, mixes PRC-10 and PRC-11 were the most workable mixes, as expected. During both the mixing and placement procedures, mixes PRC-10 and PRC-11 exhibited appropriate consistency and displayed favorable handling characteristics. The improved workability may be attributed to the rounded shape of the gravel aggregates. Furthermore, they hydrated properly during casting, without exhibiting any bleeding, while providing sufficient time for placement before initial setting occurred. Mixtures PRC-1, PRC-2, PRC-3, and PRC-6 also showed acceptable workability, although to a lesser extent than PRC-10 and PRC-11. In contrast, PRC-7 was comparatively dry and less workable, likely due to its low water-to-cementitious materials ratio, despite its overall satisfactory performance. The incorporation of a Viscosity Modifying Admixture in PRC-5 enhanced its workability.

2. Pervious concrete possesses unique properties which should be preserved by special handling when casting specimens. Over-consolidation or compaction must be avoided as it can alter the pore structure and thus influence the measured mechanical behaviour. The exposed surfaces of cylinders, prisms, and beams should be well-finished and leveled so as to provide contact with the loading apparatus in a way that will minimize eccentricity of the load thus enabling more accurate testing and better experimental consistency.
3. The 28-day compressive strengths obtained were similar and consistent with the typical range provided in ACI 522R for pervious concrete. Splitting tensile strength similarly demonstrated a trend aligned to that of compressive strength, with mixtures containing higher cement content and lower w/c ratio outperforming the lower mixes (especially PRC-2). In addition, the splitting tensile test showed smaller and more uniform variation than the compression test owing to its more stable loading configuration and precise control of loading rate.
4. The modulus of rupture f_r at 28 days varied from 1.06 MPa to 2.86 MPa. Results for flexure were the least scattered of all mechanical tests examined, with C.O.V. consistently $<10\%$. Values of flexural strength over compressive strength (f_r/f_c) are 0.12 to 0.18, which is large than that of normal concrete (Pagan et al; 2017). The relationship for f_r compared with the ACI 318 code equation determined that this equation always overestimates by approximately 25-45% the flexural strength of pervious concrete. So, the empirical formula for normal-weight concrete in ACI 318 cannot be applied to pervious concrete; And a specific correlation must be established. There is no standard relationship currently offered by ASTM and ACI 522R.
5. The value of static modulus of elasticity was highly variable between the mixtures though, which may be linked to differences in binder content and type of aggregate as well. More specifically, mixtures with rounded river gravel were shown to be significantly less stiff than crushed limestone mixes, highlighting the importance of aggregate shape and bond [10]. Higher moduli were obtained for the higher cement content mixtures. Additionally, the elastic modulus versus void ratio had a lot of scattered data with little observable pattern, suggesting that the stiffness is more function of mix composition and aggregate properties than a direct result of just void content in this test range.
6. Higher values of all mechanical properties were achieved with larger amounts of the cement and angular aggregates. The presence of fly ash in PRC-7 did not weaken the concrete, but actually achieved one of the highest moduli (17,680 MPa) suggesting PRC-7 is a viable option for sustainable pervious concrete. Strength did not always decrease with increased void ratio, confirming the heterogeneous nature of pervious concrete.
7. It is feasible to produce pervious concrete with acceptable mechanical properties for low-volume pavement and stormwater management applications using local materials. However, standard relationships developed for conventional concrete cannot be directly applied for predicting the tensile, flexural, and elastic properties of pervious concrete.

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