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Engineering properties of pervious concretes produced with recycled aggregate at different aggregate-to-cement ratio

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Abstract. Due to its capacity to address urgent environmental challenges connected to urbanization and stormwater management, pervious concrete, a sustainable and innovative material, has attracted a lot of attention recently. The aim of this study was to find the engineering characteristics of pervious concrete made from recycled aggregate (RA) at various aggregate-to-cement ratios (A/C) and the addition of 5% (by weight of total aggregate) of both natural and recycled fine aggregate to produce a very sustainable concrete product for a variety of applications. The three distinct aggregate-to-cement ratios, 6, 5, and 4, were used to produce pervious concrete using recycled aggregate in the research approach. The ratio of water to cement (w/c) was maintained at 0.3. Pervious concrete was created using single-sized recycled aggregate that passed through a 12.5 mm sieve and was held on a 9.5 mm sieve, as well as natural and recycled sand that passed through a 4 mm sieve. The production of twelve distinct concrete mixtures resulted in the testing of each concrete sample for dry density, abrasion resistance, compressive and splitting tensile strengths, porosity, and water permeability. A statistical method called GLM-ANOVA was also used to assess the characteristics of pervious concrete made using recycled aggregate. According to the experimental results, lowering the aggregate-to-cement ratio enhances the pervious concrete's overall performance. Additionally, a modest amount of fine aggregate boosts mechanical strength while lowering void content and water permeability. However, it was noted that such concretes' mechanical qualities were adversely affected to some extent. The results of this study offer insight into the viability of using recycled aggregates in order to achieve both structural integrity and environmental friendliness, which helps to optimize pervious concrete compositions.

Keywords: abrasion resistance; compressive and splitting tensile strength; pervious concrete; porosity; recycled aggregate and sand; water permeability

1. Introduction

Economy and environmental friendliness are two important factors that concrete manufacturers take into consideration when making their products. To achieve those goals, demolishing old concrete structures to obtain recycled aggregate and using it as an aggregate source for new concrete products is considered the best way. It has been demonstrated that concrete manufactured with recycled concrete aggregate could have mechanical properties similar to those of concrete made with natural aggregate if the parent concrete is of excellent grade (Xiao *et al.* 2012, Kou and Poon 2015). A carefully formulated concrete mixture known as "pervious concrete" includes water, cementitious materials, homogenous coarse aggregate, little to no fine aggregate, and frequent admixtures. Although using fine aggregate has several advantages, such as improved workability and compressive strengths, it can also have one big drawback: it can reduce pore size and fill in open void areas in the structure (ACI-522R-10 2010, Yu *et al.* 2019). The resulting concrete will therefore have more linked and porous spaces than conventional concrete. The pervious concrete porosity ranges from 18 to 35 percent (Kuo *et al.* 2013, Lori *et al.* 2019). This is significantly greater than the other forms of concrete, which typically range from 4 to 8 percent (Tennis *et al.* 2004, ACI-522R-10 2010). The grade and type of aggregates, the w/c, and the degree of compaction all affect the percentage of these pores (Neptune and Putman 2010, Sahdeo *et al.* 2021).

For pervious concrete mixtures to be able to support expected loads and let water move through their structure, the size distribution and properties of the aggregates need to be looked at in detail (Neptune and Putman 2010, Huang *et al.* 2021). Walkways, roadways with little traffic, highway shoulders, and parking lots are all frequent flat uses for permeable concrete (Meininger 1988, ACI-522R-10 2010, Obla 2010). The ability of pervious concretes to move

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significant amounts of water to the ground serves as their primary purpose. Thus, organically replenishing groundwater and minimizing or eliminating storm-water runoff issues are two of pervious concrete's greatest benefits (Meininger 1988, Neithalath 2004, ACI-522R-10 2010, Thorpe and Zhuge 2010). Utilizing pervious concrete is one of the Best Management Practices (BMP), according to the United States Environmental Protection Agency (EPA), since it can reduce pollutant concentrations and stormwater runoff (Kevern *et al*. 2009, ACI-522R-10 2010). The pervious concrete ability to absorb vehicle noise, control the temperature of Earth's surface and humidity, prevent the circumstance of the "hot island" in cities, and lessen the need for irrigation following land expansion are some of its additional environmental benefits. The pervious concrete pavement does not get wet during a downpour and does not shine at night. This improves the drivers' safety and comfort (Meininger 1988, Yang and Jiang 2003, Neithalath 2004, Tennis *et al*. 2004, ACI-522R-10 2010).

Cementitious material concentration in pervious concrete typically ranges from 270 to 415 kg/m^3 (Tennis *et al*. 2004), with a w/c of 0.25 to 0.35, and no fine aggregates or less than 10% of the maximum single-sized coarse aggregate (Kevern *et al*. 2008). Pervious concrete is typically made using a single-sized aggregate gradation (Yang and Jiang 2003, Tennis *et al*. 2004, Lian and Zhuge 2010). For the production of pervious concrete, smaller aggregate sizes are normally employed than for the production of conventional concrete. In the manufacturing process, a smaller aggregate was utilized, which made the mix better workable. It also offered a smoother surface while maintaining a high level of strength (Crouch *et al*. 2003, ACI-522R-10 2010). However, the performance of permeability is decreased by the smaller-sized aggregate (Lu *et al*. 2019). Grade and type of aggregate, A/C, w/c, and degree of compaction are only a few of the many variables that affect the qualities of permeable concrete (Crouch *et al*. 2007, Juradin *et al*. 2020, Anburuvel and Subramaniam 2022, Sathiparan *et al*. 2023). An appropriate balance between the material's two most crucial properties, void content, and strength, is the aim of pervious concrete mixture proportioning (Tennis *et al*. 2004, ACI-522R-10 2010). The pervious concrete compressive strengths normally range from 2.8 to 28 MPa, its density usually falls between 1500 and 2200 kg/m^3, and its water permeability often falls between 1.4 and 12.2 mm/s (Ghafoori and Dutta 1995, Tennis *et al*. 2004, Kevern *et al*. 2008). It is widely acknowledged that pervious concrete has less flexural and compressive strengths than ordinary concrete due to its significant porosity. In addition, typical concrete is less important than freeze-thaw resistance, durability, and chemical assault (ACI-522R-10 2010). By expanding the cement paste area, mixture strength can be increased (Murao *et al*. 2002). However, there is an opposite relationship between the pervious concrete strength and the amount of voids in the material. In other words, a reduction in porosity tends to improve the material's tensile and compressive strengths (Singh *et al*. 2020).

Previous studies have shown that the aggregate particle size, the gradation, and the A/C ratio are the key factors that affect the compressive strength, water permeability and porosity of pervious concrete, whereas the w/c has a small effect (Jiang *et al*. 2005, Yogesh *et al*. 2023). In order to make pervious concretes, Rizvi *et al*. (2010) used four RA percentages of 15, 30, 50, and 100%. Additionally, Güneyisi *et al*. (2016)'s research on pervious concrete focused on substituting recycled aggregate for natural aggregate at four distinct replacement levels: 25, 50, 75, and 100%. According to their findings, adding more RA caused in a drop in compressive strength, an improvement in permeability and an increase in porosity. In the manufacture of pervious concrete, Zhuge (2008) and Murao *et al*. (2002) both utilized RA; nevertheless, their findings showed significantly less compressive strengths at comparable permeability and porosity. Concrete's compressive strength is typically reduced when recycled aggregate is used in place of natural aggregate, and creep, drying shrinkage, and porosity are generally increased (Poon *et al*. 2004, Domingo *et al*. 2010, Wang *et al*. 2021, Xiao *et al*. 2022). According to Yang and Jiang (2003), pervious concrete's strength and abrasion resistance may be increased by utilizing carefully chosen material and sparingly adding fine aggregate. Additionally, it has been demonstrated that adding fine aggregate boosts compressive strengths and considerably lessens damage from freeze-thaw cycles (Meininger 1988). By using smaller-sized aggregate, the number of aggregate particles per unit volume can be increased. Wang (1997) found that 7% (by weight) of natural fine aggregate increased the pervious concrete strength. Additionally, the fine aggregate in the combination decreased the porosity of pervious concrete. The type of coarse aggregate has a direct impact on freeze-thaw durability, according to Kevern *et al*. (2008). Their study of the compaction of pervious concrete, Ghafoori and Dutta (1995) showed how A/C and the compaction energy affect the mechanical properties of the material. High strength is produced by a low aggregate-to-cement and high compaction energy. Therefore, it can be inferred from the literature analysis that cautious compaction and an appropriate mix design are necessary for pervious concrete (Taheri and Ramezanianpour 2021).

The goal of this study was to evaluate the engineering properties of pervious concrete made with recycled aggregate (RA), including its compressive strength, splitting tensile strength, dry density, void content, abrasion resistance, and permeability performance. Three different aggregate-to-cement (A/C) ratios (6, 5, and 4) were used to create the pervious concrete mixtures at a constant water-to-cement (w/c) ratio of 0.30. A variety of inclusion rates of recycled and natural fine aggregates (0%, 2.5% recycled, 2.5% natural, 5% natural, and 5% recycled) were also investigated. Twelve pervious concrete mixtures were made and tested after a total of 28 days of water curing. This study aims to contribute to the existing knowledge on the use of RA in pervious concrete by providing a comprehensive evaluation of the material's engineering properties and the influence of the A/C ratio and fine aggregate inclusion. The findings of this research can help fill the gap in the literature regarding the optimization of pervious concrete mixtures made with RA to achieve the desired balance between void content and strength, ultimately leading to the development of more sustainable and durable pervious concrete solutions for urban applications.

2. Experimental study

2.1 Materials

The materials operated in this research were Portland cement of the CEM I 42.5R type, single-sized recycled aggregate, and natural and recycled sand, each of which had specific gravities of 3.15, 2.54, 2.63, and 2.41. Table 1 provides information on the physical characteristics and chemical makeup of cement.

Table 1 Portland cement's chemical and physical constituents

Test category	Type of tests	Results	ASTM-C150 (2016)
Chemical tests	CaO	62.12	-
	Fe_2O_3	2.88	-
	Al_2O_3	5.16	-
	SiO_2	19.69	-
	SO_3	2.63	≤ 6
	MgO	1.17	≤ 6
	Free lime	1.91	0.66 – 1.02
	I.R	0.16	≤ 0.75
	L.O.I	2.87	≤ 6
	K_2O	0.88	
	Na_2O	0.17	-
Physical tests	Fineness (m^2/kg)	394	230 m^2/kg, the lower limit
	Specific gravity	3.15	

2.2 Recycled aggregate

Concrete with an average compressive strength of 23.2 MPa after 28 days was crushed using a two-stage crushing system that included both jaw and cone crushers. This made it possible to get recycled coarse aggregate in a single size. In the initial phase of this experimental work, cubic concrete samples were made using, respectively, 210, 280, 841, and 1024 kg/3 of water, cement, fine aggregate, and coarse aggregate. Natural river sand and gravel with specific gravities of 2.43 and 2.73, correspondingly, were utilized to produce recycled concrete. In order to create concrete with low-strength and attain the same properties as concrete produced on-site. To accomplish this goal, 210 cubic specimens were submerged under water for 7 days, and then they were kept in laboratory environments for 28 days. When the cubic specimens were tested for 28 days of compressive strength, the weaker concretes were crushed utilizing a two-stage crushing technique. Concrete samples were placed in the jaw cone, which was being utilized as a main crusher, and the aggregate was compressed into foliaceous shapes. After that, the aggregates of foliaceous-shaped were transformed into aggregates with angular-shaped by a cone crusher, which creates an impact effect by spinning axially. Following this step, the crushed recycled aggregates were sieved through 9.5- and 12.5-mm sieves to produce a single-sized aggregate. The water absorption and specific gravity of the single-sized recycled aggregate are 5.08 and 2.54 percent, respectively. The recycled aggregate was then thoroughly cleaned to remove any contaminants that could have prevented a strong connection between the cement paste and the aggregate particles. Table 2 and Fig. 1 both list the characteristics of single-sized recycled

Table 2 Specifications of aggregate

Aggregate types	Aggregate size range (mm)	Nominal aggregate size (mm)	Specific gravity	Water absorption (%)
RA*	9.5-12.5	11	2.54	5.08
RS**	0-4	2	2.41	18.97
NS***	0-4	2	2.63	17.41

RA* Recycled aggregate; RS** Recycled sand; NS*** Natural sand

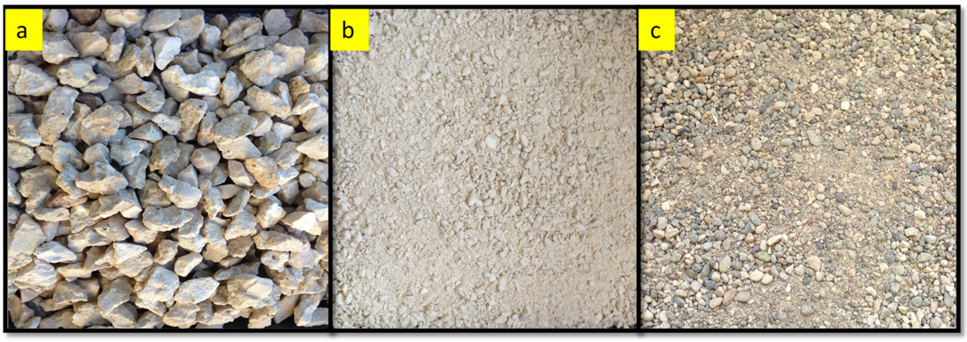

Fig. 1 Photographic of single-sized: (a) Recycled aggregate (RA); (b) Recycled sand (RS); and (c) Natural sand (NS)

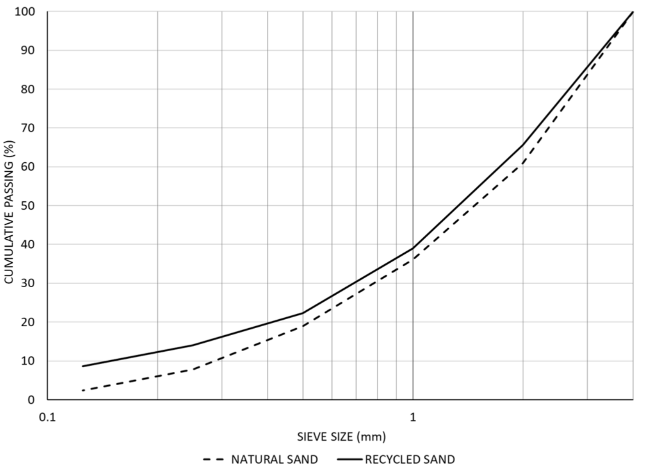

Fig. 2 Sieve analysis of natural and recycled sand

aggregate as well as a visual representation of them. Both natural and recycled sand were subjected to a sieve analysis. The findings of the sieve analysis shown in Fig. 2 indicate that the fineness moduli of natural and recycled sand are, respectively, 3.73 and 3.50.

2.3 Concrete proportioning, mixing, and casting

The pervious concrete series' designated cement contents were 300, 330, and 390 kg/m^3, respectively. At A/C ratios of 6, 5, and 4 by weight, three different pervious concrete series were created. Various inclusion rates of 0 percent, 2.5 percent recycled and 2.5 percent natural together, 5 percent natural only, and 5 percent recycled sand only were used for each series of fine aggregates. For all concrete series, the water-to-cement ratio of 0.3 was maintained constant. Table 3 lists the mix proportions for pervious concrete. While the designations RS and NS in the table stand for recycled and natural sand content, respectively, A6, A5, and A4 correspond to A/C ratios. For instance, A6RS5NS0 indicates that the pervious concrete was created using aggregate-to-cement ratios of 6 and 5 percent recycled sand and 0 percent natural sand.

After 60 minutes and 24 hours of water immersion, the recycled aggregate water absorption was measured, and the results showed that the water absorption of RA in just 30 minutes was equivalent to roughly 95 of the water absorption in 24 hours. Therefore, the RA was submerged in water for 60 minutes pervious to each casting, and any excess water was manually removed from the aggregate surface using a dry towel. The aggregate of saturated surface dry was attained in this manner, and the water used for mixing remained constant.

Wang *et al*. (2006) suggested a specific way to mix the parts of pervious concrete in a power-driven with 30-liter capacity revolving pan. This method was used to mix the parts of the pervious concrete. First, fine sand and RA were added to the pan and stirred for 30 seconds (at mixtures that utilized 5 percent fine sand). The aggregate was then covered with 10 percent cement, which was then mixed with the aggregate for 60 seconds to confirm a solid binding between the cement paste and the aggregate particles (Schaefer *et al*. 2006). After that, the remaining water and cement were added., and the mixer was used to mix the ingredients for the next two to three minutes. The molds were filled with three layers of the newly developed pervious concrete, and each of those layers was rodded 25 times. The concrete samples were stored in a lab setting and wrapped in plastic wrap. They were taken out of their molds after 24 hours and placed in water to cure until the day of testing.

2.4 Specimens and procedures for tests

For the compressive strength test, cubes with dimensions of 150 millimeters were manufactured as specimens, and for the abrasion test, prismatic specimens with dimensions of 70×70×100 millimeters were made as specimens. These sizes were selected based on DIN52108 (2002) standards and the literature (Yavuz *et al*. 2008, Gesoğlu *et al*. 2014, Güneyisi *et al*. 2016). For the purposes of determining splitting tensile strength, void content, dry density, and water permeability, cylindrical specimens with

Table 3 Pervious concrete mix proportions

Mix id	w/c	A/C	Cement (kg/m^3)	Water (kg/m^3)	RA (kg/m^3)	RS (kg/m^3)	NS (kg/m^3)	RS% by weight of NA	NS% by weight of RA
A6RS0NS0	0.3	6	300	90	1800	0	0	0	0
A6RS2.5NS2.5	0.3	6	300	90	1800	45	45	2.5	2.5
A6RS5NS0	0.3	6	300	90	1800	90	0	5	0
A6RS0NS5	0.3	6	300	90	1800	0	90	0	5
A5RS0NS0	0.3	5	330	99	1650	0	0	0	0
A5RS2.5NS2.5	0.3	5	330	99	1650	41.25	41.25	2.5	2.5
A5RS5NS0	0.3	5	330	99	1650	82.5	0	5	0
A5RS0NS5	0.3	5	330	99	1650	0	82.5	0	5
A4RS0NS0	0.3	4	390	117	1560	0	0	0	0
A4RS2.5NS2.5	0.3	4	390	117	1560	39	39	2.5	2.5
A4RS5NS0	0.3	4	390	117	1560	78	0	5	0
A4RS0NS5	0.3	4	390	117	1560	0	78	0	5

dimensions of 100 millimeters in diameter and 200 millimeters in height were utilized. There were three different specimens prepared for each test, and the results that are reported here are an average of those three different tests' outcomes.

ASTM-C39/C39M-12 (2012) was followed for conducting the compressive strength test. The formula used to determine the splitting tensile strength, as per ASTM-C496 (2011), is as follows

$$f_{split} = \frac{2P}{\pi DL} \tag{1}$$

where f_{split}, L, D, and P, are the splitting tensile strength (MPa), the length of the cylindrical specimen (mm), the diameter of the cylindrical specimen (mm) and the ultimate load (N), respectively

The formula utilized to calculate the density and void content of pervious concrete was ASTM C1754/ C1754M.12 (2012).

$$Density = \frac{K \times A}{D^2 \times L} \tag{2}$$

where K, L, D, and A are the 1 273 240 in SI units (mm^3kg/m^3g), the average length (mm), the average diameter (mm), and the dry mass (g), respectively, were used to calculate the pervious concretes densities.

The density of the water used to calculate the specimen's void content was first calculated by interpolating the values from ASTM-C29 (2010). The specimens' void content was then determined using the formula

$$Void\ Content = \left[1 - \frac{K \times (A - B)}{\rho_w \times D^2 \times L}\right] \times 100 \tag{3}$$

where B and ρ_w are, respectively, the submerged mass of the specimen (g) and the water density at the water's temperature (kg/m^3).

Using a specifically designed permeability apparatus, the method of falling head is utilized to calculate the pervious concrete water permeability coefficients. A latex membrane is placed over the cylindrical test specimen at the tip to stop water from dripping along the sample's edge while still allowing it to pass through the specimen's cross-section. A glass tube was fitted with the specimen's top and fastened to it. The test of water permeability was carried out with a 100-mm head difference. Each specimen received an average of three readings. The pervious concretes permeability coefficients (k) were then calculated by the following formula correspondingly with Darcy's law

$$k = \left(\frac{a \times L}{A \times t}\right) ln\left(\frac{h_o}{h_1}\right) \tag{4}$$

where k, h_0, h_1, t, a, L, and A are the coefficients of permeability (mm/sec), initial water head (mm), final water head (mm), time taken for the head to fall from h_0 to h_1 (sec), the pipe cross-sectional area (mm^2), the specimen length of (mm), and the specimen cross-sectional area (mm^2), respectively.

The abrasion resistance of the pervious concrete was measured by the Böhme abrasive wheel in line with DIN52108 (2002). The steel disc used in the abrasive test device has a diameter of 750 mm and rotates at a rate of 40 cycles per minute. Additionally, the instrument contains a lever that can press down on the samples with 300 N of force. Before starting the test, the prismatic specimen weighed, which had dimensions of 70×70×100 mm. The disc was then set down on the abrasion area of the wheel, and 20 g of wear dust (crystalline Al_2O_3) was dispersed there. The disc then completes 22 rotations in a single period. The specimen was rotated by 90 degrees with no change in its abrasion face between each session. A total of four cycles of rotating abrasive wheels were applied to the specimen face. A soft brush was used to clean the specimen's abrasion face and the abrasive wheel after the specimen had revolved for four cycles. This method, which is called a spin, involves a total of 4 spins on the material. The prismatic specimen was weighed following the 352 cycles, and Eq. (5) was utilized to measure the degree of deep wear.

$$\Delta L = \frac{\Delta m}{\delta R \times A} \tag{5}$$

where L, m, R, and A represent the abrasive wear after 16 cycles as determined by the average loss in specimen thickness (cm), average loss in mass after 16 cycles (g), average loss in specimen density (g/cm^3), and average loss in surface area faced to abrasion (cm^2), correspondingly.

3. Results and discussion

This section discusses the experimental study's findings. The results of the tests on dry density, compressive and breaking tensile strength, void content, water permeability coefficient, and abrasion resistance are summarized in Table 4.

3.1 Void content and dry density

Fig. 3 displays the hardened pervious concrete' densities made at three different A/C ratios. The pervious concrete density made with RA is between 1533.98 and 1768.19 kg/m^3, or between 70 and 80 percent of that of regular concrete. In this investigation, the decrease in aggregate-cement ratios led to a systematic rise in density, aligning with the findings of Najah *et al.* (2021). Moreover, the increase in sand content from 0% to 5% positively impacted the density of the pervious concrete, as supported by the study conducted by Khankhaje *et al.* (2016) and Zhou *et al.* (2023). The utilization of sand and a high cement content to fill the spaces between the aggregate particles resulted in the creation of denser pervious concrete. Furthermore, the lower specific gravity of recycled fine aggregate compared to natural fine aggregate, as highlighted by El-Hassan *et al.* (2019), explains the lower density observed when using recycled fine aggregate in comparison to natural fine aggregate in pervious concrete.

Fig. 4 plots the A/C ratio vs. the void contents of pervious concrete. The ratio of aggregate to cement in

Table 4 Engineering properties of the pervious concrete

Mix ID	Dry density (kg/m³)	Compressive strength (MPa)	Splitting tensile strength (MPa)	Void content (%)	Coefficient of water permeability (mm/s)	Abrasion resistance (mm)
A6RS0NS0	1533.98	5.6	0.58	34.12	19.3	2.65
A6RS2.5NS2.5	1578.75	6.58	0.64	32.85	15.2	2.54
A6RS5NS0	1563.26	6.46	0.6	33.26	17.2	2.6
A6RS0NS5	1595.4	6.99	0.67	30.89	13.2	2.46
A5RS0NS0	1612.75	7.95	0.66	30.35	12.8	2.3
A5RS2.5NS2.5	1652.2	8.77	0.76	28.13	9.7	2.19
A5RS5NS0	1629.17	8.53	0.7	29.01	10.5	2.21
A5RS0NS5	1664.97	9.22	0.87	27.16	8.6	2.13
A4RS0NS0	1731.82	13.22	1.1	25.15	8.3	1.74
A4RS2.5NS2.5	1754.23	14.31	1.36	21.78	7.3	1.6
A4RS5NS0	1750.01	13.58	1.13	22.56	7.7	1.7
A4RS0NS5	1768.19	14.8	1.46	21.22	6.6	1.56

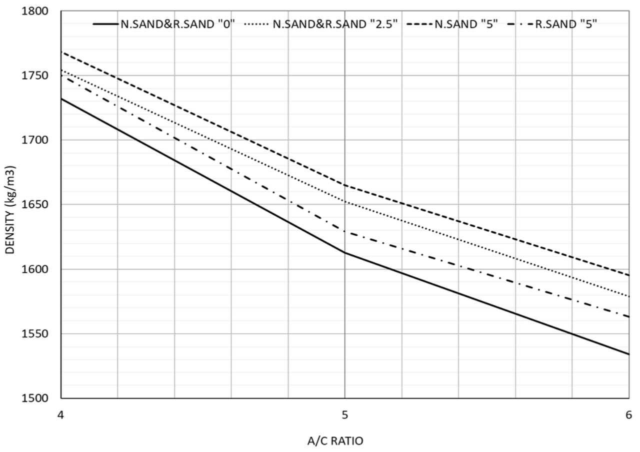

Fig. 3 Pervious concrete dry density vs A/C ratio

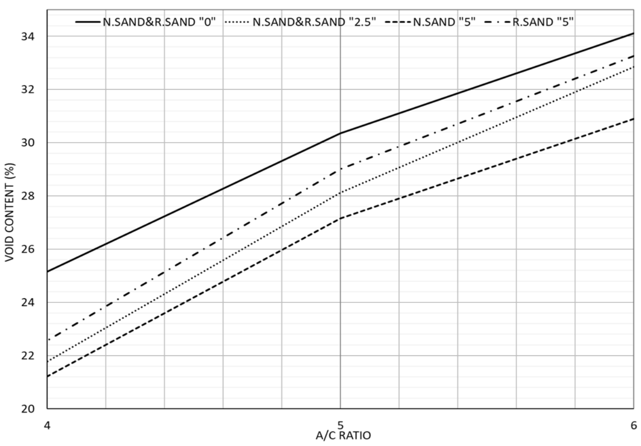

Fig. 4 Void levels in pervious concrete compared to A/C ratio

pervious concrete plays a crucial role in determining the void content of the material. A study by Tennis *et al.* (2004) demonstrated that a lower void content was achieved in pervious concrete with a higher cement concentration, emphasizing the impact of the aggregate-cement ratio on void content. Additionally, the research by Maguesvari and Narasimha (2013) further supports this, indicating that the inclusion of fine aggregate can also reduce the void content in pervious concrete. This is an obvious implementation of the particle packing density principle. The packing density of aggregate is defined as the ratio of the aggregate particles' solid volume to the total volume (Mangulkar and Jamkar 2013), according to the particle packing method, the smaller particles fill the spaces between the larger ones, decreasing the volume of the voids and raising the mixture's density as a result.

When the aggregate-to-cement ratio was lowered from 6 to 4, it produced a drop in the void content from 34.12 percent to 25.15 percent. In comparison to 5 percent natural fine aggregates, both the 5 percent recycled fine aggregate or a combination of 2.5% natural and 2.5% recycled fine aggregate, had a larger void content. According to ACI-522R-10 (2010), the void content amount of the pervious concrete generated in the current investigation are satisfactory.

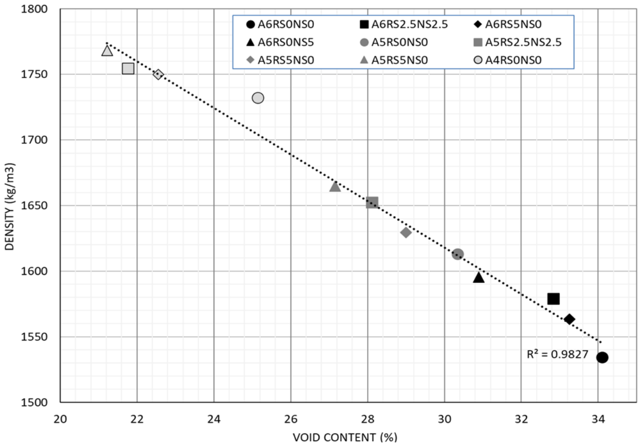

Fig. 5 Dry density vs. void content link for pervious concrete

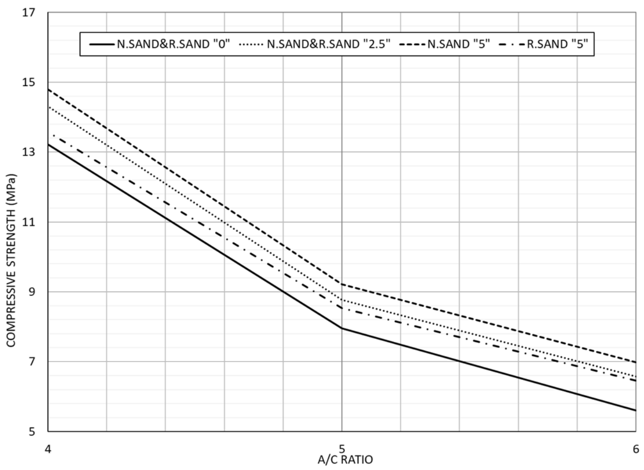

Fig. 6 Compressive strength of the pervious concrete vs A/C ratio

Additionally, based on Fig. 5, it can be inferred that the dry density has a significant correlation with the void content of pervious concrete. In the experimental work, an R-square value of 0.9827, that denotes a very excellent link between void content and dry density, was attained.

3.2 Compressive strength

The results of the pervious concrete's compressive strength and the aggregate-to-cement ratio are related (Fig. 6). The pervious concrete made at a ratio of 4 aggregate to cement showed greater compressive strength findings. And it aligns with the finding by Carsana *et al*. (2013). Also, the research by Leon Raj and Chockalingam (2020) determined that the compressive strength of mixes with aggregate-to-cement ratios of 4.5 and 5 decreased by roughly 9% to 40% and 34% to 67%, respectively, as compared to a ratio of 3.2. To create pervious concrete, thin layers of the cement paste covering the aggregate particles are required. Because these cement paste layers and the interfacial transition zone between the cement paste and aggregate particles are thin and weak, compressive failure paths typically run through them. In this study, recycled aggregates have great failure crack paths, and these crack paths can be seen with naked eyes as seen in Figs. 7(b)-(d). The cement paste layer is strongest against the recycled aggregate particles as shown in Fig. 7(c). When deep layers of the sample were investigated, most of the strength loss process was due to the cracked aggregate paths. Fig. 7(e) provides a clear illustration.

In order to increase the compressive strength of pervious concrete, it is, therefore, advantageous to improve the quality of the cement paste and increase the thickness of the cement paste layer. Although increasing cement layer thickness increases compressive strength, it also reduces the void content of pervious concrete. As reported by Zhong and Wille (2016), the aggregate/cement ratio influences the strength of pervious concrete by altering void content Additionally, the compressive strength was improved by the use of 5% fine aggregate. Several studies, including those done by Yang *et al*. (2008), Ćosić *et al*. (2015), and Lian and Zhuge (2010) have demonstrated that fine aggregate can improve cement paste dispersion. As a result, this modification has the potential to increase both compressive and flexural strengths. Because compared to coarse aggregate, fine aggregate has a higher surface area, it can be used in production to achieve higher compressive strength.

A more binding area was produced because of the aggregate's greater surface area. Despite the positive effects of the improvement in packing density of the multi-particle system's mixture. However, employing the fine aggregate also has a negative impact on void content and permeability. Concretes prepared with 5% natural fine aggregate had better compressive strength than those made with 5% recycled fine aggregate or a combination of 2.5% natural and 2.5% recycled fine aggregate. When loaded in compression, pervious specimens transfer stresses via the cement paste, leading to failure at the sample's weakest area. It is brought on by two crucial characteristics of RA

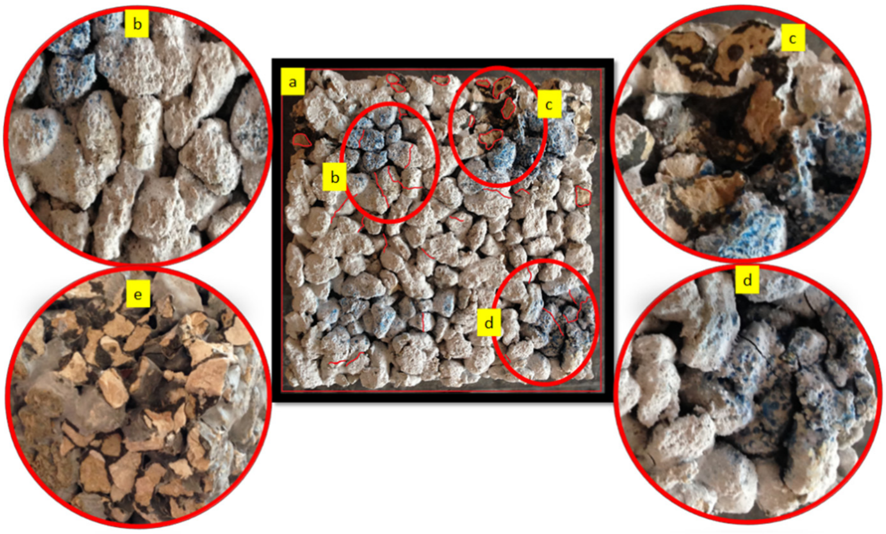

Fig. 7 Typical path of failure in: (a) compressive strength sample; (b) and (d) crack paths on recycled aggregates; (c) and (e) crack failure of recycled aggregates

that set it apart from NA. One is the interfacial transition zone between the hardened cement paste and the original aggregate, and the other is the weakly hardened cement paste on the aggregate particles (Chindaprasirt *et al*. 2008). Therefore, the compressive strength of concretes that are made with recycled aggregate may be reduced as a result of these two crucial features. In addition, another interfacial transition zone forms when recycled aggregate is used to make concrete. This zone is between the cement paste of pervious concrete and the hardened cement paste of the recycled aggregate. Another factor in the reduced compressive strength is that this transition zone is weaker than the one that developed between recycled aggregate and the cement paste of pervious concrete. Fig. 7 illustrates how the path of failure typically passed via RA and its interfacial transition zone.

For A/C ratios of 6, 5, and 4, correspondingly, the compressive strength of pervious concretes varied between 5.6 to 6.99 MPa, 7.95 to 9.22 MPa, and 13.22 to 14.8 MPa. These values align with the target classification of low- to medium-strength concrete (below 10 MPa for low and 10-20 MPa for medium), which is suitable for flat applications such as walkways, roadways with low traffic volume, highway shoulders, and parking areas. Thank you for your inquiry, and we appreciate your feedback. According to the literature, pervious concrete with compressive strengths from 3.5 to 28 MPa is suitable for a variety of requests (Tennis *et al*. 2004, ACI-522R-10 2010). In particular, the results of the experimental study's compressive strength are suitable for pervious concrete. Additionally, Fig. 8 shows the connection between the void content and the pervious concrete compressive strength. This relationship's R-square value of 0.9581 demonstrates that there is a significant correlation between void content and compressive strength. This relationship leads to the conclusion that the pervious concrete compressive strength tends to decline as the void content does.

3.3 Splitting tensile strength

The findings of the pervious concrete's splitting tensile strength are shown in Fig. 9. The load is applied to the specimen as a point load when performing the splitting tensile strength test. The specimen is split because the force from the cement paste is directly transferred to the aggregate. Recycled aggregates were the channel of compression failure for the splitting failure (Fig. 10). A lower A/C ratio resulted in pervious concrete that had a higher splitting tensile strength, corroborating the findings of Leon Raj and Chockalingam (2020). A thin cement paste layer that coats the aggregate particles can be made thicker by adding more cement. This contributed to the rise in splitting tensile strength, as shown in Fig. 10. According to Fig. 10, a splitting tensile strength test of recycled aggregates revealed more fractured channels as the cement content increased. The splitting tensile strength was discovered to be higher in concretes prepared with 5% natural fine aggregate than it was in concretes created with 5% recycled fine and a mixture of both 2.5% natural and 2.5% recycled fine aggregates. The addition of fine aggregate resulted in higher strength in A/C ratio 4 mix due to the fact that the cement-fine material interface has a big interaction surface effect on specimens. Natural fine aggregate addition has the greatest effect on splitting tensile strength than recycled sand.

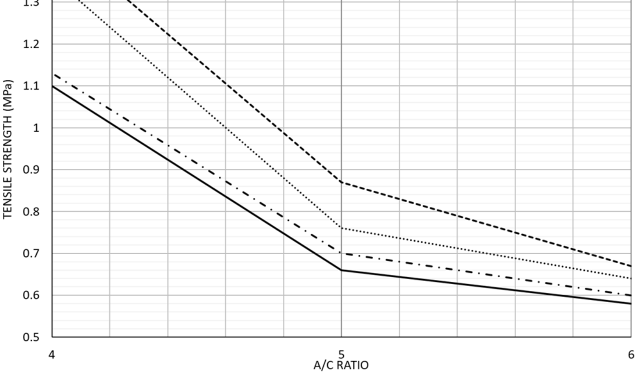

Fig. 9 Pervious concrete's tensile strength vs A/C ratio

It was possible to attain splitting tensile strengths of between 0.6 and 1.46 MPa. The pervious concrete's splitting tensile strength trend resembles that of conventional concrete, whose splitting tensile strength is roughly 10% of its compressive strength. The pervious concrete produced in this investigation had a splitting tensile strength that ranged from 12.67 to 9.33 percent of its compressive strength. Additionally, Fig. 11 demonstrates a particularly strong correlation between the results of the splitting tensile strength and compressive strength tests, with an R-square value of 0.9448.

3.4 Permeability

Fig. 12 displays the pervious concretes water permeability coefficients of created utilizing the head-falling technique. The cement concentration, aggregate-to-cement ratios, compaction level, and aggregate type and gradation all have a significant impact on permeability. According to the findings, using a high A/C ratio led to a high water permeability coefficient. Lowering the A/C ratio while maintaining the same aggregate quantity results in a higher cement content. This increased cement content leads to a thicker cement paste and facilitates the filling of voids between aggregate particles, resulting in reduced permeability, as confirmed by the research conducted by Torres *et al*. (2015). Nevertheless, the permeability property of pervious concretes was noticeably reduced by the addition of 5% fine aggregate. The pervious concrete produced at A/C values of 6, 5, and 4, had permeability coefficient values of 19.3, 12.8, and 8.3 mm/s respectively. At A/C ratios of 6, 5, and 4, a 5% addition of fine aggregate reduces the permeability values to 17.2, 10.5, and 7.7 mm/s respectively. In general, pervious concrete with the values of permeability coefficient from 0.14 to 1.22 cm/s is satisfactory (Tennis *et al*. 2004, ACI-522R-10 2010). In this investigation, however, high water permeability characteristics were obtained in the pervious concretes.

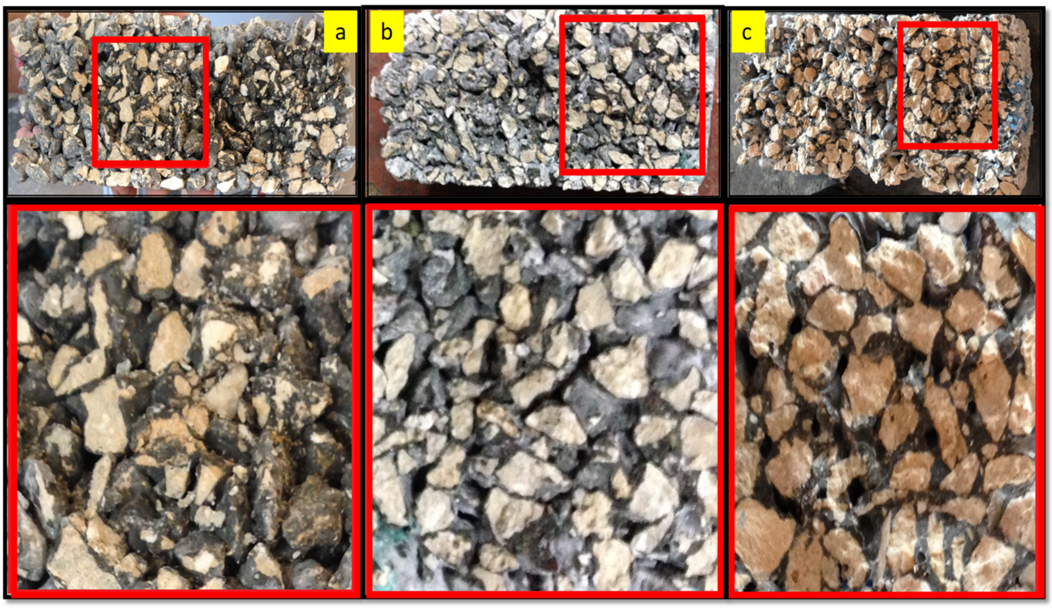

Fig. 10 Typical tensile strength test failure path: (a) A/C ratio 6; (b) A/C ratio 5; and (c) A/C ratio 4

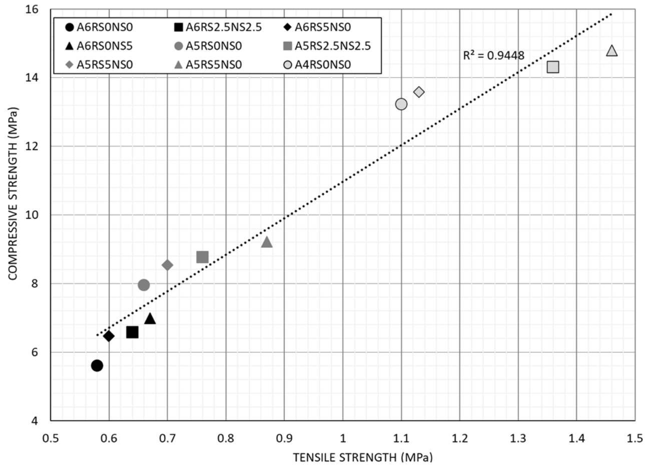

Fig. 11 Comparing the pervious concrete's splitting tensile strength with compressive strength

When fine aggregate was used, the pervious concrete void content went down. This is closely correlated with the pervious concrete's permeability and void content going down because the fine aggregate filled the network of interconnected pores. As presented in Fig. 13, there is a noteworthy correlation between the pervious concrete's permeability performance and its void content, as indicated by the R-square value of 0.8717. The results are similar to those found by Xu *et al*. (2018) and Lian *et al*. (2011), they also proposed a power function relation between permeability and porosity of previous concrete. At an A/C ratio of 6, fine aggregate addition has the greatest impact, whereas, at an A/C ratio of 4, addition's impact is the least significant. Even though there is a significant amount of scatter in the data plotted, the water permeability typically rises as the void content does. 19.3 mm/s of high permeability were achieved at a void content of 34.12%. In addition to the void content, the use of a single aggregate

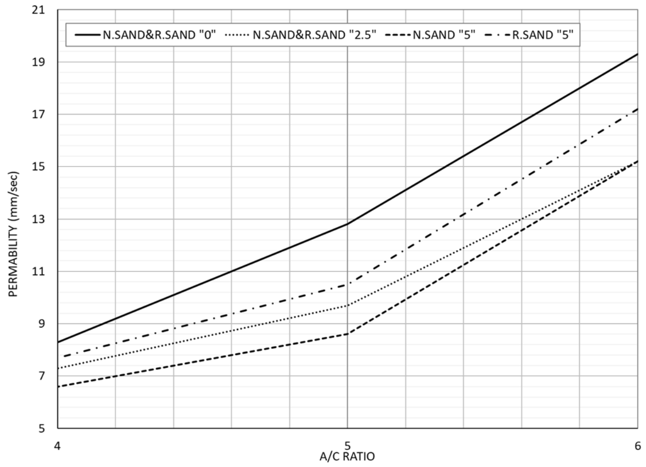

Fig. 12 Pervious concrete's permeability in comparison to A/C ratio

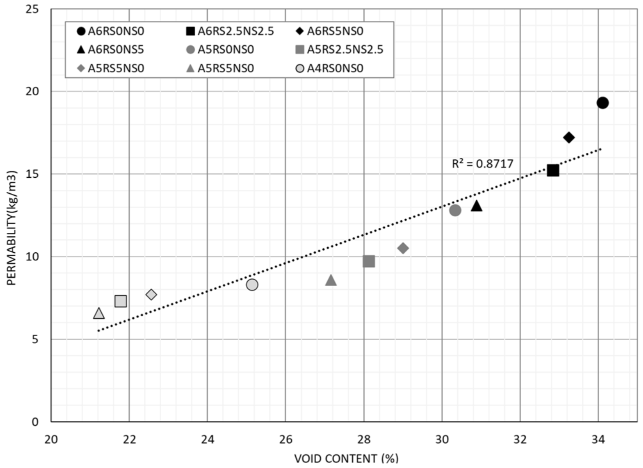

Fig. 13 Relationship of pervious concrete's permeability coefficient and void content

gradation was associated with the pore size distribution, pore connectivity, and pore roughness that influence the water permeability performance of the pervious concrete. Nevertheless, growing water permeability indicates a higher void content, which reduces the pervious concrete's ability to support loads. The pavement's lifespan may be shortened as a result of the pervious concrete's decreased compressive strength, which may also worsen pavement distresses such as joint failure and raveling. It is extremely necessary in pervious concrete because it's crucial to strike a balance between strength and draining ability (Chindaprasirt *et al.* 2008).

3.5 Abrasion resistance

Fig. 14 shows the abrasion of pervious concretes by deep wear in relation to a/ct ratios. The outcomes demonstrated that both the A/C ratio and the fine aggregate concentration had an impact on the durability performance of the pervious concrete. Because of a low and weak cement paste that binds the aggregate particles together, the high A/C ratio created a high level of abrasion in pervious concrete. Experimental results of the research by Leon Raj and Chockalingam (2020) indicate that increasing A/C ratio decreases the abrasion resistance of previous concrete. Additionally, adding fine aggregate to pervious concrete reduced abrasion. Due to the fact that fine aggregate fills in the gaps and results in a stronger mixture, this condition was expected. The abrasion of the pervious concrete was reduced from 2.65 to 1.74 mm by reducing the aggregate-to-cement ratio from 6 to 4. Similarly, the outcome of the study by Sandoval and Pieralisi (2023) showed that, the abrasion resistance of pervious concrete increases as the amount of fine-sized aggregate increases. Figs. 15-16 show the relationship between pervious concrete abrasion-compressive strength and abrasion-void content, respectively. Abrasion, compressive strength, and vacancy content are strongly correlated, as shown by the R2 of 0.9866 and 0.9785, respectively. Based on this, it can be inferred that reducing the void content enhances compressive strength, while higher compressive strength enhances the abrasion resistance of the pervious concrete. Furthermore, adding natural fine aggregate has a higher abrasion level performance than adding recycled fine aggregate or a blend of natural and recycled fine aggregate.

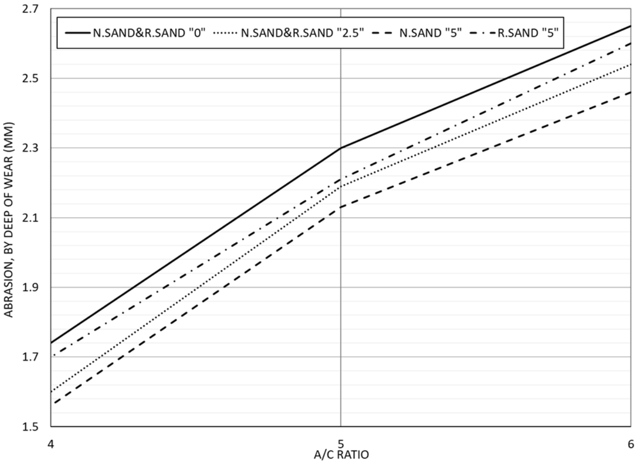

Fig. 14 Concrete's abrasion (by deep of wear) vs A/C ratio

4. Statistical evaluation

A general linear model analysis of variance (GLM-ANOVA) using the program Minitab is used to assess if an independent variable has an impact on the dependent variable (Minitab-R12 2012). By lowering the control variance, the GLM-ANOVA is a crucial statistical analysis and diagnostic technique that helps to measure the dominance of a control component. To find the experimental parameters that had an impact on pervious concrete qualities that were statistically significant, the analysis was run at a significance level of 0.05. The GLM-ANOVA was used to assess the efficacy of the test parameters. The results of the statistical analysis are displayed in Table 5. The relevance of the test parameter to the pervious concrete's properties is shown by the P-values. The parameter is satisfactory as a significant factor in the test result if the P-value is less than 0.05. The variables for

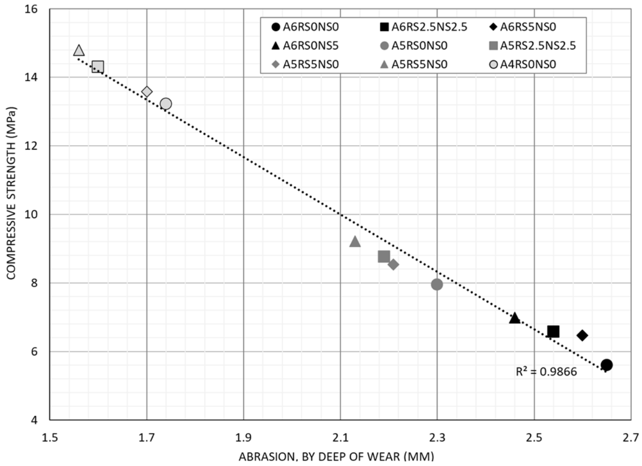

Fig. 15 Compressive strength of pervious concrete and its relationship with abrasion (deep of wear by mm)

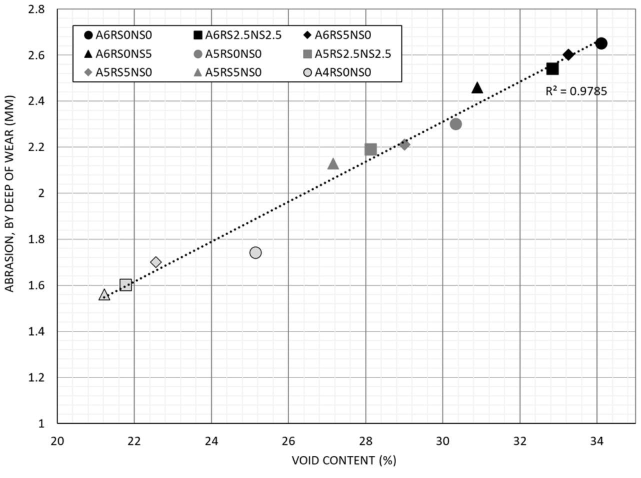

Fig. 16 Relationship between abrasion and void content of the pervious concrete (by deep of wear)

Table 5 A statistical analysis of the pervious concretes' performance characteristics

Dependent variable	Independent variable	Sequential sum of squares	Compute F	P value	Significance	Contribution (%)
Compressive strength	A/C Ratio	121.225	2125.92	0	Yes	97.29%
	R.Sand Content	0.192	48.82	0	Yes	0.15%
	N.Sand Content	2.479	105.09	0	Yes	1.99%
	R.Sand*N.Sand Content	0.54	18.94	0.005	Yes	0.43%
	Error	0.171	-	-	-	0.14%
	Total	124.607	-	-	-	100.00%
Tensile strength	A/C Ratio	0.9414	75.25	0	Yes	87.86%
	R.Sand Content	0.02103	0.13	0.73	-	1.96%
	N.Sand Content	0.0392	10.91	0.016	Yes	3.66%
	R.Sand*N.Sand Content	0.03227	5.16	0.064	-	3.01%
	Error	0.03753	-	-	-	3.50%
	Total	1.07143	-	-	-	100.00%
Permeability coefficient	A/C Ratio	280.462	64.56	0	Yes	86.21%
	R.Sand Content	7.747	11.05	0.016	Yes	2.38%
	N.Sand Content	0.467	4.2	0.086	-	0.14%
	R.Sand*N.Sand Content	23.602	10.87	0.016	Yes	7.26%
	Error	13.032	-	-	-	4.01%
	Total	325.309	-	-	-	100.00%
Dry density	A/C Ratio	0.077895	157.05	0	Yes	94.14%
	R.Sand Content	0.000014	3.47	0.112	-	0.02%
	N.Sand Content	0.000259	7.02	0.038	Yes	0.31%
	R.Sand*N.Sand Content	0.003088	12.45	0.012	Yes	3.73%
	Error	0.001488	-	-	-	1.80%
	Total	0.082745	-	-	-	100.00%
Void content	A/C Ratio	0.018226	69.83	0	Yes	88.73%
	R.Sand Content	0.000056	1.83	0.224	-	0.27%
	N.Sand Content	0.000123	6.01	0.05	Yes	0.60%
	R.Sand*N.Sand Content	0.001353	10.37	0.018	Yes	6.59%
	Error	0.000783	-	-	-	3.81%
	Total	0.020542	-	-	-	100.00%
Abrasion resistance	A/C Ratio	1.69265	730.64	0	Yes	96.79%
	R.Sand Content	0.0004	12.95	0.011	Yes	0.02%
	N.Sand Content	0.0392	41.96	0.001	Yes	2.24%
	R.Sand*N.Sand Content	0.0096	8.29	0.028	Yes	0.55%
	Error	0.00695	-	-	-	0.40%
	Total	1.7488	-	-	-	100.00%

the examined mixture proportions are categorized as present "Yes" (Y) or absent "NO" (N) in the analysis. The A/C ratio and addition of fine content were chosen as independent variables, whereas dry density, void content, compressive and splitting tensile strength, permeability coefficient, and abrasion resistance of pervious concrete were designated as dependent variables. Additionally, the percent contribution was utilized to estimate how successful each independent component was on the dependent variable; the larger the contribution, the more effective the factors were at influencing a given answer. In the same way, if the percentage contribution is small, the factors' influence on that specific reaction is low.

When the p-values from the ANOVA were taken into account, the statistical test findings showed that the a/c ratio and the volume of fine aggregate added were the independent factors that had an impact on all of the dependent variables. When the independent variables' contribution levels were observed, it was found that the A/C ratio had a higher impact on pervious concrete properties than the addition level of fine aggregate did on compressive strength, tensile strength, permeability, dry density, and void content. When the contributions of independent components were taken into account, fine aggregate addition to main mixes primarily affected recycled sand, with natural sand addition at 2.5 percent by weight of recycled aggregate. They primarily influenced the attributes of permeability and void content.

5. Conclusions

Following is a summary of the main conclusions drawn from the findings mentioned above:

- This study demonstrated that lowering the aggregate-to-cement ratio from 6 to 4 and adding 5% fine aggregate increased dry densities and lowered void content in pervious concrete. An R-square value of 0.9827 indicates a substantial association between pervious concrete dry density and void content.
- The compressive strength of the pervious concretes in this study met with acceptable compressive strength ranges, influenced by the A/C ratio and fine aggregate content. Concrete with low A/C ratios and 5% fine aggregate performed better than those with high A/C ratios and no fine aggregate.
- Pervious concrete achieved splitting tensile strengths ranging from 0.6 to 1.46 MPa. Lowering the A/C ratio and adding 5% fine aggregate improved its splitting tensile strength. Notably, both cement paste and aggregate influenced the failure path of splitting tensile strength in pervious concrete.
- The study showed that the A/C ratio and fine aggregate have a big effect on the permeability of pervious concrete. For example, when the cement content is high and the fine aggregate content is 5%, the permeability of air to concrete is lower. Despite exceeding ACI 522R 10 standards, all mixtures exhibited high water permeability coefficients. The positive correlation between permeability and void content (R square = 0.8717) emphasizes the importance of voids in enhancing permeability performance.
- The Böhme abrasive wheel test indicated that lower A/C ratios and the addition of fine aggregate, enhance pervious concrete's abrasion resistance. The strong relationship between compressive strength and abrasion resistance (R square = 0.9866) emphasizes the importance of high strength for long-term abrasion resistance in pervious concrete.
- The final result of this experiment was that the ratio of aggregate to cement and the addition of a small amount of fine aggregate had a big effect on the pervious concretes' performance characteristics. A statistical analysis derived from ANOVA showed that dry density, porosity, compressive and splitting tensile strength, permeability performance, and abrasion resistance of pervious concrete made from recycled aggregate, were more affected by A/C ratios, than the addition of fine aggregate.

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