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Roles of mortar volume in porosity, permeability and strength of pervious concrete

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Abstract

Pervious concrete is designed to be porous to allow permeation of water and air for combating the environmental and drainage problems arising from urbanization. However, despite extensive research, it is still not clear how best to design pervious concrete mixes to achieve good concurrent permeability-strength performance. In a previous study, the authors found that there is a necessity to distinguish between interconnected porosity and open porosity, and between unsubmerged permeability and submerged permeability. In this study, based on the thinking that fine aggregate may be added to reduce the paste volume provided the fine aggregate is fine enough to form a coherent mass with the paste, further research was conducted to develop the mortar type pervious concrete with reduced paste volume and investigate the roles of the mortar volume in porosity, permeability and strength. A new series of concrete mixes with varying mortar volume were tested and the results revealed that the interconnected porosity is the major factor determining the permeability while the open porosity and water/cement ratio are the major factors determining the strength. More importantly, the mortar volume plays a key role in each performance attribute.

Keywords: Concrete mix design, Mortar volume, Paste volume, Permeability, Pervious concrete, Porosity

Introduction

Urbanization augments large areas of impervious ground surface. However, large areas of impervious ground surface could cause many problems, such as the heat island effect, increased surface runoff, and blockage of underground water cycle etc. [1–5]. Pervious concrete, which is designed to be porous to allow permeation of water and air, is being employed to replace the impervious ground pavement so as to combat the above mentioned environmental and drainage problems [6–10]. However, the pervious concrete is required to meet with both high permeability and high strength requirements, which are conflicting with each other because the incorporation of more pores to achieve high permeability would reduce strength whereas the incorporation of fewer pores to achieve high strength would reduce permeability. Up to now, it remains a difficult task to achieve both high permeability and high strength at the same time.

It has been found by previous researchers that the most important characteristic of a pervious concrete is its porosity [11–13]. For measurement of porosity, Montes et al. [14] developed a porosity test method for field-obtained cores of pervious concrete based on the Archimedes principle. Deo and Neithalath [15] revealed that there is good correlation between the porosity and the mechanical properties of pervious concrete. Martin III et al. [16] observed that the vertical porosity distribution of pervious concrete has great effects on the permeability. Yu et al. [17] applied 2D and 3D computed tomography to study the pore characteristics of pervious concrete. da Costa et al. [18] showed that by controlling the bulk density of the concrete mix and the compaction

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applied during casting, the porosity of pervious concrete can be manipulated to a certain designed value.

It has also been found by previous researchers that the pore structure has direct effect on the permeability and that clogging has certain adverse effect on the permeability [19–23]. Pieralisi et al. [24] proposed an integrated model, which combines discrete element modeling and computational fluid dynamics, to analyze the permeability of pervious concrete. Zhang et al. [25] applied 3D computed tomography to reveal the seepage flow in pervious concrete. Hatanaka et al. [26] developed a nonlinear permeability model for pervious concrete and proved that the use of pervious concrete pavement can reduce and delay the peak runoff of heavy rain. Zhang et al. [27] compared the advantages and disadvantages of the constant-head and falling-head permeability test methods. Ong et al. [28] studied the effect of pore network characteristics on the permeability and concluded that the non-Darcy permeability coefficient is governed mainly by the effective porosity, mean effective pore volume and throat area. Shan et al. [29] reported that the effect of sediment clogging on the permeability of pervious asphalt concrete is influenced mainly by the porosity level of the asphalt concrete and the particle size and gradation of the sediment.

Since pervious concrete tends to have lower strength than solid concrete, some researchers focused on the strength enhancement of pervious concrete [30–33]. However, this is not at all easy even at the expense of high additional cost. For instance, López-Carrasquillo and Hwang [34] tried the addition of nano-materials, such as nano-SiO_2 and nano-Fe, and did achieve higher compressive strength and abrasion resistance, but the cost of production also became quite high. Adil et al. [35] tried the addition of silica fume and found that silica fume has similar effects. Liu et al. [36] used a silane polymer emulsion treatment method to increase the strength of recycled aggregate pervious concrete while maintaining the permeability. Wang et al. [37] added steel slag as partial substitute of natural aggregate to enhance the mechanical properties. Shen et al. [38] demonstrated that the use of an ultra-high performance paste is an effective way to enhance the strength of pervious concrete.

Overall, the authors are of the view that to develop a pervious concrete with both high permeability and high strength, more fundamental research is still needed to improve our understanding of how the porosity would affect the permeability and strength, and what the optimum porosity for balancing the permeability and strength performance should be. In a previous study, the authors' research team [39] found that there is a necessity to distinguish between interconnected porosity and open porosity, and between unsubmerged permeability and submerged permeability, which actually have different effects on the various performance attributes. Particularly, only interconnected pores which form flow paths to allow quick permeation of water through the concrete contribute to permeability, and the submerged permeability is generally larger than the unsubmerged permeability. Without such refinement of the definitions of porosity and permeability, our research would remain empirical and mix proportions design of pervious concrete would remain just by tedious trials.

The authors are also of the view that there is still lack of a systematic mix proportions design method for pervious concrete. Traditionally, pervious concrete is often designed as a no-fine concrete with no fine aggregate added such that there are unfilled voids in the concrete giving rise to a certain degree of porosity for achieving high permeability. Such no-fine concrete is effectively a bulk volume of coarse aggregate particles bonded together by just cementitious paste (cementitious materials + water). However, it has been found in the previous study [39] that to limit the degree of porosity so as to achieve a reasonable strength, the paste volume has to be at least 25% but with a paste volume > 25%, there is a tendency for the paste to drip downwards causing some of the pores at the bottom to be clogged. The traditional pervious concrete, designed as a no-fine concrete, which comprises of only paste and coarse aggregate, is herein called "paste type pervious concrete".

Herein, it is advocated that the no-fine concrete approach is not a good way of producing pervious concrete. Some fine aggregate may be added to replace an equal volume of cementitious paste without changing the mix proportions of the cementitious paste so as to reduce the cementitious materials content. Provided the fine aggregate is fine enough to form a coherent mass with the paste, say, finer than the 1.18 mm sieve based on the authors' hands-on experience, this would effectively convert the cementitious paste to a mortar (cementitious paste + fine aggregate) with the same volume. Such pervious concrete with fine aggregate added to replace part of the paste is effectively a bulk volume of coarse aggregate bonded together by mortar. It is herein called "mortar type pervious concrete" to distinguish it from the paste type pervious concrete. Such mortar type pervious concrete has lower cementitious materials content and thus would have lower cost and lower carbon footprint. To develop the above proposed mortar type pervious concrete, a new series of concrete mixes designed as mortar type pervious concrete with the mortar volume varying from 15% to 40% and the water/cement ratio varying from 0.25 to 0.40 were tested, as reported herein.

Experimental program

Mix proportions and raw materials

Totally 24 pervious concrete mixes were produced for testing. These concrete mixes were designed to have varying mortar volume (MV) and water/cement ratio by mass (W/C ratio). The MV, i.e. the volume of (fine aggregate + cement + water), expressed as a percentage of the concrete volume, was set at 15%, 20%, 25%, 30%, 35% or 40%. Meanwhile, the W/C ratio was varied among 0.25, 0.30, 0.35 and 0.40. On the other hand, the fine aggregate/cement ratio by mass was fixed at 1.0, while the superplasticizer dosage (liquid mass of superplasticizer as a percentage by mass of cement content) was set at 0.6%. For identification, each concrete mix was given a mix no. of A-B, in which A is the MV (%) and B is the W/C ratio, as listed in the first column of Table 1, where the paste volume (PV), i.e. the volume of (cement + water), expressed as a percentage of the concrete volume, and the mix proportions of the 24 concrete mixes produced are given. Comparing the MV and the PV in the table, it can be seen that with fine aggregate added to replace part of the paste, the PV was substantially smaller than the MV.

The raw materials used include cement, fine aggregate, coarse aggregate and superplasticizer. The cement used was a high-early-strength Portland cement of grade P·O 42.5R [40] with a relative density of 3.08. The fine aggregate used was river sand sieved to have the portion coarser than 1.18 mm removed so that the fine aggregate has a maximum particle size of 1.18 mm. The maximum particle size of the fine aggregate was limited at 1.18 mm because based on the authors' hands-on experience, a fine aggregate with such a small particle size would intermix well with the paste to form a coherent mass for filling into voids. On the other hand, the coarse aggregate used was crushed granite rock with a maximum particle size of 10.0 mm. The particle size distributions of the cement and fine aggregate are plotted in Fig. 1, and the properties of the fine and coarse aggregates are presented in Table 2. Lastly, the superplasticizer used was a polycarboxylate-type superplasticizer with a relative density of 1.03 and a solid mass content of 20% [41–45].

Mixing and casting procedures

The mixing of the pervious concrete mixes was executed in accordance with the Chinese Specification CJJ/T 135–2009 [46], which stipulates the following procedures: (1) add the aggregates, admixture and one half of the water

Table 1 Mix proportions of concrete mixes tested

Mix no.	Mortar volume (%)	Paste volume (%)	Water (kg/m^3)	Cement (kg/m^3)	Fine aggregate (kg/m^3)
15–0.25	15.0	9.1	39.4	158	158
15–0.30	15.0	9.4	45.0	150	150
15–0.35	15.0	9.6	50.0	143	143
15–0.40	15.0	9.9	54.5	136	136
20–0.25	20.0	12.1	52.6	210	210
20–0.30	20.0	12.5	60.0	200	200
20–0.35	20.0	12.8	66.6	190	190
20–0.40	20.0	13.2	72.7	182	182
25–0.25	25.0	15.1	65.7	263	263
25–0.30	25.0	15.6	75.0	250	250
25–0.35	25.0	16.1	83.3	238	238
25–0.40	25.0	16.5	90.9	227	227
30–0.25	30.0	18.1	78.9	316	316
30–0.30	30.0	18.7	89.9	300	300
30–0.35	30.0	19.3	99.9	286	286
30–0.40	30.0	19.8	109.0	273	273
35–0.25	35.0	21.2	92.0	368	368
35–0.30	35.0	21.9	104.9	350	350
35–0.35	35.0	22.5	116.6	333	333
35–0.40	35.0	23.0	127.2	318	318
40–0.25	40.0	24.2	105.2	421	421
40–0.30	40.0	25.0	119.9	400	400
40–0.35	40.0	25.7	133.3	381	381
40–0.40	40.0	26.3	145.4	363	363

Note: The coarse aggregate content was fixed at 1595 kg/m^3

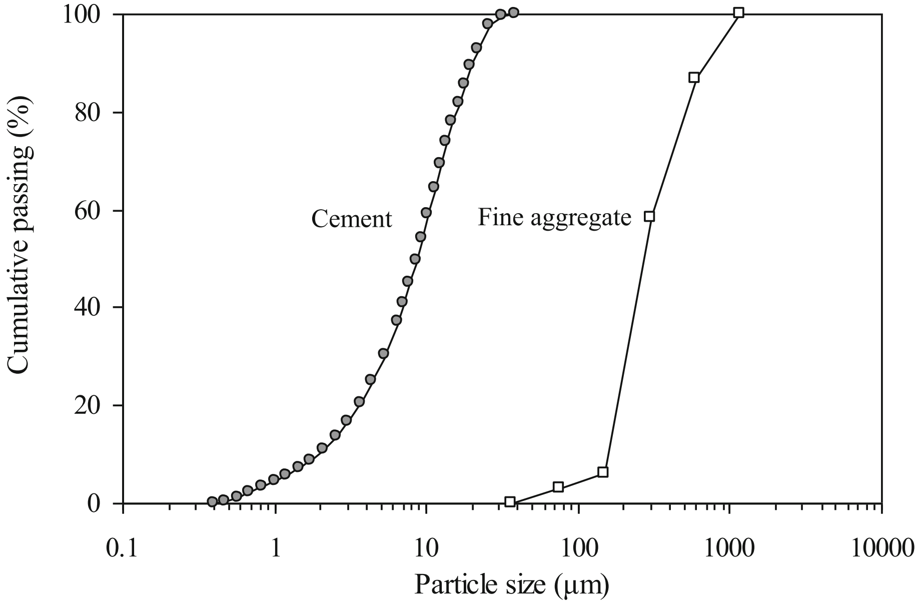


Fig. 1 Particle size distributions of cement and fine aggregate

into a mixer and mix for 30 s; (2) add all the cement into the mixer and mix for 40 s; and (3) add the other half of the water into the mixer and mix for 50 s. However, after mixing in accordance with above procedures during preliminary trial testing, it was found necessary to continue mixing so as to improve the uniformity and cohesiveness of the mortar portion in the concrete mix, especially when the W/C ratio was relatively low and the concrete mix appeared dry. Eventually, all the concrete mixes, after mixing in accordance with above procedures, were mixed for a further 10 s. As a result, the total mixing time was increased to 30 s + 40 s + 60 s = 130 s.

After mixing, the pervious concrete mixes were placed into steel cube moulds for casting. The casting procedure was different from that for normal concrete mixes. During casting of the pervious concrete mixes, no vibration was applied to avoid dripping of the mortar portion to the bottom, which could cause uneven distribution of the mortar portion and in the worst cast even clogging of some of the pores near the bottom. Instead, the pervious concrete mix was overfilled to each steel cube mould, and then compacted by pressing and rolling a heavy metal roller longer than the width of the mould along the top surface of the mould to simulate the surface pressing during actual construction on site.

From each batch of concrete mix, five 150 mm cubes were cast for porosity test, water permeability test and 28-day cube strength test. On completion of casting, the concrete cubes were covered with plastic sheets, stored in the laboratory, demoulded at the age of 1 day and then cured in a curing room with temperature controlled at 20 ± 2 °C and humidity controlled at higher than 90% until the age of 28 days.

Testing methods

The testing methods used to measure the porosity, permeability and strength were the same as those employed in the previous study [39]. As details of the testing methods have been presented before, only brief descriptions are given below.

Regarding the testing of porosity, the interconnected porosity and open porosity were separately measured. This was because in concrete, the pores fall into two types, namely, the open pores and the closed pores. The open pores are those connected to the outside surfaces, and the closed pores are those not connected to the outside surfaces. Only the open pores would allow quick ingress of water into the concrete, and among the open pores, only the interconnected pores would allow quick permeation of water through the concrete to impart

Table 2 Properties of fine and coarse aggregates

Aggregate type	Maximum particle size (mm)	Saturated density (kg/m^3)	Moisture content (%)	Water absorption (%)
Fine aggregate	1.18	2660	0.04	1.10
Coarse aggregate	10.0	2690	0.08	0.40

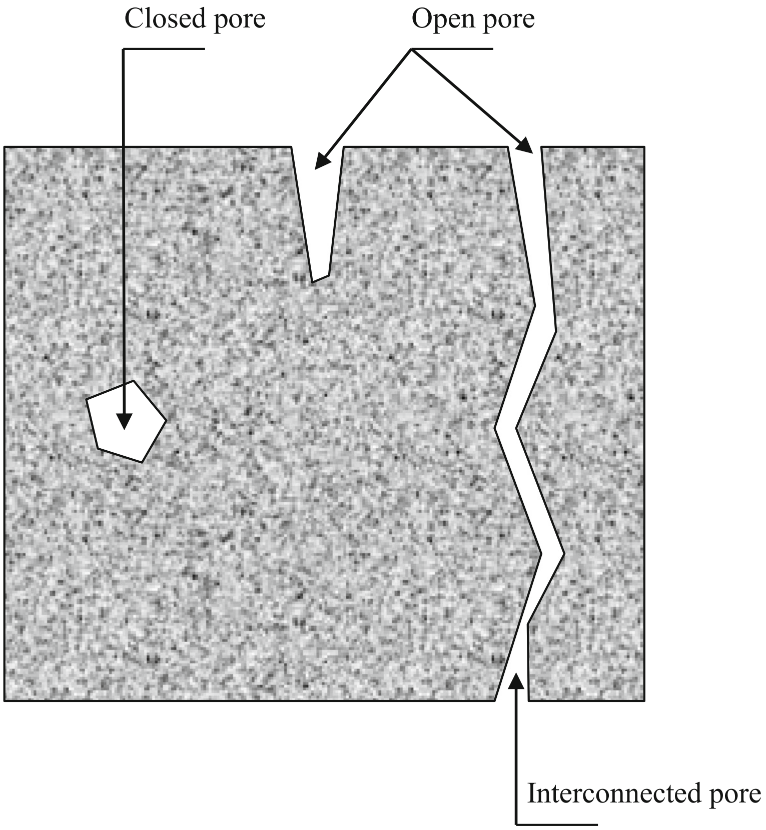


Fig. 2 Schematic diagram of pores

permeability, as illustrated in Fig. 2. To measure the porosity, the cube specimen was first sealed at the four side surfaces, and then weighed in air and in water to determine the volume of water penetrated into the cube specimen through the pores, as shown in Fig. 3. The weight in water was measured twice, once after the cube specimen was immersed in water for 30 s and then again after the cube specimen was immersed in water for 24 h. From the weight in air and the weight in water after 30 s of immersion, the interconnected porosity was determined as the volume of interconnected pores expressed as a percentage of concrete volume, and from the weight in air and the weight in water after 24 h of immersion, the open porosity was determined as the volume of open pores expressed as a percentage of concrete volume. It is envisaged that the interconnected porosity has greater effect on the water permeability whereas the open porosity has greater effect on the strength. Their separate measurement would allow more in-depth analysis of their different effects.

Regarding the testing of water permeability, the unsubmerged permeability coefficient of the cube specimen was measured with a constant water head of 300 mm applied under unsubmerged condition, whereas the submerged permeability coefficient of the cube specimen was measured with a constant water head of 150 mm applied under submerged condition, as shown in Fig. 4. After the test, the unsubmerged and submerged permeability coefficients were calculated according to Darcy's law, as recommended by Chandrappa and Biligiri [47]. The unsubmerged and submerged permeability coefficients so determined were not the same, with the submerged permeability coefficient being generally higher.

Regarding the testing of strength, three cube specimens cast from the same batch of concrete were tested after curing up to the age of 28 days. A 2000 kN compression testing machine was used and the testing procedures just followed the standard practice. The mean value of the cube strength results of the three cubes tested was taken as the 28-day cube compressive strength of the concrete.

Results and general discussions

Porosity

The interconnected and open porosity results are tabulated in Table 3. Comparing the interconnected porosity and the respective open porosity of each concrete mix, it is obvious that the open porosity was always higher than the respective interconnected porosity. To study how the MV and W/C ratio influenced the interconnected/

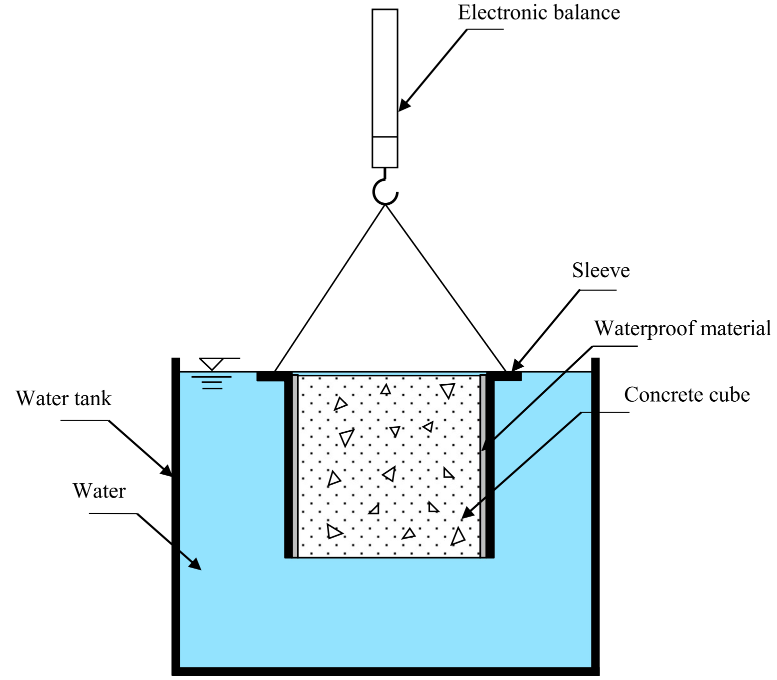


Fig. 3 Schematic diagram of porosity test

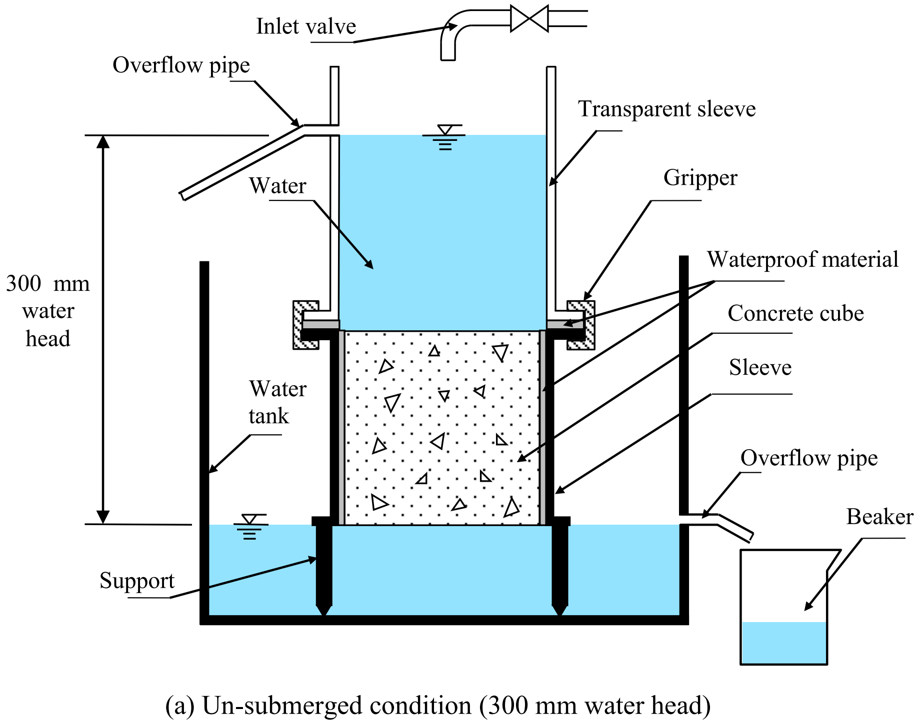
open porosities, Figs. 5 and 6 are drawn to depict the variations of the interconnected/open porosities with the MV and W/C ratio. It is noted that within the ranges of parameters covered in this study, at a fixed W/C ratio, both the interconnected porosity and open porosity gradually decreased as the MV increased from 15% to 40%. This phenomenon is reasonable because a larger MV filled into the voids between coarse aggregate particles would reduce the amount of unfilled voids in the pervious concrete. On the other hand, within the ranges of parameters covered in this study, at a fixed MV, both the interconnected porosity and open porosity were generally higher at a lower W/C ratio. The reason for this phenomenon is not exactly known, but as such variations of the interconnected/open porosities have significant effects on the permeability and strength performance, further research to study this phenomenon is recommended.

Permeability

The unsubmerged and submerge permeability results are listed in Table 4. Within the ranges of parameters covered in this study, the unsubmerged permeability coefficient varied within the range of 12.57 to 0.00 mm/s, whereas the submerged permeability coefficient varied within the range of 16.85 to 0.00 mm/s. Generally, the submerged permeability coefficient was higher than the respective unsubmerged permeability coefficient. This phenomenon is reasonable because under unsubmerged condition, the water channels were not fully filled, while under submerged condition, the water channels were fully filled. To study how the MV and W/C ratio affected the unsubmerged/submerged permeability coefficients, Figs. 7 and 8 are drawn to show the variations of the unsubmerged and submerged permeability coefficients with the MV and W/C ratio. It is evident that within the ranges of parameters covered in this study, at the same W/C ratio, both the unsubmerged/submerged permeability coefficients gradually decreased to zero as the MV increased from 15% to 40%. On the other hand, at the same MV, both the unsubmerged and submerged permeability coefficients were generally higher at a lower W/C ratio. This was because the interconnected porosity had similar variation with the W/C ratio and the permeability was directly related to the interconnected porosity.

Strength

The cube strength results are tabulated in Table 4 and plotted against the MV for different W/C ratios in Fig. 9. As expected, within the ranges of parameters covered in this study, the cube strength increased with the increase of MV. The reason is that as the MV increased, the volume of unfilled voids decreased thus alleviating the adverse effect of the voids on the strength [48–50]. However, within the ranges of parameters covered in this study, at the same MV, the cube strength first increased as the W/C ratio increased from 0.25 to 0.35 but



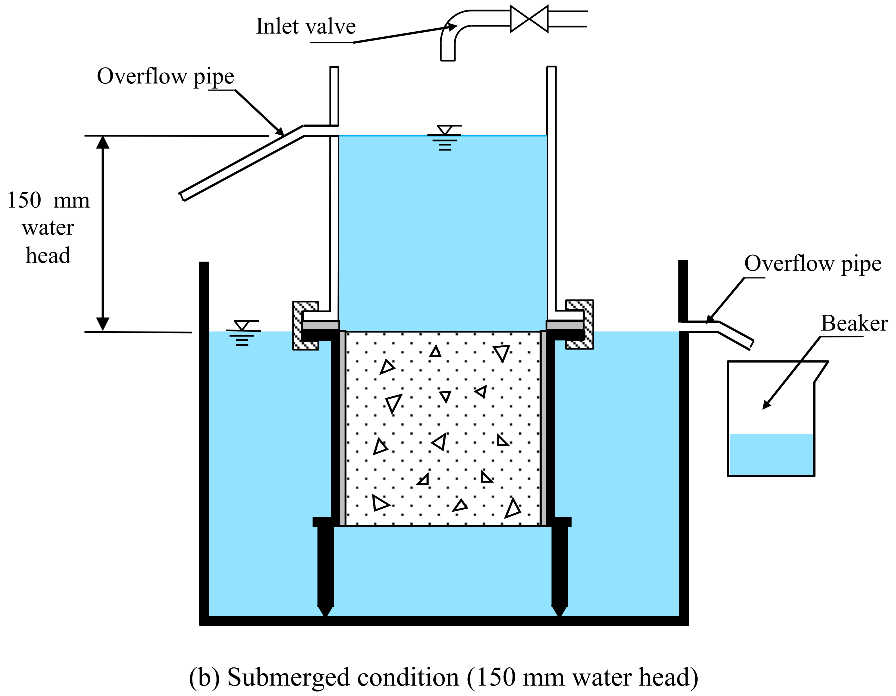


Fig. 4 Schematic diagram of water permeability test

thereafter decreased as the W/C ratio further increased to 0.40. Hence, there was an optimum W/C ratio of 0.35 at which the highest cube strength occurred. As observed during casting, the low strength at W/C ratio < 0.35 was caused by the excessive dryness of the concrete mix (see the water contents at W/C ratio < 0.35 in Table 1), which rendered the pervious concrete very difficult to cast and particularly porous. The excessive dryness might have also rendered the mortar portion of the concrete mix to be only loosely adhered to and thus weakly bonded to the coarse aggregate particles. On the other hand, the decrease of strength as the W/C ratio increased to higher than 0.35 was normal because a higher W/C ratio at W/C ratio > 0.35 would in general yield a lower concrete strength [51–53].

Table 3 Test results I

Mix no.	Interconnected porosity (%)		Open porosity (%)	
	Mean	Std. deviation	Mean	Std. deviation
15–0.25	29.8	1.64	30.0	0.98
15–0.30	29.5	2.09	29.7	1.23
15–0.35	28.7	1.40	29.6	1.33
15–0.40	28.6	1.79	29.5	1.05
20–0.25	27.0	0.82	27.9	1.34
20–0.30	25.9	1.47	26.2	0.74
20–0.35	24.7	1.31	25.4	1.16
20–0.40	24.3	1.34	24.8	0.94
25–0.25	21.1	0.67	22.7	1.11
25–0.30	18.2	1.26	19.4	0.93
25–0.35	18.0	1.11	19.3	0.78
25–0.40	14.1	0.67	16.0	0.62
30–0.25	15.4	0.41	18.0	0.90
30–0.30	12.6	0.92	12.8	0.66
30–0.35	10.0	0.62	10.7	0.45
30–0.40	6.4	0.39	9.4	0.22
35–0.25	6.2	0.40	8.9	0.41
35–0.30	4.9	0.31	6.3	0.29
35–0.35	3.4	0.22	4.5	0.22
35–0.40	0.0	0.00	3.0	0.25
40–0.25	0.0	0.00	4.9	0.36
40–0.30	0.0	0.00	1.9	0.21
40–0.35	0.0	0.00	1.8	0.08
40–0.40	0.0	0.00	1.2	0.09

Effects of porosity

Effects of interconnected porosity on permeability

In a previous concrete, since the water permeates only through the interconnected pores, it is envisaged that the water permeability is more related to the interconnected porosity, rather than the open porosity. For the purpose of evaluating how the interconnected porosity influences the unsubmerged and submerged permeability coefficients, Figs. 10 and 11 are drawn to reveal the variations of the permeability coefficients with the interconnected porosity. It is seen that as the interconnected porosity increased, both the unsubmerged and submerged permeability coefficients steadily increased. More importantly, the data points in each figure lie closely to a certain curve indicating that there is a well-defined relation between the unsubmerged/submerged permeability coefficients and the interconnected porosity. Regression analysis of the data in the two figures has been carried out, and the best-fit curves and the corresponding equations so obtained are shown directly in the figures. Very high R^2 values of 0.987 and 0.993 were achieved, showing that the interconnected porosity is a key factor determining the water permeability of pervious concrete.

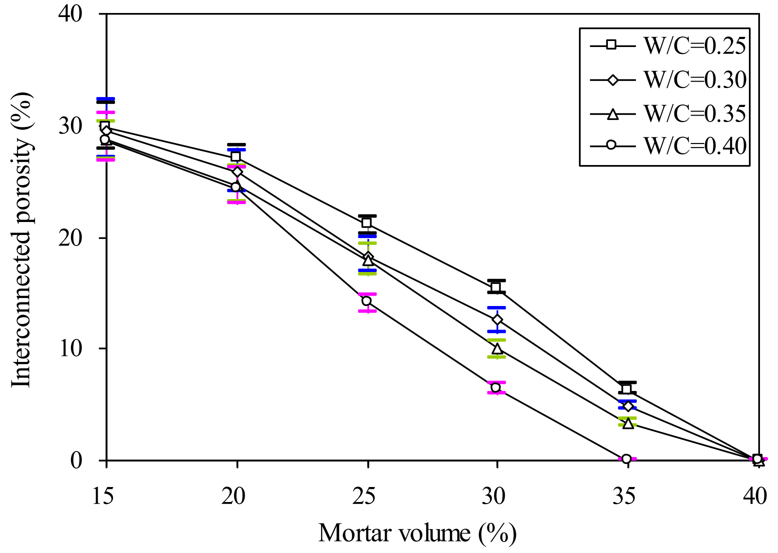


Fig. 5 Interconnected porosity versus mortar volume for different W/C ratios

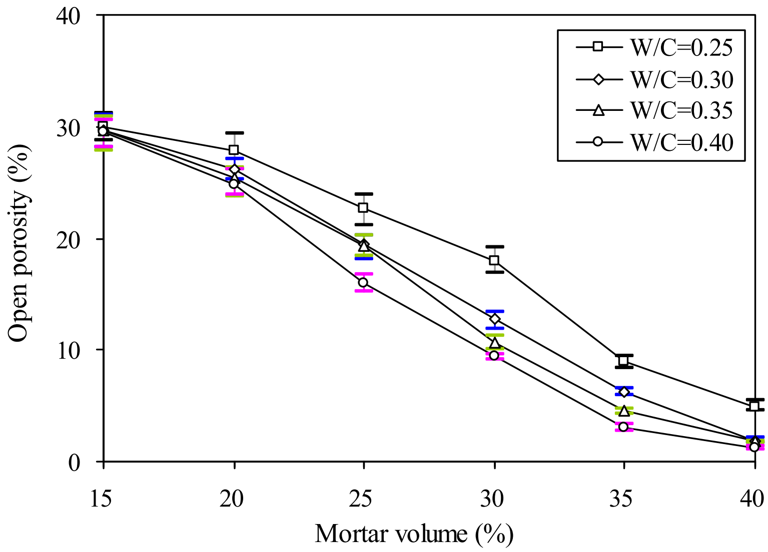


Fig. 6 Open porosity versus mortar volume for different W/C ratios

Table 4 Test results II

Mix no.	Unsubmerged permeability coefficient (mm/s)		Submerged permeability coefficient (mm/s)		Cube strength (MPa)	
	Mean	**Std. deviation**	**Mean**	**Std. deviation**	**Mean**	**Std. deviation**
15–0.25	12.57	0.32	16.85	0.66	10.2	0.43
15–0.30	12.25	0.33	16.55	0.66	12.4	0.39
15–0.35	12.19	0.19	16.32	0.33	12.7	0.59
15–0.40	12.05	0.24	16.24	0.41	12.5	0.14
20–0.25	10.77	0.59	12.21	0.39	12.5	0.37
20–0.30	9.74	0.23	11.50	0.32	17.1	0.43
20–0.35	9.34	0.09	11.32	0.22	21.0	0.50
20–0.40	7.67	0.21	10.21	0.17	20.2	0.66
25–0.25	7.85	0.15	9.45	0.23	19.8	0.73
25–0.30	4.55	0.33	5.38	0.20	25.7	0.98
25–0.35	3.66	0.15	5.21	0.16	26.9	0.75
25–0.40	1.86	0.08	2.72	0.14	23.9	0.60
30–0.25	1.52	0.07	1.88	0.10	25.9	0.69
30–0.30	1.02	0.02	1.62	0.06	31.5	0.73
30–0.35	0.79	0.03	1.23	0.04	39.1	0.70
30–0.40	0.41	0.02	0.47	0.03	37.1	0.75
35–0.25	0.51	0.02	0.79	0.06	38.4	1.08
35–0.30	0.49	0.02	0.75	0.03	46.2	0.64
35–0.35	0.48	0.02	0.70	0.02	50.8	0.45
35–0.40	0.00	0.00	0.00	0.00	47.8	0.91
40–0.25	0.00	0.00	0.00	0.00	51.8	1.24
40–0.30	0.00	0.00	0.00	0.00	59.2	1.44
40–0.35	0.00	0.00	0.00	0.00	71.9	1.44
40–0.40	0.00	0.00	0.00	0.00	64.5	0.92

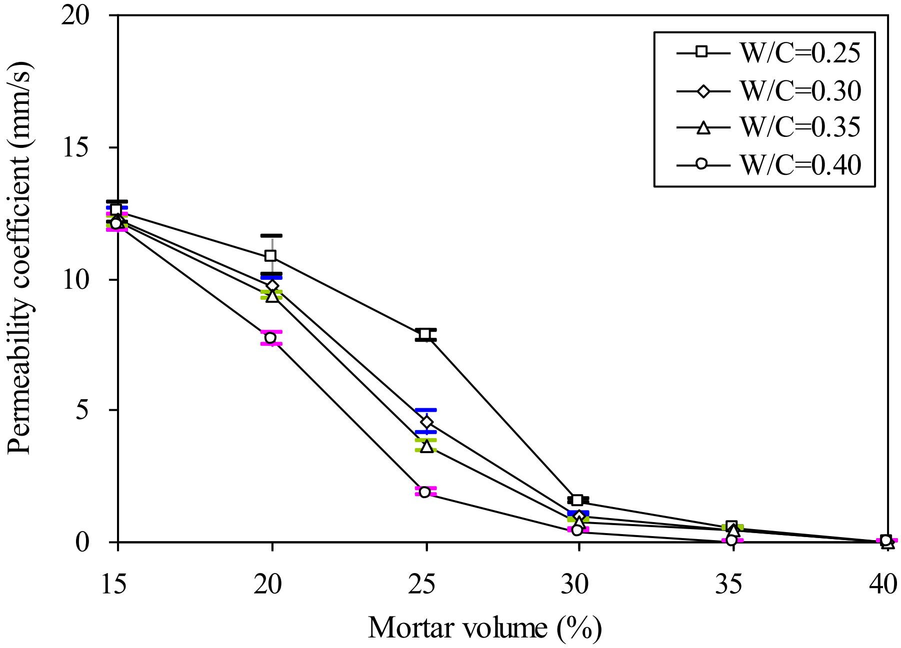


Fig. 7 Unsubmerged permeability coefficient versus mortar volume for different W/C ratios

Effects of open porosity and W/C ratio on strength

There is no doubt that the porosity and W/C ratio have great influences on the strength of all cement-based materials [42, 43, 54]. However, the porosity that governs the strength should be the open porosity, not the interconnected porosity, because both the interconnected pores and the unconnected pores, or in other words, all the pores regardless of whether they are interconnected or not, have certain effects on the strength. For the purpose of evaluating how the open porosity and W/C ratio influence the cube strength, Fig. 12 is drawn to correlate the cube strength to the open porosity and W/C ratio. It is observed that when the open porosity increased, the cube strength gradually decreased. On the other hand, the cube strength changed with the W/C ratio in a manner that the W/C ratio of 0.35 was optimum and either

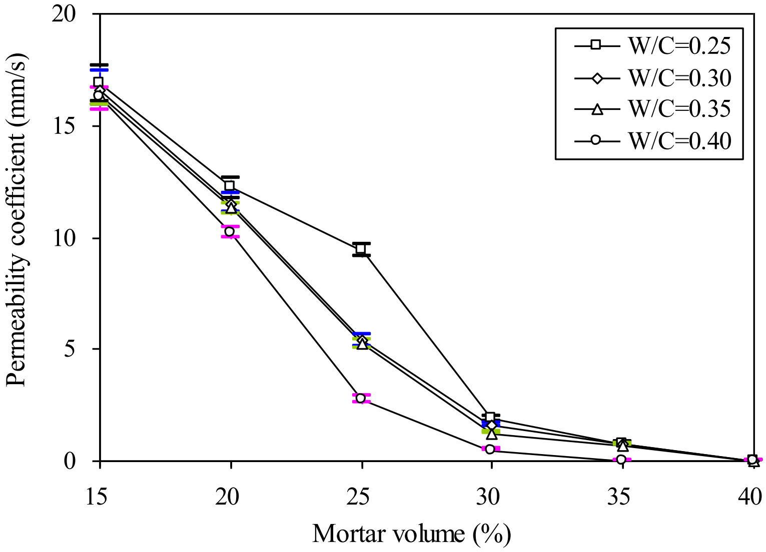


Fig. 8 Submerged permeability coefficient versus mortar volume for different W/C ratios

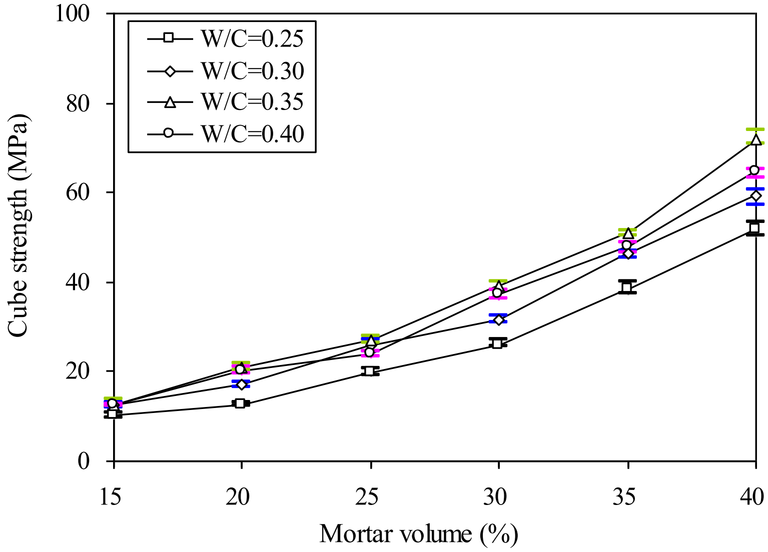


Fig. 9 Cube strength versus mortar volume for different W/C ratios

decreasing the W/C ratio or increasing the W/C ratio would cause the cube strength to decrease. The data in the figure has been analysed by multi-variable regression analysis, and the best-fit curves and the corresponding equations are shown directly in the Fig. A fairly high R^2 value of 0.938 was obtained, indicating that the open porosity and W/C ratio are together the key factors determining the cube strength of pervious concrete.

Role of mortar volume in overall performance

In paste type pervious concrete, the paste fills into the voids between coarse aggregate particle and the PV determines the amount of unfilled voids in the bulk volume of coarse aggregate. Hence, the PV has direct effect on the porosity, which then governs the permeability and strength performance of the pervious concrete. In the previous study [39], it was found that a lower PV would lead to higher permeability but lower strength, whereas a higher PV would lead to lower permeability but higher strength. Balancing the permeability and strength requirements, a PV of around 25% would give the best overall performance. Hence, the PV plays a key role in the performance of paste type pervious concrete and therefore is the first mix parameter to be determined in the concrete mix design.

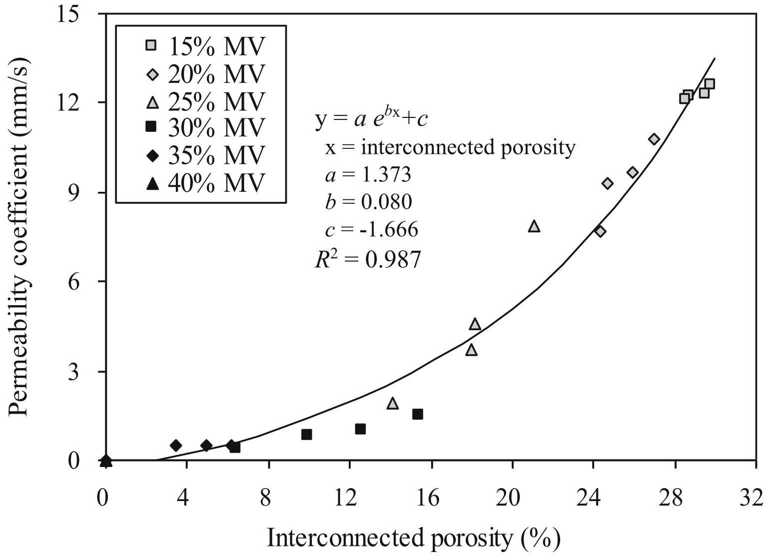


Fig. 10 Effect of interconnected porosity on unsubmerged permeability coefficient

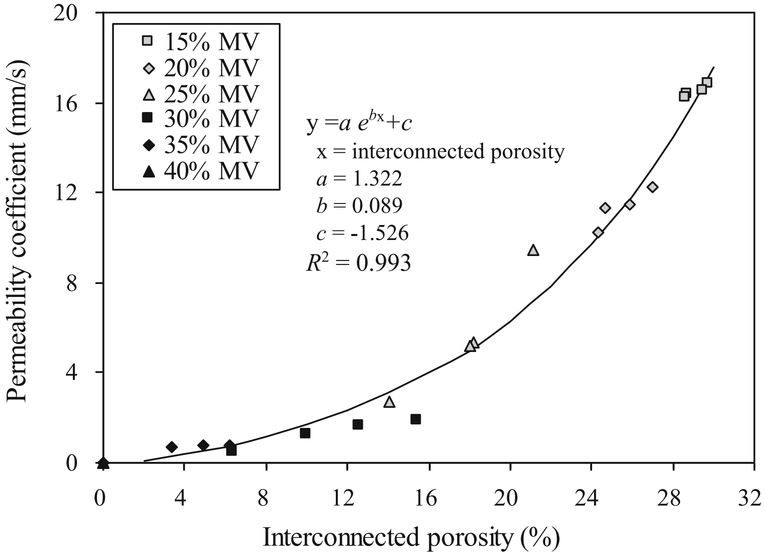


Fig. 11 Effect of interconnected porosity on submerged permeability coefficient

In mortar type pervious concrete, the mortar fills into the voids between coarse aggregate particle and the MV determines the amount of unfilled voids in the bulk volume of coarse aggregate. Hence, the MV has direct effect on the porosity, which then governs the permeability and strength performance of the pervious concrete. For this reason, it is envisaged that in mortar type pervious concrete, the MV should have great effects on the permeability and strength performance and therefore should be playing a key role in the concurrent permeability-strength performance. To study the role of the MV in the overall performance of mortar type pervious concrete, the concurrent unsubmerged permeability - strength performance and the concurrent submerged permeability - strength performance of the concrete mixes are plotted in Fig. 13(a) and (b), respectively. In these two figures, each curve plotted is for one MV value. In other words, each curve shows the concurrent permeability and strength that can be achieved at the MV value of the curve.

Firstly, it is seen that each curve has a peak giving the maximum cube strength. Somehow, all the peaks occur at W/C ratio = 0.35, regardless of the MV. These peaks may also be taken as the optimum combinations of PV

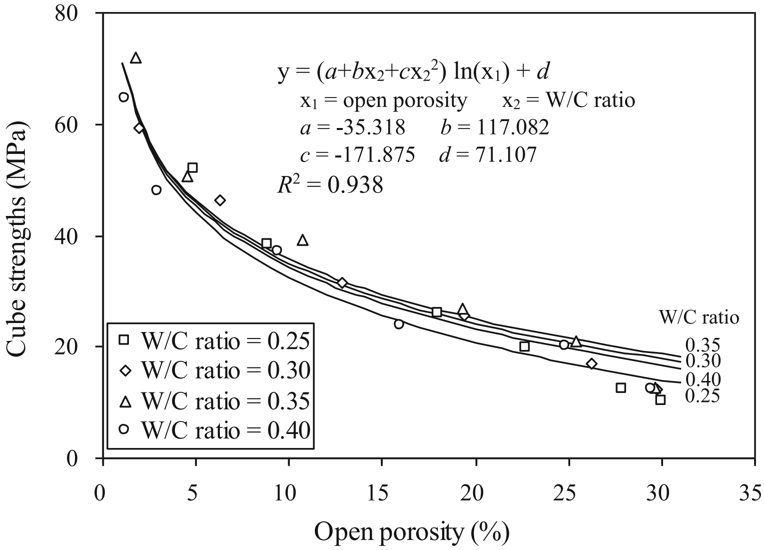


Fig. 12 Combined effects of open porosity and W/C ratio on cube strength

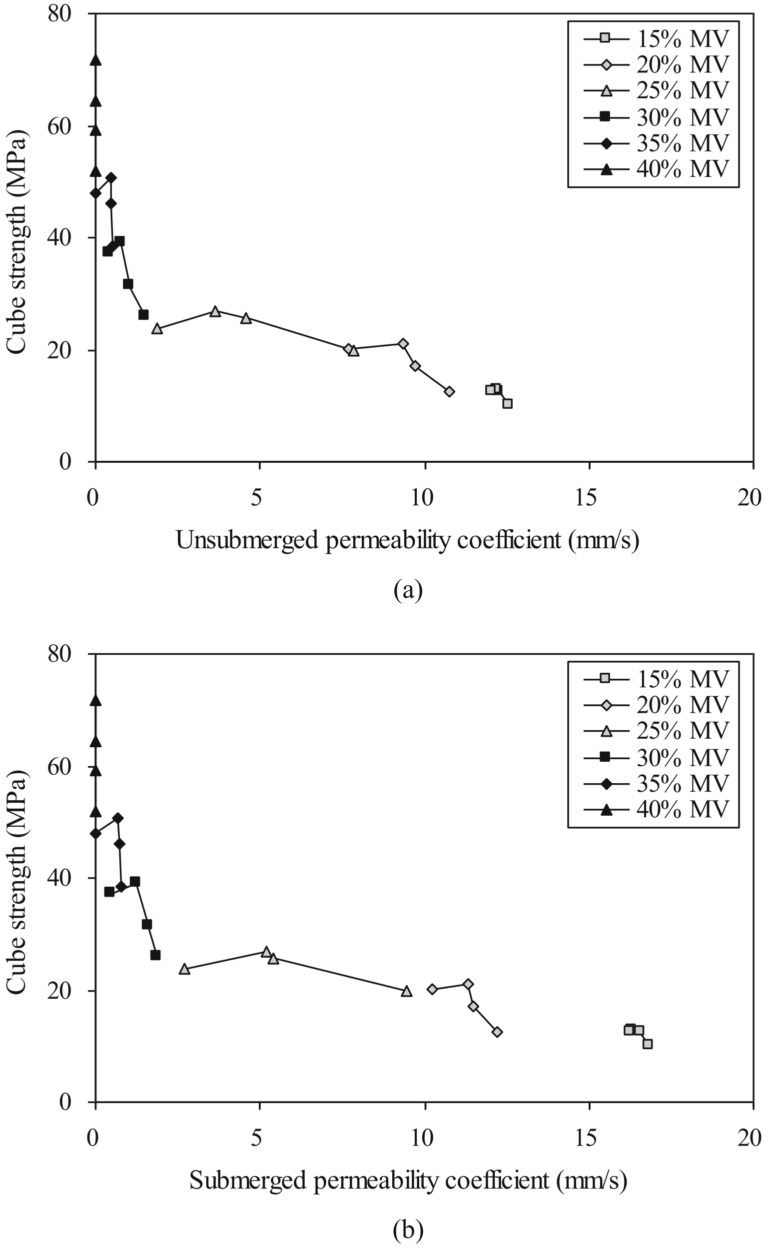


Fig. 13 Concurrent permeability-strength performance at different mortar volumes

and W/C ratio giving the best permeability - strength performance. Secondly, it is noted that at MV > 25%, it is not possible to obtain an unsubmerged permeability coefficient ≥ 1.9 mm/s or a submerged permeability coefficient ≥ 2.7 mm/s. On the other hand, at MV < 25%, it is not possible to achieve a cube strength ≥27 MPa. To strike a balance between the permeability and strength requirements, it is suggested to set the MV as 25% and the W/C ratio as 0.35, which together would give an unsubmerged permeability coefficient of 3.66 mm/s, a submerged permeability coefficient of 5.21 mm/s, and a cube strength of 26.9 MPa. While interpreting the above results, it should be noted that all the above permeability coefficients have exceeded the minimum required submerged permeability coefficient of 0.5 mm/s stipulated in the Chinese Specification CJJ/T 135–2009 [46].

From the above results, it is evident that the MV plays a key role in the overall performance of mortar type pervious concrete as for the PV which plays a key role in the overall performance of paste type pervious concrete. Coincidentally, whilst the optimum PV for best overall performance of paste type pervious concrete is around 25%, the optimum MV for best overall performance of mortar type pervious concrete is also around 25%.

Suggested improvements

For the design of mortar type pervious concrete, it is not enough to just set the MV within a small range close to 25%, although this MV should give a good overall permeability - strength performance. There are other mix parameters, such as the W/C ratio, the fine aggregate/cement ratio and the superplasticizer dosage, to be considered too. From this study, the optimum W/C ratio that gives the maximum strength appears to be 0.35. However, the relatively low strength at W/C ratio < 0.35 obtained in this study was actually caused by the excessive dryness of the concrete mix, which rendered the concrete very difficult to cast and might have weakened the bond between the mortar and the coarse aggregate particles. The excessive dryness problem was partly due to the excessive reduction of the PV after adding fine aggregate leading to a very low water content (see the low water contents in Table 1), and partly due to the use of a rather low superplasticizer dosage of only 0.6% leading to unsatisfactory wetness of the mortar portion of the concrete mix.

To mitigate this excessive dryness problem, it is suggested to adjust the fine aggregate/cement ratio downwards from 1.0 to say 0.8 or 0.6 and adjust the superplasticizer dosage upwards from 0.6% to say 1.0% when the W/C ratio is lower than 0.35 so that the mortar portion of the concrete mix is more cohesive and would adhere to the coarse aggregate particles better to improve the bond. Subject to confirmation by trial concrete mixing, such adjustments to the concrete mix should increase the strength at W/C < 0.35 and decrease the optimum W/C ratio for maximum strength to 0.30 or even 0.25. The mixing procedures and the mixing time should also be reviewed. It is suggested to mix the mortar portion of the concrete mix first until the mortar portion becomes a coherent mass before adding the coarse aggregate for final mixing, and extend the total mixing time to at least 150 s.

Conclusions

For the purpose of developing a new mortar type pervious concrete, which has fine aggregate finer than 1.18 mm added to replace part of the paste volume (PV) so as to reduce the cementitious materials content, reduce the cost and reduce the carbon footprint, a series of pervious concrete mixes with varying mortar volume (MV) and W/C ratio were tested for their interconnected porosity, open porosity, unsubmerged permeability, submerged permeability and 28-day cube compressive strength. Based on the test results, the following conclusions are drawn:

(1) The interconnected porosity is lower than the open porosity, whereas the unsubmerged permeability is lower than the submerged permeability.

(2) The MV and W/C ratio, being the key concrete mix parameters, have major effects on the interconnected porosity, open porosity, unsubmerged permeability, submerged permeability and cube strength.

(3) Correlations of the unsubmerged/submerged permeability coefficients to the interconnected porosity by regression analysis yielded very high R^2 values, indicating that the interconnected porosity is the key factor governing the water permeability.

(4) Correlation of the cube strength to the open porosity and W/C ratio by regression analysis yielded a fairly high R^2 value, proving that the open porosity and W/C ratio are the key factors governing the cube strength.

(5) For the series of pervious concrete mixes tested, the best permeability - strength performance occurs at MV = 25% and W/C ratio = 0.35, which together give an unsubmerged permeability coefficient of 3.66 mm/s, a submerged permeability coefficient of 5.21 mm/s and a cube strength of 26.9 MPa.

(6) The MV plays a key role in the performance of mortar type pervious concrete as for the PV which plays a key role in the performance of paste type pervious concrete. Whilst the optimum PV in paste type pervious concrete is around 25%, the optimum MV in mortar type pervious concrete is also around 25%.

(7) At W/C ratio < 0.35, the water content may become too low causing an excessive dryness problem, which could adversely affect the strength. To mitigate this problem, it is suggested to decrease the fine aggregate/cement ratio, increase the superplasticizer dosage and extend the mixing time.

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Authors' contributions

L.G. Li: planning, supervision of students and drafting of manuscript; J.J. Feng: completing experiments; B.F. Xiao: data analysis; S.H. Chu: drafting of manuscript; A.K.H. Kwan: advising and drafting of manuscript. All authors read and approved the final manuscript.

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Availability of data and materials

All data have been presented in the Paper.

Declarations

Ethics approval and consent to participate
Not applicable.

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

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