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RESEARCH

Experimental Investigation on the Properties of Sustainable Pervious Concrete with Different Aggregate Gradation

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Abstract

Pervious concrete (PC) as a green infrastructure material has been increasingly used due to its positive environmental impacts, such as controlling storm water runoff, removing water pollutants and reducing heat island effect. The aggregate gradation is a critical factor influencing the physical properties of PC. Therefore, this paper represents an attempt to determine the effects of aggregate gradation on the various physical properties of PC, and then to explore relationships between them. To this end, three aggregate gradations 4.75–9.5 mm, 9.5–19 mm and 19–31.5 mm were recombined with various proportions (20–80%) to obtain five different gradations named as A, B, C, D and E. PC mixtures were prepared with these five aggregate gradations. Then, physical and mechanical properties of PC including porosity, permeability, compressive strength and water stability were investigated, according to the available specification. The results suggested that it was feasible to use waste concrete for permeable pavement, because all the specimens provided required specification requirements. Different linear relationships were also found between the maximum aggregate size and porosity, permeability coefficient, compressive strength and its loss rate. That is, porosity and permeability increased with the proportion of larger size aggregate increased, however, compressive strength reduced. Thus the compressive strength had an inverse correlation with the porosity and water permeability. Among five different aggregate gradations, group C (20% of 4.75–9.5 mm aggregate, 50% of 9.5–19 mm aggregate and 30% of 19–31.5 mm aggregate) can be seen as the optimum gradation and is suitable for base layer materials of permeable pavements.

Keywords Pervious concrete, Aggregate gradation, Porosity, Permeability coefficient, Compressive strength

1 Introduction

Urbanization progress, associated with the population growth over the last decades, has led to the increase of impervious surfaces and a consequent decrease in natural areas. The impermeable pavement which cuts off the moisture and heat exchange between earth and air, is the primary agent responsible for many serious environmental problems, such as waterlogging, water pollution and urban hot island phenomena (Kia et al., 2021; Li et al., 2017). This, along with altered climate patterns around the world, further poses challenges to the sustainable development. Especially for parking lots that occupy a significant portion of urban areas, their surfaces are typically impervious (e.g., asphalt, concrete) (McPherson, 2001; Onishi et al., 2010; Revitt et al., 2014). Where impervious parking surface exists, almost all the incident rainfall can produce surface runoff except for evaporative losses, resulting in nitrogen and phosphorus nutrients, suspended solids (SS) and chemical oxygen demand (COD) accumulated as well as increase urban flood risks

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(Kumar et al., 2016a; Morabito et al., 2016; Revitt et al., 2014; Wang et al., 2020). Therefore, many countries are actively seeking strategies to combat these problems, including sponge city (SC), best management practices (BMPs), smart city, water sensitive city (WSC), low impact development (LID), etc. (Guan et al., 2021; Pellicer et al., 2013; Wong & Brown, 2009).

Among them, permeable pavements as a type of LID solution have been widely used in parking lots and roadways because of their environmental, social and economic well-being (Elizondo-Martínez et al., 2022; Golroo & Tighe, 2011; Nguyen et al., 2014). In Europe, the permeable pavement has been applied for construction of parking garages, parking lots, and some minor roads in England and Switzerland (Maynard, 1970). In the United States, the first success of porous pavement applied for parking lot and service roads (Thelen and Howe, 1978). These devices contain the pore structures that allow storm water to infiltrate through the surface into the underlying base layer, offering many environmental advantages not only in the reduction of runoff, recharge of groundwater and pollution mitigation, but also in the decrease of heat island effect and noise reduction (Huang et al., 2016; Ma et al., 2020; Sañudo-Fontaneda et al., 2014; Wang et al., 2018).Therefore, it is receiving renewed interest, although it is not a new product. In addition, Montalto et al. (2007) and Lee et al. (2010) showed that permeable pavements were most cost-effective compared to other solutions by a cost-effectiveness analysis. In general, a permeable pavement is comprised of a permeable paving layer, bedding layer, base and sub-base layers (Scholz & Grabowiecki, 2007). Pervious concrete (PC) is mainly composed of reasonably graded coarse aggregates and cementing materials, possessing advantages of lower density, thermal conductivity and lower drying shrinkage (Aliabdo et al., 2018), thus can be considered as a promising base material for permeable pavements (Kamarul Zaman et al., 2022; Kováč & Sičáková, 2018). Compared to ordinary concrete (OC) or asphalt, PC has a large and porous structure with non-uniformly distributed internal pores, which allows water can penetrate through the concrete quickly and so reduce storm-water runoff (Chandrappa & Biligiri, 2016; Shan et al., 2022; Wu et al., 2016). Other environments benefit of this material include the ability to limit the amounts of contaminants entering the groundwater and reduce tire–pavement interaction noise (Haselbach et al., 2011; Neithalath, 2004; Tennis et al., 2004). In addition, PC offers various economic benefits such as lower installation costs because of elimination of costly storm drains, lower lifecycle cost because of fever repairs and recyclability at the end of life. It consumes less raw material than normal concrete, and provides superior insulation values. Previous study reported a typical example cost comparison of PC vs conventional concrete for a car park in Thailand, and concluded that the total savings is Rs. 135/m^2 (32 THB/m^2) (Priyadarshana et al., 2012). There is no doubt that their key properties such as the porosity, permeability and compressive strength have important effect on the pavement performance. Thus, many researches have been carried out in that field, focused essentially on mixture design, testing, characterization and so on (AlShareedah & Nassiri, 2021; Cui et al., 2017).

A PC mixture is composed of water, cement and coarse aggregates (with little or no fine aggregate, admixtures), possessing a high interconnected porosity ranged from 15% to 30% with pore sizes ranging from 2 to 8 mm (Huang et al., 2021; Kováč & Sičáková, 2018; Sandoval et al., 2019; Zhong et al., 2016). The water/cement (W/C) ratio and aggregate/cement (A/C) ratio as critical parameters are very important in PC mix design, which influence the mechanical and hydrological properties of pervious concrete. High W/C ratios can generate excess cement paste, and thereby choke pores, disturbing interconnectivity of pores. On the contrast, the low W/C ratio may lead to insufficient consistency and cohesion, thus lead to low workability (Debnath & Sarkar, 2020). In general, a W/C ratio should vary from 0.26 to 0.4 according to ACI 552R-10 (2010). For a wide application of pervious concrete mixes, Wang et al. (2006) suggested the W/C ratios range from 0.27 to 0.34. In addition, A/C ratio have the similar effect as W/C ratio on the properties of PC mixture, that is the low A/C ratio can result in enhanced contact between particles, and thereby occupy the void spaces and hydraulic channels, causing the reduction of hydraulic conductivity, whereas high A/C ratio generates weak contact between particles and thus decrease strength (Tong, 2011). The A/C ratio is varied across mix designs, and previous studies stated that the A/C ratio in mixture design was traditionally varied from 2.0 to 10.0 (Chandrappa & Biligiri, 2016; Deo & Neithalath, 2011; Maguesvari & Narasimha, 2013; Mohammed et al., 2016; Zhong et al., 2018). Ni et al., (2021) investigated interface reinforcement of PC and pointed out the appropriate aggregate–binder ratio ranges 3.5–3.8 for the PC. The cementing material generally used for PC is Ordinary Portland Cement (OPC) confirming to ASTM Standard C150, as it can provide enough paste thickness to coat around aggregates that improves strength and durability characteristics of PC (Debnath & Sarkar, 2020; Li et al., 2017). Except for OPC, researchers have used supplementary cementitious materials (SCMs), such as silica fume, fly ash as partial replacement for OPC, but these SCMs decrease the strength properties of PC after a certain threshold partial replacement as reported in Fu et al., (2014). Typically, the permeability coefficient for

PC varies from 1.5 to 30 mm/s, and compressive strength ranges from 5.5 to 20.5 MPa (Xie et al., 2019). Previous reports have shown that a higher porosity would give higher permeability but lower strength and vice versa, which presents many challenges for designing of PC (Li et al., 2021; Schaefer & Wang, 2006). Furthermore, since the lack of recognizing methods of mix design at present time, more experimental studies need to be performed on the constituents including parameters aggregates and cementitious materials, along with other parameters, such as aggregate gradation, W/C ratios and A/C ratios (Anburuvel & Subramaniam, 2022).

As investigated by Ayda et al. (2013), aggregate properties have been found to most dominantly affect the mechanical properties of porous concrete because of the effectiveness of coarse aggregates in forming the skeleton structure. Especially, aggregate gradation is considered as one of the critical roles on control of pore size, permeability and strength properties of PC. The existence of large-sized aggregates in PC mixture lead to increase in porosity and permeability but loss in strength, while small-sized aggregates can improve the distribution of cement paste and thus results in increased strength but reduced porosity and permeability (Anburuvel & Subramaniam, 2022; Xu et al., 2018). This can be explained that the utilization of smaller size aggregates would allow the larger total bond area between neighboring aggregates, lead to more window for contact between aggregate and cement, and thus increase strength properties (Sahdeo et al., 2020; Zhong & Wille, 2016). However, the smaller size aggregates with closely packed have less interconnectivity between pores and cause the reduction in porosity. Therefore, aggregate gradation determines the porosity in PC mixture which has a vital effect on the properties of materials (Ghafoori & Dutta, 1995). Some researches on the influence of aggregate gradation on various properties of PC have been carried out during the past few decades, as summarized in Table 1. Clearly, most studies were focused on the compressive strength and porosity. As briefed earlier, crack patterns in PC are also influenced by aggregate size. The cracks more frequently developed through the aggregate grain when the aggregates were large, and developed through the cement paste with a smaller aggregate size (Agar-Ozbek et al., 2013). Therefore, exploring rational combination of larger and smaller sized aggregates to achieve good balance between porosity, permeability and compressive strength in PC is very important before its applications.

It is reported that 43.78 million tons of waste was generated in Australia a year, 38% of which was from the construction and demolition (C&D) stream. In China, around 30% of the world's municipal solid waste will produced and the proportion of C&D waste is about 40%, building-related construction generates about 100 million tons yearly, while demolition of old properties annually generates around 200 million tons of waste (Yang et al., 2017). This poses a huge challenge to the construction waste handling facilities. Application of recycled aggregates (RA) from C&D waste, such as waste concrete blocks, waste glass, and crushed bricks, into pavement materials was considered to be an ideal waste management solution, which could reduce waste concrete stockpiles at landfills and decrease the need of natural aggregate sources (Silva et al., 2014; Yaowarat et al., 2018). Therefore, many studies were conducted to evaluate the possibility of using recycled C&D waste, specifically the effect of RA on the performance of pavement materials (Tam et al., 2018). For example, Chen et al. (2003) determined the mechanical properties of recycled aggregates containing waste concrete, bricks and tiles from damaged structures. Based on the laboratory testing program, building rubble could be transformed into useful recycled aggregate. Ćosić et al. (2015) investigated the influence of aggregate type (dolomite or steel slag) and size on the properties of pervious concrete, and suggested that connected porosity for the estimation of pervious concrete efficiency was influenced more by the aggregate type than its size. Table 1 summarizes the details of previous works done on RA in PC. Moreover, several studies confirmed that the use of RA in concrete has a positive effect on the environmental impact and cost (Estanqueiro et al., 2018; Evangelista & de Brito, 2007; Flower & Sanjayan, 2007). In the research of Evangelista and de Brito (2007), the use of 30% and 100% RA reduced the environmental impact by up to 8% and 23%, respectively. Similarly, in Mah et al. (2018), using 30% RA and 100% RA instead of natural aggregate (NA) in concrete resulted in net cost benefits of 9% and 28%, respectively. Moreover, the environmental and cost impacts were reduced by 50.8% and 68.1% when waste concrete was used to produce RA concrete (Wijayasundara et al., 2018). Conversely, the use of 50% RA was found to be the optimum percentage in terms of environmental impact and cost efficiency (Marinković et al., 2010). In addition, Rizvi et al. (2009) reported on the effect of RA replacement levels of 25%, 50%, 75%, and 100% on properties of PC and concluded that the best RA replacement ratio was 50%.

Considering that replacing natural aggregates with recycled aggregates is a trend for future, the recycled concrete aggregate was used in this paper to contribute to waste reuse and increase cost-effectiveness. As explained previously, the use of 50% RA was found to have the best environmental impact and cost efficiency, thus 50% RA was applied in this study. In addition, although the aggregate gradation is investigated widely in detail for pavement, the experimental research about its influence on

Table 1 Details of aggregate gradations used in previous studies

Aggregate gradations (mm)	Aggregate type	W/C	A/C	Compressive strength (MPa)	Porosity (%)	References
3–5, 5–10, 10–20, 15–30	NA (gravel, sand)	0.33–0.35	/	7.1–13.8	7.8–8.9[a]	(Yang & Jiang, 2003)
0.075–4.75, 4.75–12.7	NA (natural sand), RA (waste concrete, bricks and tiles)	0.38, 0.46, 0.56, 0.67, 0.80	2.26–2.87	About 15.5–56.5	/	(Chen et al., 2003)
2.5–5.0, 5.0–3.0, 13.0–20.0	NA (crushed limestone)	0.225	/	5–40	15–30	(Chindaprasirt et al., 2009)
9.5–12.7, 4.8–9.5, 2.4–4.8	NA, RA (waste concrete)	0.35	3.90–7.23	About 5–13	11–27	(Cheng et al., 2011)
2–4, 4–8	NA (crushed basalt, river gravel)	0.30	/	5.05–61.1[b]	17.9–26.7	(Agar-Ozbek et al., 2013)
4.75–9.0, 9.0–12.5, 12.5–16.0, 16.0–19.5	NA (crushed gravel)	0.34	4.75	9.6–26.2	0.40–1.26	(Maguesvari & Narasimha, 2013)
2.4–4.8, 4.8–6.4, 6.4–9.5, 9.5–12.7	NA (pebbles)	0.25–0.45	/	7.5–25.7	0.03–0.14[a]	(Fu et al., 2014)
4.75–9.5, 9.5–12.5, 12.5–19.0	NA (crushed stone)	0.25–0.35	2.0–4.5[c]	5.5–9.4	13.5–33.1	(Joshaghani et al., 2015)
0–4, 4–8, 8–16	NA (crushed dolomite stone), RA (steel slag)	0.33	5.8–6.8	20.2–69.5[b]	14.2–22.2	(Ćosić et al., 2015)
1.2–4.8	NA (quartz)	0.22–0.55	2.5, 3.0, 3.5[c]	8.8–65.8	17.02–32.75	(Zhong & Wille, 2016)
4.75–9.50	NA (limestone), RA (concrete block)	0.24	4.54	≤ 17	13–25	(Zaetang et al., 2016)
6.3–12.5	NA (granite stones)	0.35	3.3[c]	9.5–23.5	16.5–22.0	(Elango & Revathi, 2017)
≤ 9.5	NA (crushed stone), RA (construction and demolition waste)	0.4	/	About 28–55	/	(Bui et al., 2017)
2–4, 4–8, 8–16	NA (gravel)	0.38, 0.4, 0.6	8[c]	11.3–36.2	16.4–34.5	(Sun et al., 2018)
2.36–4.75, 4.75–6.0, 6.0–8.0, 8.0–9.5, 4.75–9.5, 10.0–12.5, 12.5–15.0, 10.0–15.0	NA (basalt)	0.31	4.51	19.9–32.0	20.5–21.3	(Yu et al., 2019a, 2019b)
2.36–5, 5–10	NA (Crushed granites), RA (waste concrete and glass)	0.29–0.45	4.47	About 19–32	about 23.5–27	(Lu et al., 2019)
2.36–4.75, 4.75–9.5, 9.5–13.2	From construction site	0.31	3.85–5.56	24.5–31.6	17.3–25.6	(Dai et al., 2020)
1.18–12.5, 4.75–6.7, 10.0–12.5, 12.5–19.0, 10–12.5 + Fine (5%), 10–12.5 + Fine (10%)	/	0.30–0.38	1.0–2.0	13.0–24.0	8–27	(Sahdeo et al., 2021a, 2021b)
4.75–26.5	RA (waste concrete and red bricks)	0.30	2.73, 3.24, 3.5, 4.0	About 3–10	14.2–15.2	(Cai et al., 2021)
12–18, 18–25	NA (gneiss rock)	0.30	2.5, 5.0	About 5–30	5.8–39.4	(Anburuvel & Subramaniam, 2022)

[a] Permeability in cm/s

[b] With superplasticizer

[c] Aggregate/paste

the various properties of PC is relatively more limited on the base of using RA. Therefore, in this study, the influence of aggregate gradation on the mechanical properties of PC, including compressive strength, permeability coefficient and porosity was first to be investigated using 50% RA. This was completed through limiting the small-sized aggregate proportion during experiment. Then, the other associated properties, i.e., water stability and crack patterns were also evaluated to achieve optimal mixture design of PC to meet the required standards for mixture used in construction. Particularly, admixture was considered to improve the properties of materials. The obtained experimental data provided a reliable guide for the use of aggregates in pervious concrete. Furtherly, the results of this work could be valuable for the development of sustainable permeable pavement techniques, and thus promote environment protection.

2 Materials and Methods

2.1 Materials

There are four main materials in the fabrication of PC: aggregates, cement, admixture and water.

2.1.1 Aggregates

The main objective of the experiment is to study the influence of aggregate gradation on the PC properties. Therefore, two types of aggregates were used in this work, i.e., recycled aggregate (RA) and natural aggregate (NA), both coming from the local company. The RA was obtained from waste concrete with original strength of C30 mixing a small amount of bricks, and the particle size was initially 4–35 mm. These aggregates were then cleaned, oven dried, sorted and screened using sieves to achieve three grades of aggregates, 4.75–9.5 mm, 9.5–19 mm, 19–31.5 mm, as shown in Fig. 1a, b and c. Table 2 summarizes properties of RA and NA aggregates. The used aggregate comprised of significantly low internal pores as designated by water absorption, and packing density of NA is commonly higher than that of RA.

The basalt aggregate produced by Nanjing Dadi Construction Group was selected as NA, and the particle size was initially 4–35 mm. Similarly, three grades of aggregates, 4.75–9.5 mm, 9.5–19 mm, 19–31.5 mm, were obtained. Figure 1d, e and f shows the particle shape and texture of natural coarse aggregates.

2.1.2 Cement

According to previous studies (Debnath & Sarkar, 2020; Li et al., 2017), the ordinary Portland cement can provide sufficient coating around the aggregates to improve PC properties, such as strength and durability characteristics. Thus, the cement used in this experiment was Conch brand 42.5R ordinary Portland cement, and its physical properties and chemical composition are, respectively, presented in Tables 3 and 4.

2.1.3 Admixture and Water

The admixture as the reinforcing agent of cement-based materials was obtained from Jiangsu Subote New Materials Co., Ltd. It had the purpose of delaying spalling phenomenon and enhancing the freeze–thaw resistance, strength and durability of PC. Clear water from the tap

Fig. 1 Recycled coarse (**a** 4.75–9.5 mm, **b** 9.5–19 mm and **c** 19–31.5 mm) and Natural aggregates (**d** 4.75–9.5 mm, **e** 9.5–19 mm and **f** 19–31.5 mm) particle size ranges used

Table 2 Characteristics of aggregate

Type	Sieve size (mm)	Characteristics			
		Wet weight (kg)	Dry weight (kg)	Water absorption rate (%)	Packing density (kg/m^3)
Natural aggregate (NA)	4.75–9.5	0.669	0.658	1.67	1372
	9.5–19	0.599	0.597	0.34	1342
	19–31.5	0.657	0.655	0.31	1310
Recycled aggregate (RA)	4.75–9.5	0.639	0.598	6.86	1274
	9.5–19	0.615	0.576	6.77	1184
	19–31.5	0.592	0.567	4.41	1154

Table 3 Physical properties of the cement

Water requirement of normal consistency (%)	Density (g/cm^3)	Stability	Setting time (minutes)		Flexural strength (MPa)		Compressive strength (MPa)	
			Initial	Final	3 days	28 days	3 days	28 days
26.8	3.10	Qualified	185	240	5.41	8.14	22.63	48.65

Table 4 Chemical composition (wt%) of cement

SiO_2	K_2O	SO_3	CaO	Al_2O_3	Fe_2O_3	MgO	Na_2O
20.33	0.42	2.15	65.50	4.83	4.90	1.30	0.10

was used for both the mixing and curing processes in the experiment.

2.2 Mix Design

As mentioned above, three aggregate grades (4.75–9.5 mm, 9.5–19 mm, 19–31.5 mm) were selected in this work. According to previous study (Yang et al., 2008), the suitable content of 4.75–9.5 mm aggregate was around 20% which the porous concrete could achieve satisfactory strength and permeability. Meanwhile, the use of 50% RA was found to be the optimum percentage in terms of environmental impact and cost efficiency (Marinković et al., 2010). Therefore, the proportion of aggregate with size ranging 4.75–9.5 mm was controlled to 20% in this paper, and 50% replacement ratio of RA was used. The range of W/C ratio for PC reported in most literature is commonly 0.3–0.35, as shown in Table 1. Furtherly, the optimum range of A/C ratio in view of both water permeability and compressive strength is between 0.30 and 0.38 (Lian & Zhuge, 2010). For this study, a W/C of 0.30 was chosen for all the mixtures refer to the previous study and PC had zero slumps (Anburuvel & Subramaniam, 2022). In addition, Mulligan (2005) reported that the A/C ratios should be limited to less than 5:1, because higher A/C ratios do not supply enough cement. Ni et al., (2021) investigated interface reinforcement of PC and pointed out the appropriate aggregate–binder ratio ranges 3.5–3.8 for the PC. In our study, the A/C ratio for all the considered gradations was 3.5. To prepare PC mixes, this study settled to use A/C ratio of 3.5.

Table 5 Details of aggregate gradations

Groups	Proportion of different aggregate size (%)		
	4.75–9.5mm	9.5–19mm	19–31.5mm
A	20	80	–
B	20	60	20
C	20	50	30
D	20	40	40
E	20	30	50

Finally, five aggregate gradations, namely, A, B, C, D and E, were made and A of which was used as control. All mixes have an RA replacement ratio of 50%, W/C ratio of 0.3 and A/C ratio of 3.5 on condition that the proportion of 4.75–9.5 mm aggregate is 20%. The obtained proportions of the different gradations and gradation curves are shown in Table 5 and Fig. 2. It should be noted that, this design controlled mixture proportions of 250–400 kg/m^3

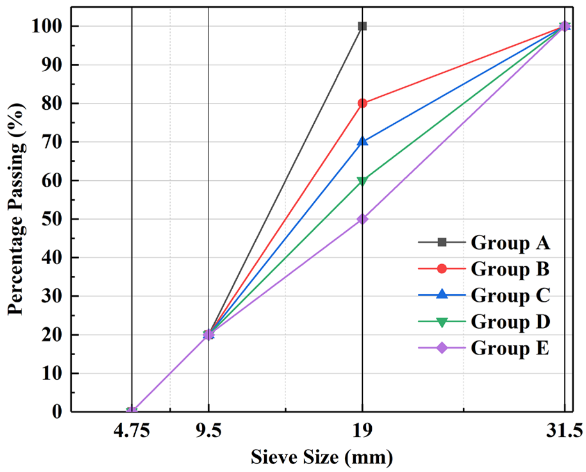

Fig. 2 Gradation curves used in experiments

of binder material, 1400–1700 kg/m^3 of coarse aggregate and 80–150 kg/m^3 of water. The detailed requirements were estimated using respective W/C ratio and A/C ratio.

2.3 Experimental Method

2.3.1 Specimen Preparation

According to the specification (China, 2020), the mixing of the concrete specimens was implemented in the professional concrete mixer. First, aggregates, cement and admixture (to keep A/C ratio of 3.5) were added while mixing for 45 s. Then, half of the total water was added, and mixing continued for another 30 s. The remaining water was subsequently added with mixing for 2 min to complete the mixing, as shown in Fig. 3a. Finally, the fresh mix was placed into concrete molds and cured in the laboratory for 24 h (Fig. 3b, andc). The samples were then demolded and transferred to a standard curing room of 20 ± 2 °C and greater than 95% relative humidity for 28d. For each group, 150 mm side-length cubes were made for measuring compressive strength, and cylindrical samples of 100 mm in diameter and 200 mm in height were produced following JTG 3420–2020 (China, 2020), for determining porosity and permeability coefficient.

2.3.2 Porosity Measurement

The underwater weighing method was used to determine the porosity of PC referring to ASTM C1754 (2012). First, the specimen was fully immersed into a water bath until no more air bubbles emerged from the specimen (Fig. 4), and then weigh it underwater (m_1) using the hydrostatic balance. The Specimen was subsequently removed from the water and dried at 105 °C for 24 h in an oven, then determine the mass (m_2) after cooling. The effective porosity (P_e) was calculated as follows:

$$P_e = \left(1 - \frac{m_2 - m_1}{V\rho}\right) \times 100\% \quad (1)$$

where P_e is the effective porosity (%), m_1 is the mass of specimens in water (g), m_2 is the dried mass of specimens in air (g), V represents the volume of specimen (cm^3), and ρ represents the density of water (g/cm^3).

2.3.3 Permeability Coefficient Measurement

Falling-head (FH) method and constant-head (CH) permeameters have been widely used in permeability measurements on PC pavements at the laboratory (Li et al., 2013; Ranieri et al., 2012; Zhang et al., 2020). Compared to FH method, the CH permeability test can possess the advantage of significant time, coefficient of variation (COV) and economic (Kevern, 2015; Qin et al., 2015). The preparation of CH test is briefer and requires a less meticulous process (Sandoval et al., 2017). In addition, many studies have applied CH method to measure permeability, indicating the feasibility of this method (Seifeddine et al., 2023; Xu et al., 2020; Zhang et al., 2023). Therefore, in this study, permeability tests were conducted using a CH method according to Chinese Standard (CJJ/T 135–2009) "Technical specification for pervious cement concrete pavement", and the setup for testing the permeability coefficient was shown in Fig. 4b. The specimens used were ϕ 100 × 100 mm cylinders, and the measurement process of the constant head method was as follows:

Fig. 3 Specimen preparations. **a** Concrete mixing; **b** concrete molds; **c** samples number

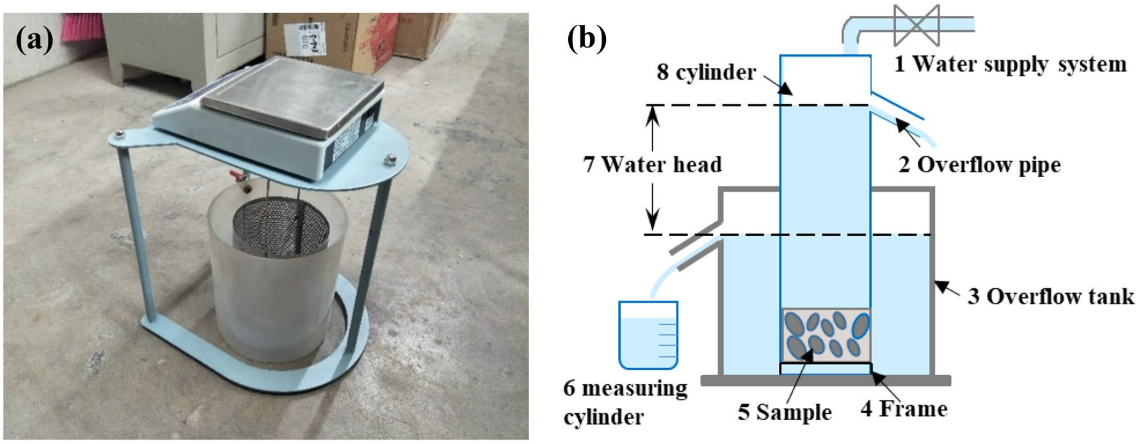

Fig. 4 Experimental setups. **a** Porosity measurement; **b** permeability measurement

(1) Measuring the diameter (D) and thickness (L) of the cylindrical sample with a steel ruler twice, taking the average value, accurate to 0.1 cm, and calculating the surface area (A) of the sample. Then, waterproof tape was used to seal the sides of the cylindrical samples cured to ensure water flowed from the upper to lower surfaces of the samples.
(2) Placing the concrete specimen in the vacuum barrel, evacuating it to reach the pressure of (90 ± 1) kPa, and keeping it for 30 min. Then, adding water to the vacuum barrel to make the water level higher than the specimen by 10 cm, and stopping vacuuming for 20 min and removing the sample from the vacuuming barrel.
(3) Following the schematic diagram shown in Fig. 4b, the test sample (denoted as 5 in Fig. 4) was put into the cylinder (i.e., 8). The frame (i.e., 4) was put at the bottom of overflow tank (i.e., 3). Then, the water supply system (i.e., 1) was opened. The water flows would through the cylinder and pass through the PC sample into the overflow tank until water in the cylinder started being discharged through the overflow pipe (i.e., 2). The water inflow amount was then adjusted to balance the water inlet and the overflow pipe. Finally, the water amount (denoted as Q) in the graduated cylinder (i.e., 6) and the water-head difference (i.e., 7, denoted as H) in the steady period were recorded. The temperature at the same time was also recorded.

The coefficient of water permeability was calculated using Eq. (2) by the principle of Darcy's Law, complying with existing Standard (ASTM D2434: Standard Test Method for Permeability of Granular Soils) (Soil & Rock, 2006):

$$K_{\mathrm{T}} = \frac{QL}{AHt}t \quad (2)$$

where K_{T} is the coefficient of water permeability at T°C (cm/s), Q is the water content (mL), L is thickness of specimen (cm), A is the surface area of specimen (cm^2), H represents the water head above the sample (cm), and t represents outflow time (s).

2.3.4 Strength Measurement

The compression experiment was carried out using 150 mm × 150 mm × 150 mm cube specimens with a digital-display pressure test machine (type YES-1000) (Fig. 5). For each PC mix, three specimens were prepared, following Chinese standard JTG 3420-2020 (China, 2020). The compressive strength (f) can be obtained using the following equation:

Fig. 5 Test setup of compressive strength for the PCs

$$f = \frac{F}{A} \tag{3}$$

where f represents the compressive strength of specimen (MPa), F represents maximum load (N) and A is compression area (cm^2).

2.3.5 Sulfate Dry–Wet Cycle Experiment

For the wet–dry cycle test, 1 day was chosen as one dry wet circulation, that is, submerged in 5% Na_2SO_4(aq) for 14 h, removed and dried in air for 2 h, and then oven-dried for 2 h, finally cooling in air for 6 h. It should be noted that, in this work, the number of dry–wet cycles includes 20, 30 and 40. The compressive strength loss rate (Δf_{dw}) of the PC was calculated using the following equation:

$$\Delta f_{dw} = \frac{f_{d0} - f_{dn}}{f_{d0}} \times 100\% \tag{4}$$

where Δf_{dw} represents the compressive strength loss rate after n cycles of dry–wet in after n cycles of dry–wet in Na_2SO_4(aq) (%), f_{d0} represents the initial compressive strength of specimens (MPa) and f_{dn} is the compressive strength of specimens after n cycles of dry–wet in Na_2SO_4(aq) (MPa).

3 Results and Discussion

3.1 Porosity and Permeability

The most important parameter of PC is its water permeability, which is affected by the amount of pores in the concrete—that is, porosity or void ratio. In this work, the results for porosity and permeability coefficients with various aggregate gradations are shown in Table 6, including mean values and their COVs to indicate the discreteness of test data (Gogo-Abite et al., 2014). In Table 6, all data represent an average of triplicate testing with a COV of less than 15%, which demonstrated a high level of consistency in the determination of porosity and permeability measurements for PC.

The porosities of samples are respective 17.4% for group A, 20.1% for group B, 21.3% for group C, 23.3% for group D and 25.9% for group E. All values of groups meet the specification requirements within the range of 15–25% and have low errors, except for group E. Meanwhile, from the analysis of test results it is shown that porosity of concrete continuously increases due to the increase in the maximum aggregate size, and a well relationship is observed between the porosity and the maximum aggregate size ($y = 0.1649x + 16.984$, $R^2 = 0.973$, y—porosity and x—proportion of 19–31.5 mm aggregate) in Fig. 6a. Clearly, Group A (no 19–31.5 mm aggregates) contained a small number of pores in comparison with other four groups.

In general, permeability is affected by the distribution of voids, voids number and voids interconnectivity (Akkaya & Çağatay, 2021). Gradations with higher proportion of larger aggregates had more voids, and thus cause the higher permeability (Deo & Neithalath, 2011; Neithalath et al., 2010). Specifically, the previous study showed that the pore size and the content of large pores have great influence on the permeability coefficient of PC (Yu et al., 2019a). The pores tend to be more irregular with increasing aggregate sizes (Lu et al., 2019; Marolf et al., 2004). For the same porosity, larger aggregate size or pore size could increase the pore connectivity factor, which is pivotal to determine the hydraulic transport properties of PC (Sumanasooriya & Neithalath, 2011). Meanwhile, concretes with porosity $< 15\%$ tend to give very slow water percolation due to insufficient interconnected voids (Meininger, 1988). Porosities $> 35\%$ result in highly permeable, but very weak concretes. Therefore, group prepared with large aggregate size such as group C exhibited good water permeability because of the large pore size and high pore connectivity. As shown in Fig. 6, the measured permeability coefficients of samples are respective 0.61 cm/s for group A, 0.89 cm/s for group B, 1.05 cm/s for group C, 1.19 cm/s for group D and 1.32 cm/s for group E, which can meet the requirements

Table 6 Porosity, permeability coefficients and compressive strength with coefficient of variations (COVs) of five groups

Groups	Porosity		Permeability coefficients		Compressive strength			
					7d		28d	
	Average value (%)	COV (%)	Average value (cm/s)	COV (%)	Average value (MPa)	COV (%)	Average value (MPa)	COV (%)
A	17.40	1.15	0.61	8.20	9.63	5.61	15.26	2.56
B	20.10	2.99	0.89	11.24	8.87	8.46	13.47	2.67
C	21.30	2.35	1.05	7.62	8.37	11.95	11.53	3.99
D	23.30	3.43	1.19	7.56	6.59	13.66	8.13	4.92
E	25.90	3.86	1.32	5.30	5.14	19.46	5.97	14.24

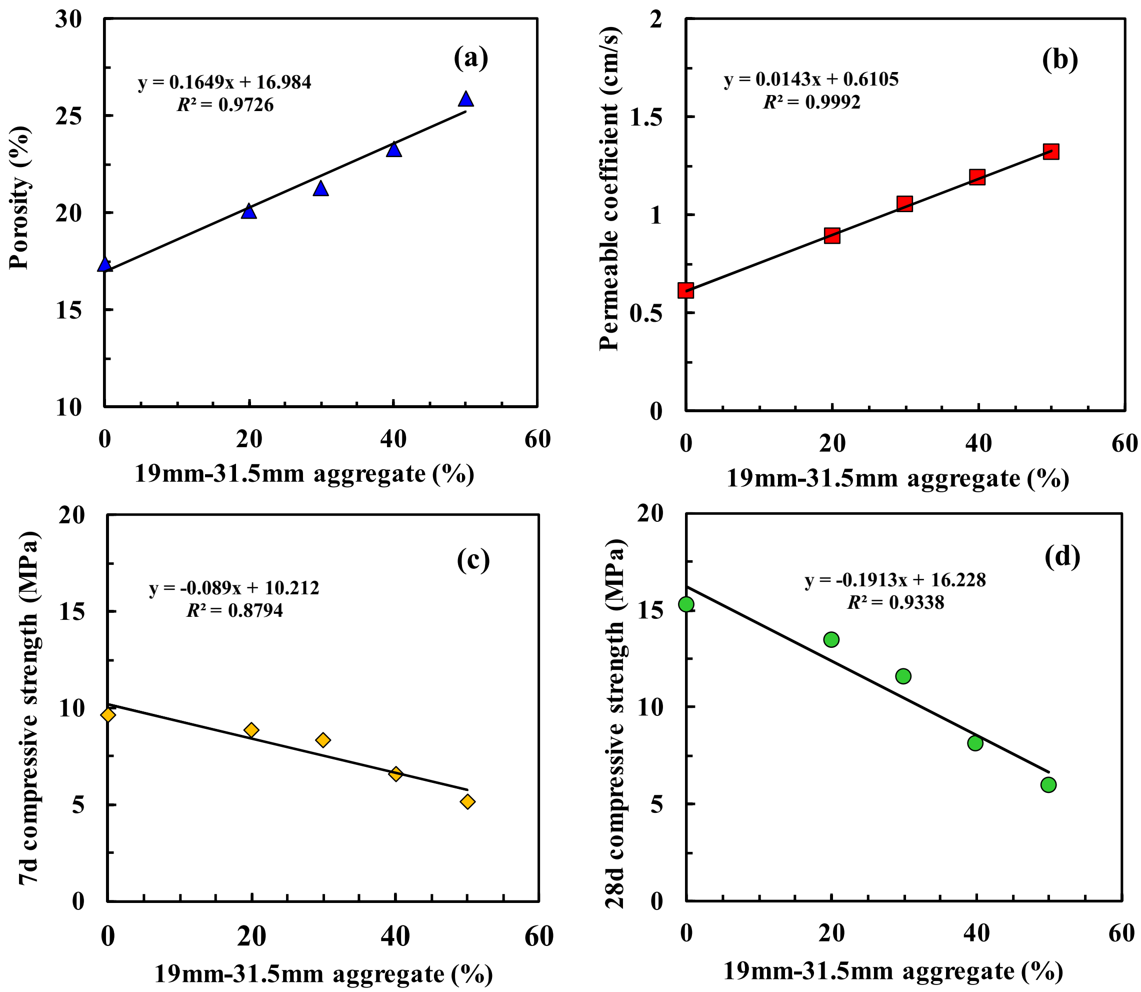

Fig. 6 Relationship between 19 mm and 31.5 mm aggregate and **a** porosity, **b** permeability coefficient, **c** 7d and **d** 28d compressive strength

for greater than 1.5 mm/s. That is, the permeability coefficients of other groups are all higher than group A. Therefore, the results show that as the 19–31.5 mm aggregate increases, the permeability coefficient increases for a given aggregate group of PC. In addition, there is a good linear relationship between the permeability and the maximum aggregate size ($y = 0.0143x + 0.6105$, $R^2 = 0.999$, y—permeability and x—proportion of 19 mm–31.5 mm aggregate) as shown in Fig. 6b.

3.2 Compressive Strength

The results for 7d and 28d compressive strength with various aggregate gradations are shown in Table 6. The values of COV greater than 15% are highlighted in bold. In general, the dispersion of the test results is small except. The 7d compressive strength values of samples are respective 9.63 MPa for group A, 8.87 MPa for group B, 8.37 MPa for group C, 6.59 MPa for group D and 5.14 MPa for group E. It can be seen that the majority of errors are high for 7d compressive strength values of samples. This may be a result of short periods of curing and low curing humidity. As for the 28d compressive strength, the groups A, B, C, D and E values are, respectively, 15.26 MPa, 13.47 MPa, 11.53 MPa, 8.13 MPa and 5.97 MPa, as well as the most errors are low. Meanwhile, the compressive strength of all the specimens can meet the requirements of use.

As shown in Table 6, the different aggregate gradations have a significant effect on the compressive strength, which is in agreement with the findings of previous studies (Ćosić et al., 2015; Yu et al., 2019b). It is noticed that 7d and 28d compressive strength varied significantly decreased with the increase of content of large size aggregate, especial when the amount of this aggregate more than 30%. Therefore, compressive strength of group A (no 19–31.5 mm aggregates) was higher than other four groups. The decrease in compressive strength results using large size aggregate may be due to segregation and increase in void spaces due to the usage of bigger sized aggregates (Kumar et al., 2016b). Meanwhile, compressive strength and the maximum aggregate size follow well linear relationships ($y = -0.089x + 10.212$ with $R^2 = 0.879$, y—7d compressive strength and x—proportion of 19 mm–31.5 mm aggregate; $y = -0.1913x + 16.228$ with $R^2 = 0.934$, y—28d compressive strength and x—proportion of 19 mm–31.5 mm aggregate) (Fig. 6c, d).

3.3 Water Stability

The results of wet–dry cycle tests for five groups are shown in Table 7. Due to the low variability of these parameters (i.e., COV < 10%), the tests can be considered reasonable 'computational replicates' of the PC mixture. For 20 cycles of dry–wet test, the compressive strength loss is 0.20–1.27 MPa and the loss rate is 1.3–21.3%. For 30 cycles of dry–wet test, the compressive strength loss is 0.53–1.61 MPa and the loss rate is 3.5–27.0%. For 40 cycles of dry–wet test, the compressive strength loss is 0.85–2.38 MPa and the loss rate is 5.6–39.8%. It is can be seen that the highest strength loss occurred in group E, and these loss rate values were affected by the number of dry–wet cycles significantly. Conversely, the loss rate of groups A and C showed relatively less change with changes of cycle numbers. That is, the loss rates are respective 1.3%, 3.5% and 5.6% for 20, 30 and 40 cycles of dry–wet in group A, as well as 7.8%, 10.5% and 13.9% for 20, 30 and 40 cycles in group C.

3.4 Failure Characteristics

The failure characteristics of five groups were also investigated in this work. Higher water content and less dense packing of cement grains close to the aggregate surface increase ITZ porosity (Akçaoğlu et al., 2004). When the proportion of course aggregate is increased, there will be an associated increase in interfacial transition zone porosity volume (Basheer et al., 2005). As shown in Fig. 7, there are two typical failure types exist for the specimens, including failure along the interfacial transition zone (ITZ) and aggregate failure, based on the test results. It is known that the crack growth generally begins at the matrix–aggregate interfaces, because transition zones are the weakest link of the cementitious material (Giaccio & Zerbino, 1998). The ITZ failure will occur when the load exceeds the peak strength, which represent the aggregate–paste bond is weak. If the aggregate–paste bond is strong enough, diverted transversal forces will be taken up by the aggregate and lead to the increase of external load (Bogas & Gomes, 2013). The aggregate failure will occur when the aggregate reaches the tensile strength, and crack can penetrate into the aggregate. In this test, the failure characteristics of groups A, B and C are the ITZ failure with no through crack, while the failure types of groups D and E are the aggregate failure with through crack. This can be explained that, the tensile strength decreases as the aggregate size increases. Therefore, more critical ITZs with a more condensed microcrack cloud in a narrower region (higher tensile stress distribution) with increasing aggregate size.

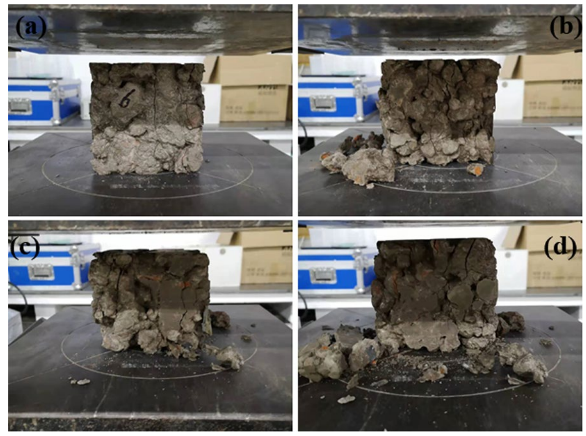

Fig. 7 Failure characteristics of five groups, including **a**–**c** aggregate failure and **d** ITZ failure

3.5 One-Way ANOVA

In this study, a one-way ANOVA was conducted using SPSS 20.0 to verify the effect, in terms of statistical significance, of independent variables on dependent ones and whether significant interaction effects exist among independent variables in a set of experimental data (Sambucci

Table 7 Compressive strength loss rate of five groups by dry–wet test

Groups	Original strength (MPa)	Strength of dry–wet test (MPa)						Loss rate (%)		
		20 cycles	COV (%)	30 cycles	COV (%)	40 cycles	COV (%)	20 cycles	30 cycles	40 cycles
A	15.26	15.06	1.40	14.73	1.54	14.41	1.98	1.3	3.5	5.6
B	13.47	12.72	1.91	12.15	2.46	11.52	2.18	5.6	9.8	14.5
C	11.53	10.63	2.06	10.32	3.47	9.93	2.86	7.8	10.5	13.9
D	8.13	7.15	3.39	6.67	4.51	6.38	5.44	12	17.9	21.5
E	5.97	4.70	5.05	4.36	6.08	3.59	7.73	21.3	27	39.8

& Valente, 2021). The physical properties (i.e., porosity, permeability coefficients and compressive strength) are dependent variables and only packing density is independent. Therefore, one-way ANOVA was chosen for the analysis of the significant difference between the properties with regard to the packing density. In general, the significance level (p value) was kept at 0.05 for the statistical evaluation of the experimental results, representing 95% level of confidence (Sahdeo et al., 2021a, 2021b). A p value less than 0.05 indicates the statistically significative effect of packing density on material performances. Based on the experimental results, the ANOVA results is shown in Table 8, which indicated that packing density was significantly affect the porosity, permeability coefficients and compressive strength of PC for these mixtures.

3.6 Optimal Group

In this work, 5 related parameters were measured, including porosity, permeability coefficient, compressive strength and the compressive strength loss rate. For PC design, it shows significant gains in permeability and clogging resistance when the porosity is raised beyond 20% (Fwa et al., 2015). Concrete pavement has an average porosity of 20% (Moretti et al., 2019), while porosity of group A is 17.4%. Therefore, group A is not the best choice. According to the requirements of the relevant specifications (JTG/T D33-2012, 2012), all values of groups meet the requirements of permeability coefficient (≥ 0.35 cm/s). As for compressive strength, according to Specifications for Design of Highway Cement Concrete Pavement (JTG D40-2011) (2011), all values of groups meet the specification requirements within the range of 7–20 MPa and have low errors, except for group D and E. The compressive strengths of group D are 6.59 MPa for 7d and 8.13 MPa for 28d, respectively, while group E are respective 5.14 MPa for 7d and 5.97 MPa for 28d. Therefore, it is not recommended to use the concrete with aggregate 19–31.5 mm greater than 40%. In addition, as shown in Table 7, the loss rate of group C showed fewer changes with increase of cycle numbers compared with group B. That is, the loss rates are respective 7.8%, 10.5% and 13.9% for 20, 30 and 40 cycles of dry–wet in group C, while 5.6%, 9.8% and 14.5% for 20, 30 and 40 cycles in group B. Among these groups, group C can be seen as the optimum gradation, possessing the optimal overall performance, i.e., the high porosity and the better water stability. Therefore, group C with 50% RA (20% of 4.75–9.5 mm aggregate, 50% of 9.5–19 mm aggregate and 30% of 19–31.5 mm aggregate) can be used as base layer material for permeable pavements.

4 Conclusion

In this study, the influence of aggregates with various gradations are investigated, using 50% RA and 50% NA. Porosity, permeability coefficients, compressive strength and its loss rate with five different aggregate gradations (groups A, B, C, D and E) are performed. The main conclusions that can be drawn from this paper are summarized as follows:

(1) From the current investigation, it is observed that the size of aggregates plays a crucial role in the porosity, permeability and strength of PC mixes. The concrete with aggregate 19–31.5 mm greater than 40% is not recommended to use because of its low compressive strength.
(2) Packing density of NA is commonly larger than that of RA, and the ANOVA results indicate that packing density is significantly affect the porosity, permeability coefficients and compressive strength of PC for these mixtures.
(3) With the increase of aggregates size, the porosity and permeability of the PC increases, whereas the strength of the PC decreases. Especially for 19–31.5 mm aggregate, the good linear relationships between its content and porosity, permeability coefficients and compressive strength are observed, with high R2 values.
(4) Aggregate gradation of group C (20% of 4.75–9.5 mm aggregate, 50% of 9.5–19 mm aggregate and 30% of 19–31.5 mm aggregate) is regarded as the optimum gradation among these groups. Thus, group C is recommended to use for base layer of permeable pavements.

The presented research can be further extended to study the impact of the natural aggregate replaced with the recycled aggregate as the next step, including

Table 8 ANOVA results on experimental data

Source of variation	Alpha value	Sum of Squares	Mean Square	F	Sig
Porosity	0.05	124.080	31.020	39769.231	0.00
Permeability coefficients	0.05	0.913	0.228	33.781	0.00
7d compressive strength	0.05	39.979	9.995	623.895	0.00
28d compressive strength	0.05	173.956	43.489	8527.247	0.00

environmental impact and cost analysis. This extension will help to formulate optimum design and find the optimal mixture. With the basis established in this study, further assessment on the influence of aggregate type, grading type and W/C ratio or A/C ratio can be possible. In addition, more microstructural studies such as characterization of concrete structures should be carried out for future research, to explore how to improve the performance of pervious concrete.

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Author Contributions
JZ: conceptualization, methodology, formal analysis, data curation, writing—original draft, writing—review and editing. HS: methodology, data curation. XS: methodology, formal analysis. WC: writing—reviewing and editing, supervision.

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Availability of Data and Materials
The data sets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing Interests
The authors declare that they have no competing interests.

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