

Article

Development of Aggregate Skeleton–Cementitious Paste-Coating Pervious Concrete

Weixiong Zeng, Jiajian Chen * and Tianxiang Chen 

Department of Civil Engineering, Foshan University, Foshan 528000, China

* Correspondence: chenjiajian@fosu.edu.cn

Abstract

To avoid cumbersome casting procedures in the production of pervious concrete, a new type of casting method through coating cementitious paste onto the preplaced aggregate skeleton is developed. To optimize the key performances and reveal their governing mechanism, aggregate skeleton–cementitious paste-coating pervious concrete (ACPC) mixes with different porosity, water/cement (w/c) ratio and sand ratio were produced and had their permeability and strength tested. This study demonstrated that it is successful to produce pervious concrete by the novel casting method. Vibration of aggregate skeleton and high w/c ratio should not be adopted to avoid the formation of a layer of hardened paste at the bottom of the mix to block the vertical passage of water. In contrast to conventional concrete, a higher w/c ratio (from 0.23 to 0.34) generally resulted in a higher strength (from 3.77 to 8.71 MPa) of ACPC. A small amount of sand increased both the permeability and strength through the balling bearing effect and filling effect, respectively. Both the optimum sand ratio to achieve the highest vertical permeability and strength were found to be 0.05, which offered this porous structure concurrently satisfactory permeability (permeability coefficient higher than grade K2) and acceptable strength (compressive strength higher than 5 MPa). Key influencing factors of permeability and strength of ACPC were analyzed. This study can advance the technology of casting concrete and the production of pervious concrete as road pavement in the construction of “sponge city”.

Keywords: aggregate skeleton; casting method; pervious concrete; porous structure; preplaced aggregate; sand ratio; sponge city



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1. Introduction

Pervious concrete, a porous, eco-friendly building material [1], serves as a pivotal product in line with the “sponge city” policy issued by the Chinese government [2]. It is a porous structure formed by coating a thin layer of cementitious paste on the coarse aggregate skeleton [3,4]. “Sponge city” refers to the effective control of rainwater in buildings, roads, green spaces and water systems [5,6]. This approach can effectively mitigate surface runoff and regulate surface temperatures [7]. In recent years, with the increasing popularization and advancement of the “sponge city” concept, pervious concrete has demonstrated remarkable effectiveness in addressing urban waterlogging, noise reduction, sound insulation, recycling water resources and mitigating the urban heat island effect [8]. It plays a significant role in protecting the human ecological environment.

According to the “sponge city” policy, pervious concrete is of cardinal importance in road pavement because of its water permeability [9]. However, the mechanical properties, which are represented by compressive strength, of pervious concrete decrease with the

increase in porosity [10]. Researchers have studied the effect of raw materials on the mechanical properties and water permeability of pervious concrete. Yang et al. [11] showed that the addition of TiO_2 /LDHs reduced both the porosity and permeability by approx. 20%, and increased the compressive strength of recycled-aggregate pervious concrete by approx. 40%. Sandoval et al. [12] found that pervious concrete mixes with ceramic construction waste and concrete block waste as aggregate yielded similar abrasion resistance (38% and 36% mass loss) to reference aggregates (38% mass loss), while mixes with electric furnace slag aggregates showed significantly weaker abrasion resistance (73% mass loss). Oskar et al. [13] demonstrated that replacement of aggregate in pervious concrete with recycled concrete aggregate (8/31.5 mm) by 50% by mass improved the mechanical properties, while replacement of rubber waste aggregate (2/5 mm) by 10% by volume reduced the compressive strength by a maximum of 11.4%. By quantitative evaluation of the mesostructure of pervious concrete, Zhou et al. [14] pointed out that the larger the particle size of the aggregate, the larger the average diameter of voids, but the fewer the number of voids. Zheng et al. [15] demonstrated that the total void ratio and water permeability of the pervious concretes increased with the addition of copper slag. Hilal et al. [16] observed that coarse recycled concrete aggregate replacement had a more noticeable negative effect on compressive strength of pervious concrete, while recycled fine glass replacement was more impactful on splitting tensile and flexural strengths. Huang et al. [17] found that a larger aggregate particle size resulted in lower permeability for pervious concrete with single-size granite aggregate. Like conventional concrete, the addition of silica fume increased the compressive strength, while the addition of fly ash decreased the compressive strength. Carmichael et al. [18] showed that pervious concrete with a cement/coarse aggregate ratio of 1:6, a water/binder ratio of 0.34 and nano fly ash content as a cement replacement of 40% had optimum compressive and tensile strength. Subramaniam et al. [19] demonstrated that fly ash or rice husk ash as cement replacement impaired the permeability of pervious concrete, and 10% to 15% fly ash and 5% rice husk ash best improved the compressive strength.

Particularly, many studies have been carried out to balance the permeability and strength of pervious concrete. Fan et al. [20] tried to optimize the pore structure of pervious concrete to enhance both strength and permeability through CT scanning and image analysis, and showed that pore structure optimization reduced the porosity by 5%, but finally increased the average pore size. This interesting phenomenon was because it decreased the small pores significantly, but yielded little effect on the porosity of large and medium pores. Claudino et al. [21] optimized cement paste and granular skeleton composition to balance the strength and permeability of pervious concrete, and showed that a w/b ratio of 0.35 and sand ratio of 10% best balanced these two key properties. Ramírez et al. [22] pointed out that an increase in the w/c ratio led to higher compressive and flexural tensile strength; Rodrigo et al. [23] showed that the addition of nanosilica and polypropylene fibers into permeable concrete significantly improved the compressive strength and flexural strength at the cost of a relatively lower permeability; through CT scanning, Zhu [24] demonstrated that a decrease in cementitious paste volume increased the porosity of pervious concrete and weakened the compressive strength and flexural strength.

The conventional procedures to cast pervious concrete include mixing all the raw materials together, transporting and pumping the fresh concrete mix into the mold, and vibrating the mix to achieve sufficient compaction. These casting steps are cumbersome and labor-consuming. In remote locations lacking large-scale concrete mixing plants, long-distance transportation using concrete trucks results in long construction time, consumption of manpower and wastage of raw materials. Compared to the conventional casting method to produce pervious concrete, a novel aggregate skeleton–cementitious

paste-coating method is advocated and demonstrated in this study. It does not mix cementitious paste and aggregates together. Instead, the aggregate mix is placed in the mold and forms a skeleton, allowing the cementitious paste to infiltrate into the voids between the skeleton under gravity, and, finally, forms a porous but stable structure [25–27]. In contrast to the conventional way to cast pervious concrete, the novel casting method addresses engineering challenges, including the scarcity of mixing plants in remote areas, the wastage of raw materials during long-distance transportation and the susceptibility to pipe blockage during pumping. Furthermore, it facilitates the formation of more interconnected pores in pervious concrete to improve its permeability [28].

As far as the authors' knowledge, there is no study on the production of pervious concrete through coating cementitious paste onto the aggregate skeleton. To demonstrate the feasibility of this novel casting method and reveal the effects of the key influencing factors, this study produced aggregate skeleton–cementitious paste-coating pervious concrete (ACPC, also called frame concrete or large-pore concrete [29] or two-stage concrete [30] or prepacked concrete [31]) and experimentally investigated the effects of major mix design parameters on the permeability and strength. Finally, the ACPC mix that was able to achieve, concurrently, satisfactory permeability and strength is concluded. The findings obtained in this study can advocate the technology and application of the aggregate skeleton–cementitious paste-coating method and the production of pervious concrete.

2. Research Protocol

2.1. Raw Materials

Pervious concrete is composed of water, cement, coarse aggregate, fine aggregate and water reducer. The cement used is grade 42.5 ordinary Portland cement. The mixing water was sourced from municipal tap water in Foshan City. The fine aggregate is manufactured limestone sand with particle sizes ranging between 1.18 mm and 2.36 mm, which is obtained by simple mechanical sieving. These particles exhibit irregular polygonal shapes with distinct edges and angular surfaces. The coarse aggregate is crushed limestone with a rough surface, irregular and angular in shape, with a particle size range of 10–25 mm and needle content not higher than 10%. A polycarboxylate-based high-performance water reducer was incorporated. According to its supplier, it reduced water content by up to 30% at the same flowability. The densities of cement, fine aggregate and coarse aggregate were measured to be 3130 kg/m³, 2480 kg/m³ and 2600 kg/m³, respectively.

2.2. Process Performed

The ACPC mixes are designed adopting the unit volume method [32,33] and the Chinese standard CJJ/T135-2009 for pervious concrete pavement [34]. The design steps are as follows: (a) Measure the packing density of aggregate mix, adopt the packing density value as aggregate volume in 1 m³ concrete to form dense aggregate skeleton in the mold, and calculate the skeleton voidage V_{void} as per Equation (1); (b) set paste-filling ratio R_f (ratio of voidage of skeleton filled by the paste) according to the designed void ratio, calculate the paste volume V_{paste} in 1 m³ concrete as per Equation (2); and (c) calculate cement content and water content in 1 m³ concrete based on the paste volume and w/c ratio.

$$V_{\text{void}} = 1 - \frac{m_{\text{aggregate}}}{\rho_{\text{aggregate}}} \quad (1)$$

$$V_{\text{paste}} = V_{\text{void}} \times R_f \quad (2)$$

To investigate the optimal mix ratio to successfully produce ACPC and make their permeability and strength conform to the engineering requirements, a total of six groups of

mixes were designed to carry out the tests. Group 1 is to verify the feasibility of application of vibration to aggregate skeleton; Group 2 is to reveal the effect of sand ratio; Group 3 is to verify the feasibility of coating mortar onto the coarse aggregate skeleton; Group 4 is to reveal the effect of designed void ratio; Group 5 is to reveal the effect of w/c ratio or cementitious paste flowability; and Group 6 is to reveal the effect of sand ratio (ratio of sand in total amount of aggregate).

2.3. Mix Proportion

Following the common way to produce modern concrete, a water reducer was added to the paste [35,36]. The dosage of water reducer was set constant at 1% by mass of cement for all the mixes [37]. The volume-based concrete mix design parameters and mix proportions of all the ACPC mixes are tabulated in Table 1. As can be seen from the designed void ratio and paste-filling ratio, the paste-filling ratio decreases with the designed void ratio.

Table 1. Mix design parameters and mix proportions.

Group	Mix No.	Mix Design Parameter					Mix Proportion (kg/m ³)					Note
		Designed Void Ratio (%)	Water/Cement Ratio	Sand Ratio	Coarse Aggregate Packing Density	Paste-Filling Ratio	Cement	Water	Sand	Coarse Aggregate	Water Reducer	
1	①	10.50	0.30	0.10	0.625	0.72	422.6	130.9	155.0	1462.5	4.2	5 s aggregate skeleton vibration
	②	10.50	0.30	0.10	0.625	0.72	422.6	130.9	155.0	1462.5	4.2	10 s aggregate skeleton vibration
2	③	10.50	0.30	0.10	0.625	0.72	422.6	130.9	155.0	1462.5	4.2	-
	④	10.50	0.30	0.20	0.625	0.72	422.6	130.9	310.0	1300.0	4.2	-
	⑤	10.50	0.30	0.30	0.625	0.72	422.6	130.9	465.0	1137.5	2.6	-
3	⑥	24.00	0.23	0.05	0.625	0.36	234.8	57.7	77.5	1543.8	2.3	Coating mortar onto aggregate skeleton
	⑦	24.00	0.23	0.10	0.625	0.36	234.8	57.7	155.0	1462.5	2.3	Coating mortar onto aggregate skeleton
4	⑧	10.50	0.23	0.10	0.625	0.72	422.6	115.4	155.0	1462.5	4.7	-
	⑨	24.00	0.23	0.10	0.625	0.36	234.8	57.7	155.0	1462.5	2.3	-
	⑩	26.25	0.23	0.10	0.625	0.30	195.6	48.1	155.0	1462.5	2.0	-
	⑪	28.13	0.23	0.10	0.625	0.25	163.0	40.1	155.0	1462.5	1.6	-
5	⑫	28.13	0.23	0.00	0.625	0.25	163.0	40.1	0.0	1625.0	1.6	-
	⑬	28.13	0.25	0.00	0.625	0.25	163.0	42.9	0.0	1625.0	1.5	-
	⑭	28.13	0.28	0.00	0.625	0.25	146.7	45.5	0.0	1625.0	1.5	-
	⑮	28.13	0.30	0.00	0.625	0.25	139.7	47.8	0.0	1625.0	1.4	-
	⑯	28.13	0.34	0.00	0.625	0.25	133.4	49.8	0.0	1625.0	1.3	-
6	⑰	28.13	0.23	0.00	0.625	0.25	163.0	40.1	0.0	1625.0	1.6	-
	⑱	28.13	0.23	0.05	0.625	0.25	163.0	40.1	77.5	1543.8	1.6	-
	⑲	28.13	0.23	0.10	0.625	0.25	163.0	40.1	155.0	1462.5	1.6	-
	⑳	28.13	0.23	0.15	0.625	0.25	163.0	40.1	232.5	1381.3	1.6	-

As shown in Table 1, the variables of the ACPC mixes include water/cement ratio, sand ratio and designed void ratio, and the major technological factors in the casting process are whether vibration is applied, like conventional concrete, and whether sand is blended with the cementitious paste to coat the aggregate skeleton. All the above-mentioned mix variables and technological factors were delved into in this study. The flowchart of this study is shown in Figure 1.

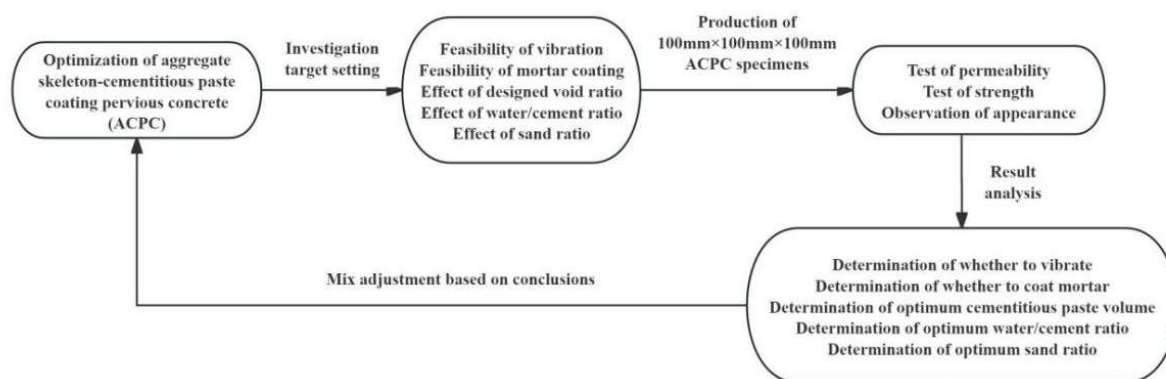


Figure 1. Study diagram.

2.4. Production of ACPC

The procedures to produce ACPC include preplacing aggregate to form a skeleton, mixing cementitious paste and coating the paste onto the aggregate skeleton, which differs from conventional casting methods to produce pervious concrete. Firstly, the coarse aggregate and sand (if any) were mixed as per the mix design in Table 1 and placed through 3 layers into the 100 mm × 100 mm × 100 mm molds. Secondly, the cementitious paste was mixed as per the ratio of each ingredient designed in Table 1. Thirdly, the cementitious paste was poured onto the aggregate skeleton with a scoop and penetrated under gravity. The mass of the mixing bowl with cementitious paste was measured from time to time until the predetermined content of cementitious paste was used. At 24 h of age, the specimens were demolded and placed inside a curing chamber with a temperature set at 20 ± 2 °C and relative humidity set at $95 \pm 2\%$. The procedures to produce ACPC are graphically shown in Figure 2.

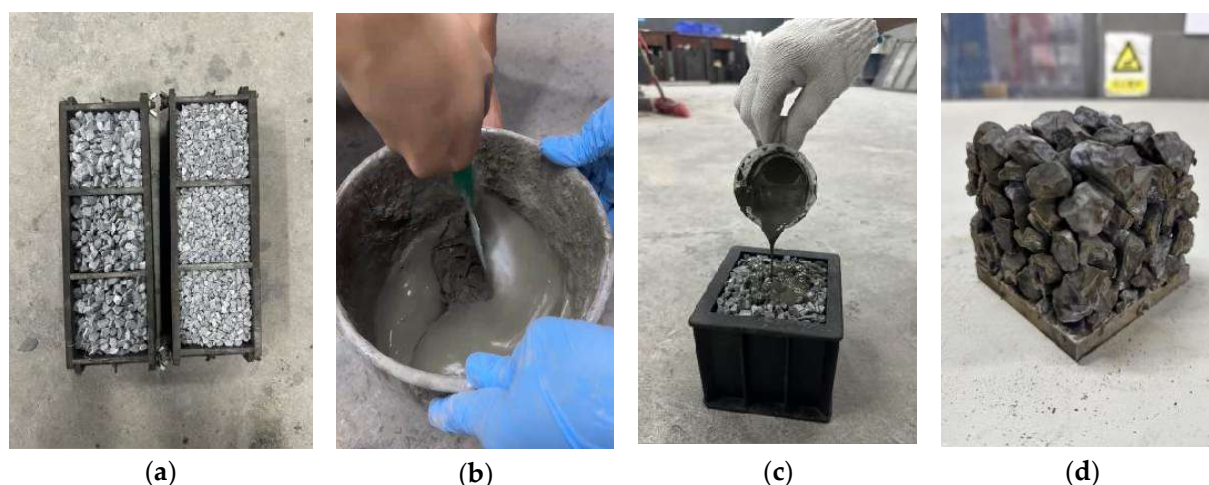


Figure 2. Photos showing the process of the novel casting method. (a) Production of aggregate skeleton; (b) Production of cementitious paste; (c) Coating aggregate skeleton with cementitious paste; (d) ACPC specimen.

2.5. Test Methods

For all the measurements in this study, which included tests on aggregate, cementitious paste and ACPC mixes, three samples were produced and tested, and their average value was taken as the result.

2.5.1. Aggregate Packing Density

The packing density of aggregates was defined as the volumetric fraction occupied by aggregates in the mold. The test was carried out as per British Standard BS 812-2 [38], which is the standardized way to measure the packing density of the aggregate. It places aggregate mix inside a standard container to measure the solid to bulk volume ratio.

2.5.2. Cementitious Paste Flowability

The flowability of cementitious paste was quantified as per GB/T 2419 [39]. It measured the flow spread of a sample dropping from a mini-slump cone with an upper diameter of 70 mm, a lower diameter of 100 mm and a height of 60 mm.

2.5.3. Permeability

The permeability of pervious concrete is quantified by the vertical permeability coefficient calculated as per Chinese standard JC/T2558-2020 [40,41], as shown in Figure 3. The higher the permeability coefficient, the better the permeability of the mix.



Figure 3. Photos showing the vertical permeability testing device and experimental process.

The theoretical formula [42–46] is expressed by Formula (3), as follows:

$$K = \frac{QL}{AHt} \quad (3)$$

where K is the permeability coefficient (mm/s), Q is the total water volume to pass the pervious concrete (mm³), L is the height of the specimen (mm), A is the cross-sectional area of the specimen (mm²), H is the hydraulic head (mm), t is the time during the test(s).

As the cementitious paste tended to drop downward and accumulate at the bottom of ACPC, a thin hardened cementitious paste layer may exist and stop the vertical passage of water during the traditional JC/T 2558-2020 test. To quantify the permeability, a horizontal permeability test was also carried out. A fixed volume of 3 L of water was poured into a sealed prismatic device and allowed to horizontally pass through the ACPC mixes, as shown in Figure 4. The time to complete this horizontal passage of water was recorded by a stopwatch to indicate the horizontal permeability. The longer the passing time, the worse the permeability of the mix.

To minimize the experimental error from water absorption of aggregate, all specimens were immersed in the water tank for 24 h to make the aggregate fully saturated before the permeability test.



Figure 4. Photos showing the horizontal permeability testing device and experimental process.

2.5.4. Compressive Strength

The compressive strength was measured as per Chinese standard GB/T 50081-2016 [47] at 28-day age by a hydraulic servo-controlled machine. The loading was controlled by displacement, and the test stopped if the displacement under compression reached 7.5 mm. The loading rate was maintained at 0.3 MPa/s.

3. Experimental Results

3.1. Feasibility of Aggregate Skeleton Vibration on ACPC Production

To vividly show the effect of aggregate vibration on the production of ACPC, the photos showing the bottom of mixes produced with aggregate vibrated for 5 s (mix ①) and 10 s (mix ②) are displayed in Figure 5. In contrast to the conventional concrete, which achieves homogenous mixing through sufficient vibration, vibration rendered the ACPC mix of poor quality. This is because the sand under vibration passed through the void between the aggregate skeleton, accumulated inside the ACPC mix and blocked the penetration of cementitious paste. Under these circumstances, there was insufficient cementitious paste to bond the aggregate at the bottom of the mix. This verified that vibration for the aggregate skeleton is harmful to the production of ACPC. It is noteworthy to mention that vibration still slightly increased the strength, possibly due to the higher packing density of the aggregate skeleton [48], as shown by slightly lower compressive strength for Mix ① (24.22 MPa) than that of Mix ② (26.83 MPa). This finding agreed with the results of Li et al. [49], who showed that the compressive strength of polymer pervious cement concrete increased with the increase in vibration time.

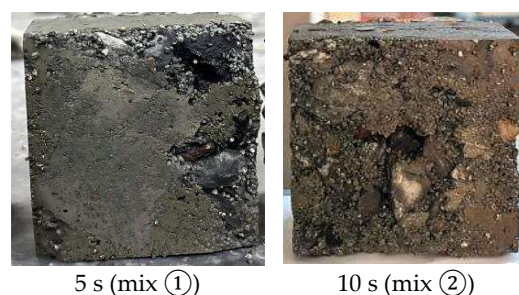


Figure 5. Photos showing the bottom of ACPC mixes with different aggregate skeleton vibration times.

3.2. Feasibility of Mortar Coating on ACPC Production

As the aggregate skeleton and cementitious paste are separately produced, the sand may not necessarily be mixed with the coarse aggregate and may be mixed into the

cementitious paste to form mortar to coat the coarse aggregate skeleton. To disclose the feasibility of the latter way to add sand, mixes ⑥ and ⑦ were produced by mixing sand with cementitious paste to form mortar and coating the mortar onto the coarse aggregate skeleton. The ACPC mixes ⑥ and ⑦ were shown in Figures 6 and 7, respectively. As can be seen from the photos, the top of the mixes was basically filled up by the mortar, which blocked the path for water to penetrate the aggregate skeleton. This is because the sand in the mortar accumulated at the top of the mix. Therefore, producing ACPC by coating mortar onto the coarse aggregate skeleton is infeasible.



Figure 6. Photos showing mix ⑥.



Figure 7. Photos showing mix ⑦.

3.3. Effect of Cementitious Paste Flowability on ACPC Production

As the cementitious paste/mortar is required to penetrate the coarse aggregate skeleton and avoid accumulation at the bottom of the ACPC mix, its flowability is critical for the successful production of ACPC. As a rule of thumb, water/binder ratio (the same as w/c ratio since cement is the only binder in this study) and sand ratio are the most important parameters affecting the flowability of cementitious paste/mortar. The result of the cementitious paste/mortar flowability is tabulated in Table 2. The production of ACPC samples demonstrated that the w/c ratio and sand ratio adopted in this study exhibit sufficient flowability to penetrate the coarse aggregate skeleton.

Table 2. Flow spread of cementitious paste/mortar mixes with varying w/c ratios.

w/c ratio	0.23	0.25	0.28	0.30	0.34	0.23	0.23
sand ratio	0	0	0	0	0	0.05	0.10
Flow spread (mm)	363	385	425	450	475	415	398

To vividly show the effect of cementitious paste flowability on ACPC production, the photos showing ACPC mixes with different w/c ratios are displayed in Figure 8. It is observed that higher cementitious paste flowability generally resulted in thicker hardened paste at the bottom of the mix. This is because the higher flowability allowed the paste to more easily penetrate the aggregate skeleton and reach the bottom of the aggregate mix.

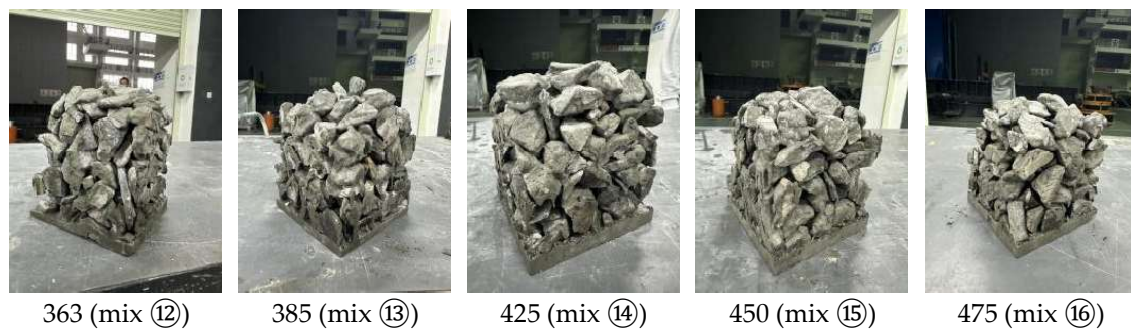


Figure 8. Photos showing ACPC mixes with different cementitious paste flow spreads.

At a w/c ratio of 0.23, only a thin layer of paste formed at the bottom and did not completely seal the bottom of ACPC, which left a path for the passage of water. However, at a w/c ratio equal to or higher than 0.25, a thick layer formed at the bottom of ACPC (as shown in Figure 9), which resulted in poor permeability or even impermeability. Two typical w/c ratios, i.e., 0.23 (thin layer of paste) and 0.30 (thick layer of paste), were chosen for the mixes except Group 5.

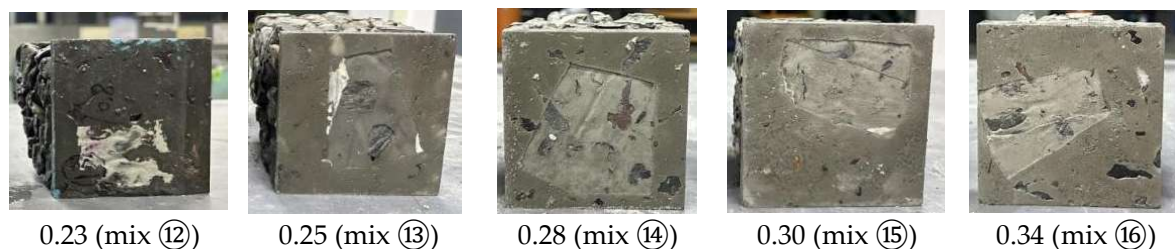


Figure 9. Photos showing the bottom of ACPC mixes with different w/c ratios.

3.4. Effect of Void Ratio on ACPC Production

The porosity of pervious concrete typically ranges between 15% and 35% [50], which is significantly higher than 1% to 10% for conventional concrete [51–53]. Since the aggregate packing density is constant at a given aggregate mix, the permeable void of pervious concrete is determined by the paste volume. For conventional concrete, sufficient cementitious paste volume is required to fill up the voids between the aggregate skeleton to provide high strength and durability [54,55]. However, for pervious concrete, a high cementitious paste volume may result in insufficient permeability because the hardened cementitious paste blocks the path for water to pass through. As a result, the cementitious paste volume is critical for the successful production of ACPC. To produce pervious concrete with satisfactory permeability and strength, the cementitious paste volume has to be carefully determined to be (1) sufficiently high to bond the aggregate together to form an integral structure; and (2) sufficiently low to avoid the formation of a thick hardened layer that blocks the passage of water.

The effect of void ratio on the ACPC mix is shown in Figure 10. The photos clearly show that a layer of hardened cementitious paste formed at the bottom of the ACPC mixes, which would result in extremely low permeability. As revealed from the photos, the increase in the designed void ratio (in other words, the decrease in cementitious paste volume) thinned down the paste layer. When the designed void ratio was lowered to 28.13% (in other words, the paste-filling void ratio was lowered to 0.25), there was only a thin layer of cementitious paste at the bottom of ACPC, which could provide acceptable permeability.

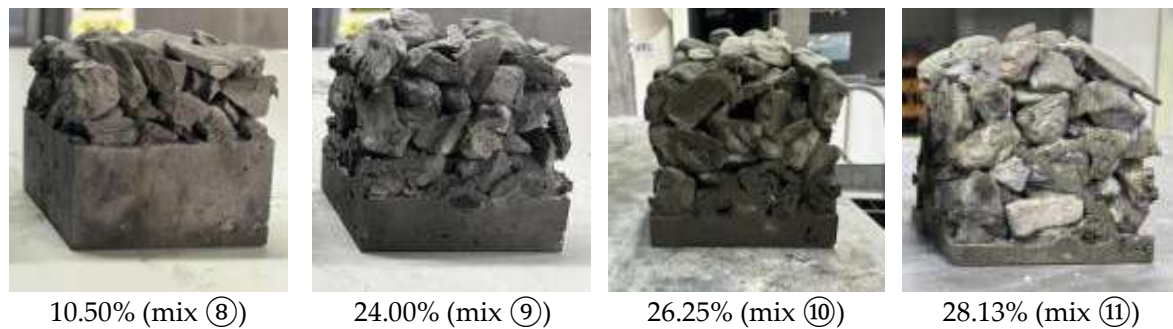


Figure 10. Photos showing ACPC mixes with different designed void ratios.

4. Analysis of Key Influencing Factors of Permeability of ACPC

According to the previous findings [56–58], the pervious concrete mixes typically do not adopt fine aggregate. However, the appropriate amount of sand can turn the cementitious paste into mortar and improve its adhesiveness to the coarse aggregate. This improved bonding between the paste/mortar and coarse aggregate can significantly increase the strength. What is more important, the existence of sand can improve the cohesiveness of the paste/mortar. This lowers the amount of paste/mortar that penetrates through the aggregate skeleton and accumulates at the bottom of the ACPC mix. To reveal the effect of sand, the permeability coefficients of mixes with varying sand content (Group 6 listed in Table 1) were plotted against the sand ratio in Figure 11. Results showed that the horizontal permeability always decreased with the sand ratio. This is expected because the sand particles inside the coarse aggregate skeleton obstruct the passage of water.

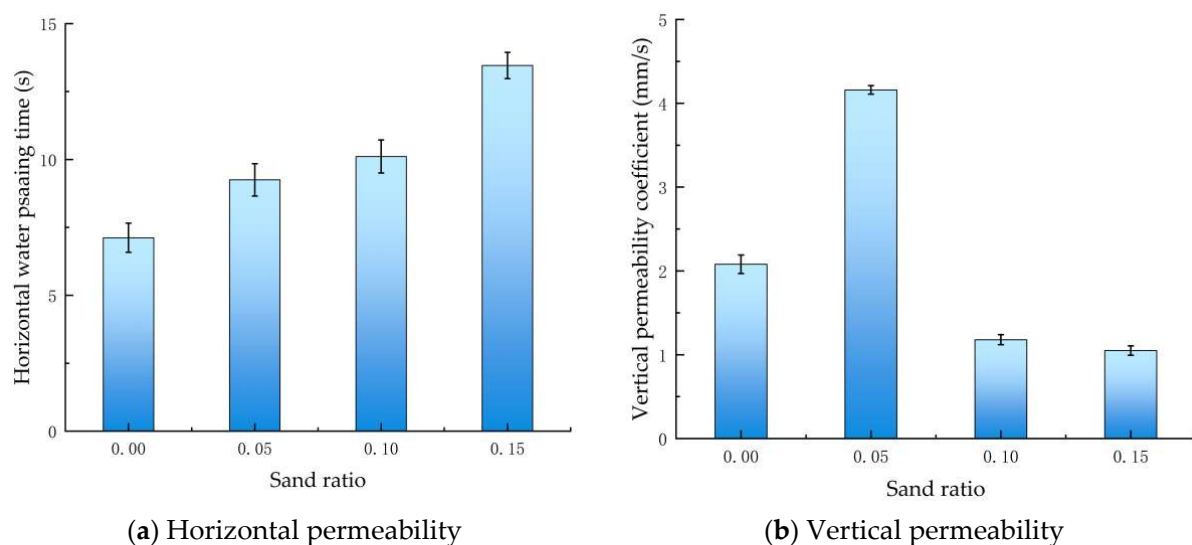


Figure 11. Permeability versus sand ratio.

Interestingly, the vertical permeability dramatically increased with the sand ratio up to 0.05, but turned to decrease with further increase in sand ratio. A possible explanation is that a low amount of sand acted as ball bearings to push apart the coarse aggregate (as shown in Figure 12), which formed a continuous flow channel and allowed the water to pass through the ACPC mix, while a high amount of sand mainly affected the vertical permeability by the obstruction effect. Clearly, the optimum sand ratio to achieve the highest vertical permeability was 0.05.

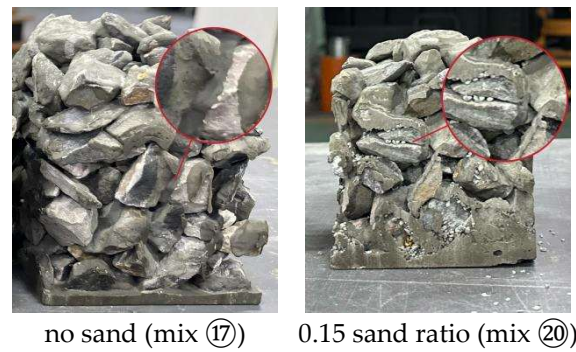


Figure 12. Photos showing ball-bearing effect of sand.

5. Analysis of Key Influencing Factors of the Strength of ACPC

The compressive strength results of all the mixes in this study are tabulated in Table 3. For conventional concrete, the most important governing parameter of strength is the w/c ratio. For pervious concrete, the strength is governed by the bonding of the aggregate skeleton. This bonding is determined by the distribution and adhesiveness of cementitious paste. The former is mainly affected by the w/c ratio, and the latter is mainly affected by the sand ratio. The effects of these two key influencing factors on the strength of ACPC are presented and discussed herein.

Table 3. Compressive strength results.

Group	Mix No.	Compressive Strength (MPa)
1	①	24.22
	②	26.83
2	③	24.22
	④	22.23
	⑤	12.03
3	⑥	11.35
	⑦	7.82
4	⑧	24.22
	⑨	7.82
	⑩	4.70
	⑪	4.45
5	⑫	3.77
	⑬	2.51
	⑭	3.34
	⑮	7.53
	⑯	8.71
6	⑰	3.77
	⑱	5.54
	⑲	4.82
	⑳	3.59

5.1. Effect of Designed Void Ratio

The mixes with different designed void ratios are shown in Figure 13. As expected, a higher designed void ratio, i.e., a lower paste-filling ratio, rendered a lower strength. This is because a higher amount of cementitious paste increased the aggregate surface area that contacted the paste, which improved the bonding between the aggregate skeleton and the paste [59].

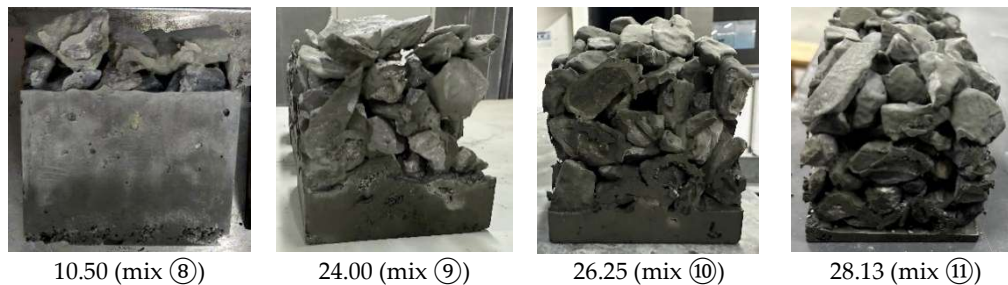


Figure 13. Photos showing mixes with various designed void ratios.

5.2. Effect of Water/Cement Ratio

It is well-established knowledge that the w/c ratio is of cardinal importance to the strength of conventional concrete because it determines the amount of voids in the hardened concrete mix. As ACPC is produced by coating the cementitious paste/mortar onto the coarse aggregate to bond the skeleton together, the role of the w/c ratio is likely different from its role in conventional concrete. To reveal the effect of w/c ratio on the strength of ACPC, the 28-day compressive strength of mixes with varying w/c ratio (Group 5 listed in Table 1) was plotted against the w/c ratio in Figure 14. Results indicated that the strength of ACPC generally increased with the w/c ratio, except for a relatively high strength result at a w/c ratio of 0.23, which may be due to experimental error.

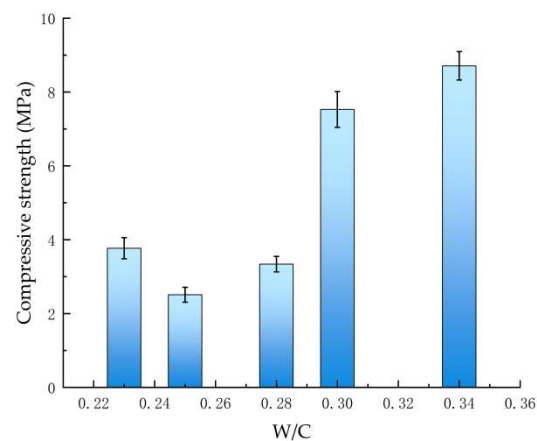


Figure 14. Variation in compressive strength with w/c ratio.

This effect of w/c ratio on ACPC is contradictory to that on conventional concrete. The reason is that, to maintain sufficient void volume for high permeability, the amount of cementitious paste in pervious concrete is low, and its bonding effect on the aggregate skeleton is weak. A higher w/c ratio allows the paste to more easily infiltrate into the interstitial voids between the aggregate skeleton under gravity, which improves the integrity of the ACPC mix through better bonding of the aggregate skeleton together, as shown in Figure 15.



Figure 15. Photos showing ACPC mixes different w/c ratios.

5.3. Effect of Sand Ratio

As the addition of sand effectively increases the packing density of concrete mix [60], it is expected to improve the strength of ACPC. To reveal the effect of sand on strength, the 28-day compressive strength of mixes with varying sand ratios (Group 6 listed in Table 1) was plotted against the sand ratio in Figure 16. Under the same designed void ratio, adoption of sand up to a 0.05 sand ratio increased the compressive strength. This strengthening mechanism could be attributed to the filling effect of sand, which partially filled the voids between coarse aggregates. However, further addition of sand resulted in a decrease in the compressive strength of ACPC. The possible reason was that the excessive sand weakened the bond between the cementitious paste and coarse aggregate skeleton.

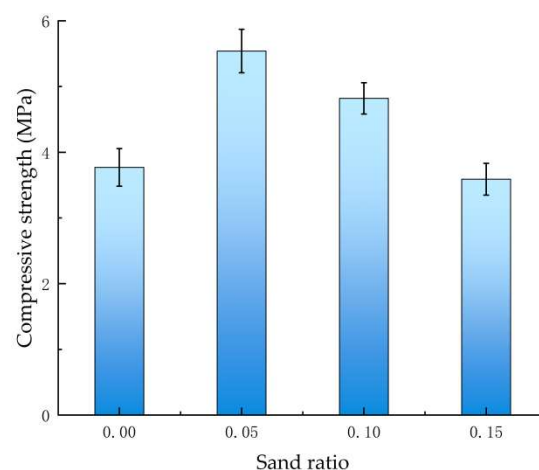


Figure 16. Variation in compressive strength with sand ratios.

6. Optimum Sand Ratio to Achieve Concurrently Satisfactory Permeability and Strength

Permeability and strength are two key properties for pervious concrete. Their satisfactory performances are not easy to concurrently achieve because the permeability generally requires a low packing density, while the strength generally requires a high packing density. For pervious concrete, an appropriate amount of sand should (1) increase the paste-aggregate contact area and improve the interfacial bonding strength; (2) improve the connectivity of the internal void structure; (3) and form a dense skeletal framework while maintaining efficient water transport pathways.

As can be seen from the above-mentioned results, adjustment of sand ratio changes these two performances at the same time. As a result, an optimum sand ratio is likely to achieve, concurrently, satisfactory performances. The concurrent strength and permeability performances of mixes with varying sand ratios (Group 6 listed in Table 1) are graphically shown in Figure 17, where the sand ratios are directly juxtaposed with the data points in the figure. Results show that the addition of sand up to a sand ratio of 0.05 concurrently improved the permeability and strength. However, further addition of sand turned to

concurrently decreased the permeability and strength. Evidently, 0.05 was the optimum sand ratio to optimize both the permeability and strength of ACPC. It allowed the ACPC to achieve a satisfactory vertical permeability coefficient $\geq$ grade K2 (according to Chinese standard JC/T 2558-2020 for permeable concrete [61]) and an acceptable compressive strength $\geq$ 5 MPa.

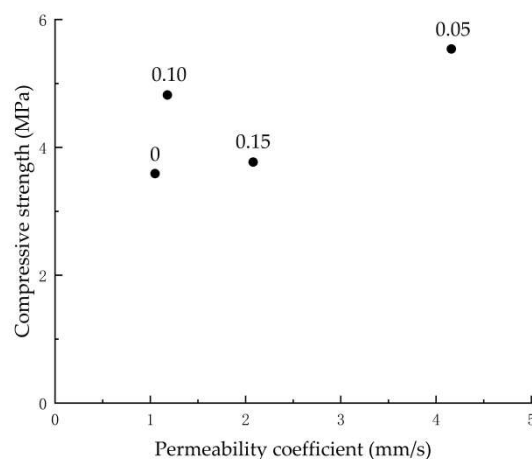


Figure 17. Concurrent strength and permeability.

7. Discussion

Results show that the compressive strength of the ACPC mixes in this study ranged from 2.51 to 8.71 MPa. This range of the 28-day compressive strength is higher than the results (i.e., 3.4–4.8 MPa) from Yuan et al. [62] for conventional and recycled aggregate pervious concrete, comparable to the results (i.e., 7.5–11.5 MPa) from Zhu et al. [24] for pervious concrete with 25%–35% porosity, and lower than the results (i.e., 9.5–10.5 MPa) from Xin et al. [63] for recycled aggregate pervious concrete. The strength of ACPC in this study is insufficient for load-bearing structural use, but still meets the requirements for non-structural use, such as permeable pavements [64].

It is noteworthy to point out that the robustness of the strength of ACPC may be low, as revealed by the wide range of strength results obtained in this study. This is because the porous structure is not filled with the paste, and the distribution of the paste is inhomogeneous [55]. Therefore, the use of ACPC has to be limited to non-structural applications for safety reasons.

The permeability and strength of ACPC were measured in this study, but the durability has not been covered yet. As the quality of a porous structure is sensitive to the freezing and thawing cycles [65], further study, carrying out freeze–thaw cycles or frost resistance or water filtration tests, is recommended to demonstrate the long-term adhesion between the hardened cementitious paste and the aggregate.

8. Conclusions

To investigate the feasibility of producing pervious concrete through coating cementitious paste onto aggregate skeleton as opposed to the conventional mixing method, this study examined the effects of vibration time, cementitious paste flowability and volume on the production of aggregate skeleton–cementitious paste-coating pervious concrete (ACPC). The key factors influencing permeability and strength were analyzed. Finally, the optimal sand ratio for balancing these properties was determined. The major findings are as follows:

1. The pervious concrete was successfully produced by coating cementitious paste onto the aggregate skeleton method. When sand is adopted to produce ACPC, vibration of

the aggregate skeleton and coating mortar onto the coarse aggregate skeleton should not be applied.

2. A too-high w/c ratio (above 0.23 for the mix parameters in this study) or too-low void ratio (above 28.13% for the mix parameters in this study) resulted in a hardened cementitious layer that sealed the bottom of ACPC and blocked the path of the vertical permeability.
3. In contrast to the effect of w/c ratio on conventional concrete, a higher w/c ratio generally resulted in a higher strength of ACPC because the paste could more easily infiltrate into the interstitial voids between aggregate and better bond the aggregate skeleton together.
4. Compared to the mix without sand, the addition of a small amount of sand increased both the permeability and strength. The reason for the increase in permeability was the suitable ball-bearing effect to push apart the coarse aggregate and form a continuous flow channel, and the reason for the increase in strength was the filling effect without excessively weakening the bond between the cementitious paste and aggregate skeleton. The optimum sand ratio to achieve the highest vertical permeability and strength was 0.05.
5. With the optimum sand ratio of 0.05, the ACPC owned concurrently satisfactory permeability (permeability coefficient $\geq$ grade K2) and acceptable strength (compressive strength $\geq$ 5 MPa).

This study can advance the state of the art of ACPC, which is of significant use in construction practice where the production of pervious concrete by conventional methods is difficult or less economical.

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