Experimental Study on Porosity, Permeability and Strength of Pervious Concrete

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Research Article

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Abstract

Pervious concrete, which has pores to allow permeation of water and air, is being used as one of the solutions for combating the problems induced by urbanization. For the purpose of evaluating the main factors affecting the performance attributes of pervious concrete, a total of 24 pervious concrete groups with varied mortar volumes and water/cement ratios were made for porosity, water permeability and cube strength measurements. Based on the test results and regression analysis, it was found that interconnected porosity plays major role in the water permeability, while the open porosity and W/C ratio are together the key factors governing the cube strength.

1. Introduction

Urbanization augments a large amount of impervious ground surfaces. However, overuse of impervious ground surfaces would induce many problems, such as the urban waterlogging, heat island effect, blockage of underground water cycle [1–5]. Pervious concrete, which contains pores to allow permeation of water and air, is being used as one of the solutions for combating the above problems [6–10].

As the most characteristic feature of pervious concrete, porosity has been paid much attention by many scholars [11–13]. 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] found that there is good relation between the porosity and 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 or 3D computed tomography (CT) technology to study the pores characteristics of pervious concrete. da Costa et al. [18] indicated that by controlling bulk density and compaction effort, the porosity of pervious concrete can be designed.

Permeability, describing the ability to transfer water through pores, has also been wildly studied [19–21]. Haselbach et al. (2017) investigated the permeability of sand-clogged pervious concrete pavement system. Pieralisi et al. [23] proposed an integrated model, which combines discrete element modeling and computational fluid dynamics, to assess the permeability of pervious concrete. Hatanaka et al. [24] developed a nonlinear permeability model for pervious concrete and proved that the use of pervious concrete pavement can reduce and delay a peak runoff of heavy rain. Zhang et al. [25] compared the advantages and disadvantages of the constant-head and falling-head permeability measurement methods. Ong et al. [26] pointed out that the increase in non-Darcy permeability coefficient can of pervious concrete is correlated to a higher effective porosity. Shan et al. [27] reported that the particle size and gradation of sediment can significantly affect the lateral permeability of pervious asphalt concrete.

However, the increase of water permeability often leads to the decrease of strength, seeking the way of strength enhancement has become the research direction of many scholars [29–30]. For instance, López-Carrasquillo and Hwang [31] reported that nano-sized silica and iron can improve the compressive strength and abrasion resistance of pervious concrete, while Adil et al. [32] observed that the use of silica fume has similar effects. Liu et al. [33] used silane polymer emulsion treatment method to increase the strength of recycled aggregate pervious concrete while maintaining its permeability. Wang et al. [34] found that steel slag can be applied as natural aggregate substitution to enhance the mechanical properties of pervious concrete. Shen et al. [35] indicated that using ultra-high performance paste is an effective way to promote the strength of pervious concrete.

For the purpose of finding out the main factors affecting the performance attributes of pervious concrete, a series of pervious concrete groups with varied mortar volumes and water/cement ratios were made for porosity, water permeability and cube strength measurements. Based on the test results, regression analysis was carried out.

2. Experimental Details

2.1 Mix proportion and raw materials

Totally 24 pervious concrete groups were produced for testing. For these concrete groups, two mix parameters are mortar volume (MV) and water/cement (W/C) ratio. The MV, i.e. the volume of mortar (fine aggregate + cement + water), as a percentage of the volume of concrete without considering voids, was set at 15%, 20%, 25%, 30%, 35% or 40%. The W/C ratio, i.e. the water to cement ratio by mass, was varied from 0.25 to 0.40 in steps of 0.05. Besides, the cement/fine aggregate ratio by mass for each concrete group was fixed at 1.0, while the water reducer dosage (liquid mass of water reducer as a percentage by mass of cement content) was set at 0.6%. For identification, each concrete group was given a code of A-B, in which A means the MV (%) and B means the W/C ratio, as shown in the first columns of the Table 1.

Table 1
Test results

Mix no.	Interconnected porosity (%)	Open porosity (%)	Un-submerged permeability coefficient (mm/s)	Submerged permeability coefficient (mm/s)	Cube strength (MPa)
15-0.25	29.8	30.0	12.57	16.85	10.2
15 – 0.30	29.5	29.7	12.25	16.55	12.4
15-0.35	28.7	29.6	12.19	16.32	12.7
15 – 0.40	28.6	29.5	12.05	16.24	12.5
20-0.25	27.0	27.9	10.77	12.21	12.5
20 – 0.30	25.9	26.2	9.74	11.50	17.1
20-0.35	24.7	25.4	9.34	11.32	21.0
20 – 0.40	24.3	24.8	7.67	10.21	20.2
25-0.25	21.1	22.7	7.85	9.45	19.8
25 – 0.30	18.2	19.4	4.55	5.38	25.7
25-0.35	18.0	19.3	3.66	5.21	26.9
25 – 0.40	14.1	16.0	1.86	2.72	23.9
30-0.25	15.4	18.0	1.52	1.88	25.9
30 – 0.30	12.6	12.8	1.02	1.62	31.5
30-0.35	10.0	10.7	0.79	1.23	39.1
30 – 0.40	6.4	9.4	0.41	0.47	37.1
35-0.25	6.2	8.9	0.51	0.79	38.4
35 – 0.30	4.9	6.3	0.49	0.75	46.2
35-0.35	3.4	4.5	0.48	0.70	50.8
35 – 0.40	0.0	3.0	0.00	0.00	47.8
40-0.25	0.0	4.9	0.00	0.00	51.8
40 – 0.30	0.0	1.9	0.00	0.00	59.2
40-0.35	0.0	1.8	0.00	0.00	71.9
40 – 0.40	0.0	1.2	0.00	0.00	64.5

The raw materials used include cement, fine aggregate, coarse aggregate and water reducer. The cement used was a high-early-strength ordinary Portland cement (PžO 42.5R) [36] with relative density of 3.08. The fine aggregate used was local river sand and the coarse aggregate applied was crushed granite rock. The particle size distributions of the cement and fine aggregate were shown in Fig. 1, and the properties of the fine and coarse aggregates were listed in the Table 2. The water reducer used was a polycarboxylate-type superplasticizer (SP) with relative density of 1.03 and solid mass content of 20% [37, 38].

Table 2
Properties of fine and coarse aggregates

Aggregate type	Maximum particle size (mm)	Density at saturated surface dry condition (kg/m^3)	Moisture content (%)	Water absorption (%)
Fine aggregate	1.18	2660	0.04	1.10
Coarse aggregate	10	2690	0.08	0.40

2.2 Producing process

The mixing procedure of the previous concrete was followed the Chinese Specification CJJ/T 135–2009 [39]: (1) one half of water, water reducer, fine and coarse aggregates were added into a mixer and mixed for 30s; (2) the cement was placed into the mixer and mixed for 40s; (3) the last water was dosaged and further mixed for 60s.

After mixing, 150 mm cubes were cast for porosity test, water permeability test and 28-day cube strength tests. To avoid uneven distribution of paste, no vibration was applied during casting. Instead, a heavy metal roller was used to compact the fresh pervious concrete after the moulds were filled up. After casting, the cubes were covered with plastic sheets, demoulded after 1 day and then cured in a curing room for 28 days.

2.3 Testing methods

In this study, a porosity test [40] was applied to measure the interconnected porosity (the percentage of interconnected pores volume to the bulk volume of concrete) and open porosity (the percentage of open pores volume to the bulk volume of concrete) of the previous concrete mixes. The theory of the porosity test was based on water displacement method (as shown in Fig. 2), and the details of the test can be referred to a previous paper [40].

After the porosity test, the concrete cube was transferred to water permeability test setups to carry out water permeability test. In this study, two alternative setups were designed: the first one was for testing of water permeability at a constant water head of 300 mm under un-submerged condition, as shown in Fig. 3(a); the second one was for evaluating of water permeability at a constant water head of 150 mm under submerged condition, as shown in Fig. 3(b). During the test, the un-submerged and submerged permeability coefficients can be calculated according to Darcy's law [41] and the details of the test can be referred to a previous paper [40].

For the cube compressive strength test, three 150 mm cubes cast from each concrete mix were tested by a 2000 kN compression testing machine at the age of 28 days. The 28-day cube strength was defined as the mean value of the cube compressive strengths of the three cubes.

3. Test Results

3.1 Porosity

The test results of interconnected porosity and open porosity are tabulated in the second and third columns of Table 1, respectively. By comparing the interconnected porosity and open porosity for each concrete group, it is obvious that the open porosity was always higher than the respective interconnected porosity. To study how W/C ratio and mortar volume influenced the interconnected/open porosities, Figs. 4 and 5 were drawn, respectively. It can be found that when the W/C ratio was fixed, the interconnected and open porosities gradually decreased to zero as the mortar volume increased from 15–40%. This phenomenon was reasonable and the reason was that a larger mortar volume filled into the voids between the coarse aggregate particles would directly reduce the amount of unfilled voids in the pervious concrete. On the other hand, by fixing the mortar volume, it can be observed that as the W/C ratio increased from 0.25 to 0.40, the interconnected/open porosity generally decreased. This was because a higher W/C ratio would make the mortar more flowable to fill into the voids between the coarse aggregate particles in the pervious concrete.

3.2 Permeability coefficient

The results of un-submerged/submerged permeability coefficient are tabulated in Table 1. From the table, it is noted that the un-submerged 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 un-submerged permeability coefficient was lower than the respective submerged permeability coefficient, because under un-submerged condition, the water channels inside the pervious concrete were not fully filled, while under submerged condition, the water channels were fully filled.

To further study how W/C ratio and mortar volume affected the un-submerged/submerged permeability coefficient, Figs. 6 and 7 were drawn, respectively. From the figures, it is evident that at the same W/C ratio, the un-submerged/submerged permeability coefficient gradually decreased with the increase of mortar volume. On the other hand, at the same mortar volume, a higher W/C ratio would lead to a lower un-submerged/submerged permeability coefficient. These phenomena are expected since the increases of mortar volume and/or W/C ratio would reduce the porosity of the pervious concrete thus making water permeation more difficult.

3.3 Cube strength

The cube strength results are tabulated in the last column of Table 1 and presented in Fig. 8. As expected, the cube strength increased with the increase of mortar volume. The reason is that as the mortar volume increased, the volume of unfilled voids decreased thus alleviating the decline in strength caused by the presence of voids [42–44]. However, at the same mortar volume, the cube strength first increased as the W/C ratio increased from 0.25 to 0.35 but declined 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. The low cube strength at W/C ratio ≤ 0.35 was caused by the excessive dryness of the concrete mix, which rendered the pervious concrete very difficult to cast and particularly porous. The decrease of cube strength when W/C ratio > 0.35 was normal, because a higher W/C ratio at W/C ratio > 0.35 would in general yield a lower concrete strength [45–47].

4. Roles Of Porosity

4.1 Roles of interconnected porosity in water permeability

In pervious concrete, water permeates 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 interconnected porosity influences the un-submerged and submerged permeability coefficients, Figs. 9 and 10 were drawn, respectively. It is obvious that as the interconnected porosity increased, the un-submerged and submerged permeability coefficients gradually improved. More importantly, the data points in both figures lie closely to a certain curve indicating that there is a well-defined relation between the water permeability and interconnected porosity.

Then, regression analysis was applied. The best-fit curves and the corresponding equations were showed directly in the figures. Very high R^2 values of 0.987 and 0.993 were achieved, showing that the interconnected porosity play key roles in the water permeability of pervious concrete. The reason is that the increase in interconnected porosity renders water permeation through the pervious concrete easier.

4.2 Roles of open porosity and W/C ratio in cube strength

There is no doubt that the W/C ratio and porosity have significant influences on the strength of cement-based materials [48–50]. Nevertheless, the porosity should be the open porosity, not the interconnected porosity, because the influence of porosity on strength is not dependent on whether the pores are interconnected or not. For the purpose of evaluating how open porosity and W/C ratio influence the cube strength, Fig. 11 was drawn. 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 decreasing the W/C ratio or increasing the W/C ratio would cause the cube strength to decrease.

Then, multi-variable regression analysis was applied. The best-fit curves and the corresponding equations were showed directly in the figure. Farley high R^2 value of 0.938 was obtained, indicating that the open porosity and W/C ratio play key roles in the strength of pervious concrete.

5. Concurrent Strength-permeability Performance

For pervious concrete, there is a corner that decreasing the mortar volume to increase the porosity would improve the water permeability but simultaneously diminish the strength. Therefore, achieving both high water permeability and high strength is a difficult task. To assess the concurrent strength-permeability performance of the pervious concrete mixes tested, Figs. 12(a) and 12(b) were drawn. In these two figures, each curve plotted is for one mortar volume (MV).

First of all, it can be found that each curve has a peak giving the maximum cube strength. Somehow, all the peaks occur at a W/C ratio of 0.35, regardless of the MV. These peaks may also be taken as the combinations of PV and W/C ratio giving the best strength-permeability performance. Then, it should be noted that at MV ≥ 30%, it is not possible to obtain an un-submerged water permeability coefficient of higher than 1.9 mm/s or a submerged water permeability coefficient of higher than 2.7 mm/s. On the other hand, at PV ≤ 25%, it is not possible to get a cube strength of higher than 25 MPa. To strike a balance between water permeability and strength, it is recommended to set the MV as 25% and the W/C ratio as 0.35, which together would give un-submerged/submerged water permeability coefficients of 3.66 mm/s and 5.21 mm/s, and a cube strength of 26.9 MPa.

6. Conclusions

In this study, a series of pervious concrete mixes with the W/C ratio changing from 0.25 to 0.40 and the mortar volume changing from 15–40%, were made for carrying out the porosity test, water permeability test and compressive strength test. Based on the test results, some conclusions are listed below:

(1) The interconnected porosity is lower than the open porosity, the un-submerged water permeability is lower than the submerged water permeability.

(2) The W/C ratio and mortar volume, as the fundamental mix parameters, have major effects on the interconnected porosity, open porosity, un-submerged water permeability, submerged water permeability and cube strength.

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

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

(5) The best strength-permeability performance generally occurs at a W/C ratio of 0.35. Striking a balance between strength and permeability, it is recommended to set the paste volume at 25%, which together with a W/C ratio of 0.35, would give water permeability coefficients of around 3 to 5 mm/s and a cube strength of about 27 MPa.

7. Declarations

List of abbreviations

Not applicable.

Acknowledgement

Not applicable.

Ethics approval and consent to participate

Not applicable.

Authors' contributions

L.G. Li: writing - original draft preparation; J.J. Feng: completing experiments; B.F. Xiao: data analysis; S.H. Chu: writing - review editing. The authors read and approved the final manuscript.

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Availability of data and materials

All data have been presented in the Position Paper.

Competing interests

The authors declare that they have no competing interests.

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Figures

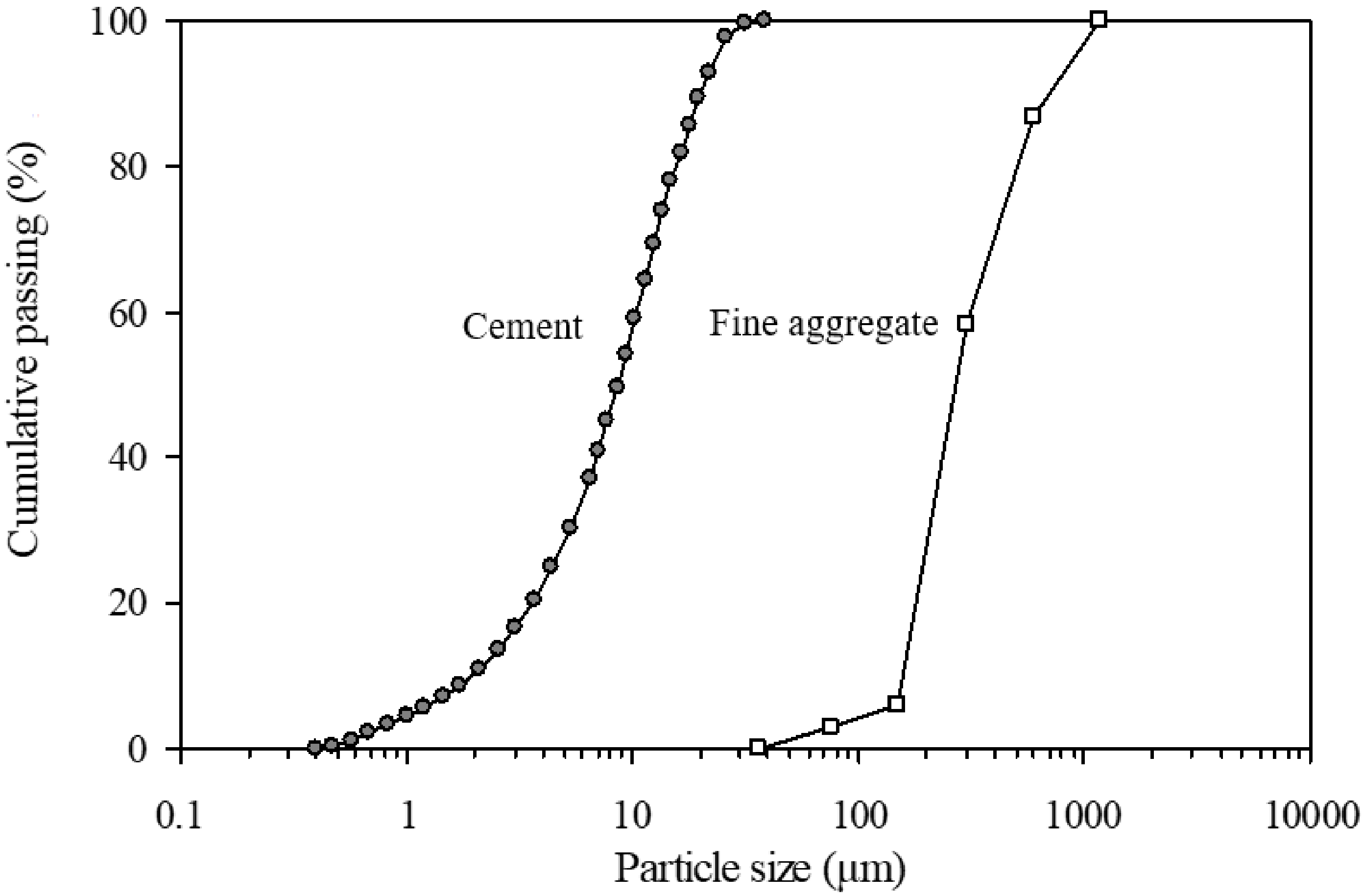

Figure 1

Particle size distribution of cement and fine aggregate

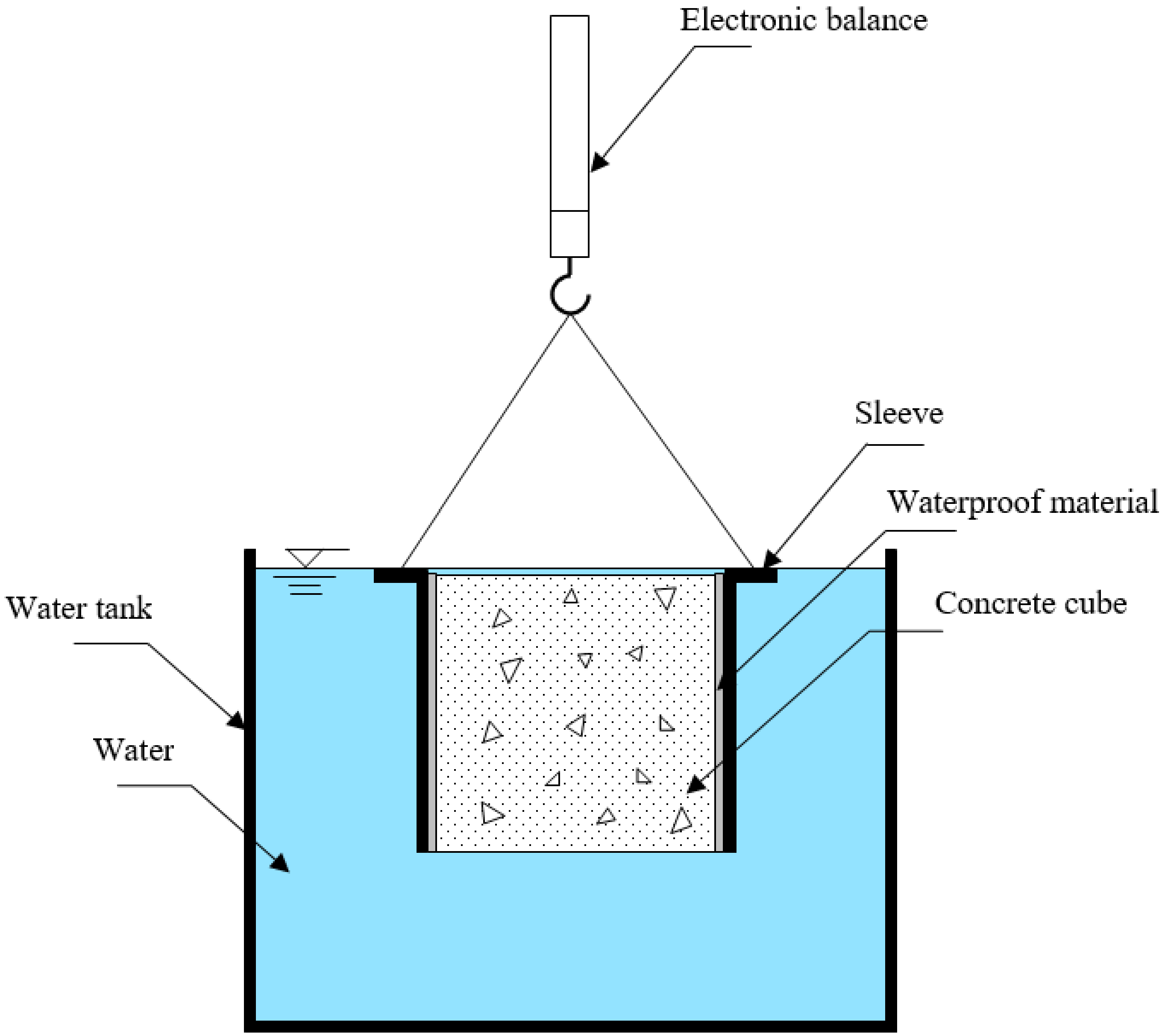

Figure 2

Schematic diagram of porosity test

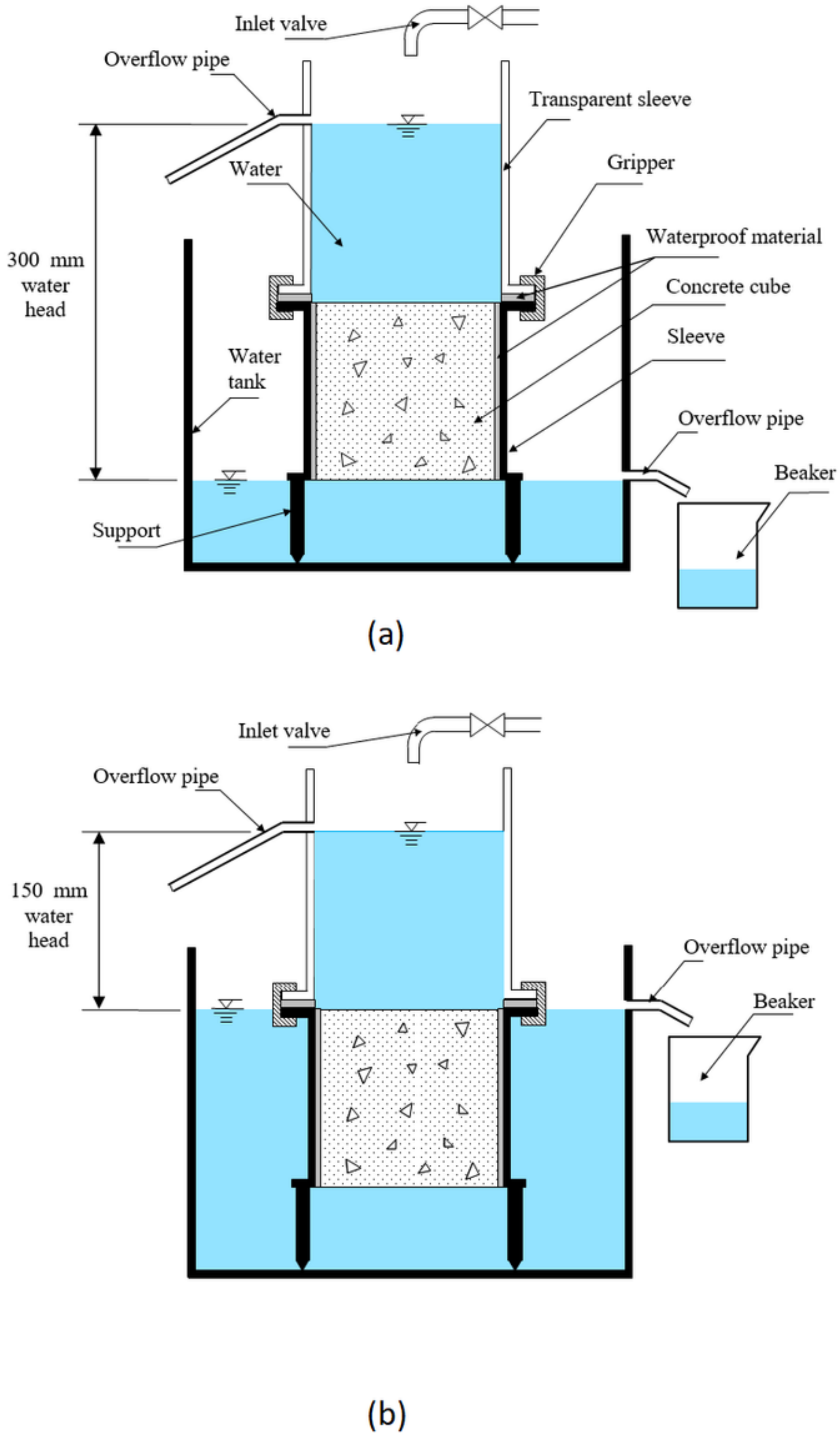

Figure 3

Schematic diagram of water permeability test (a) Un-submerged condition (300 mm water head) (b) Submerged condition (150 mm water head)

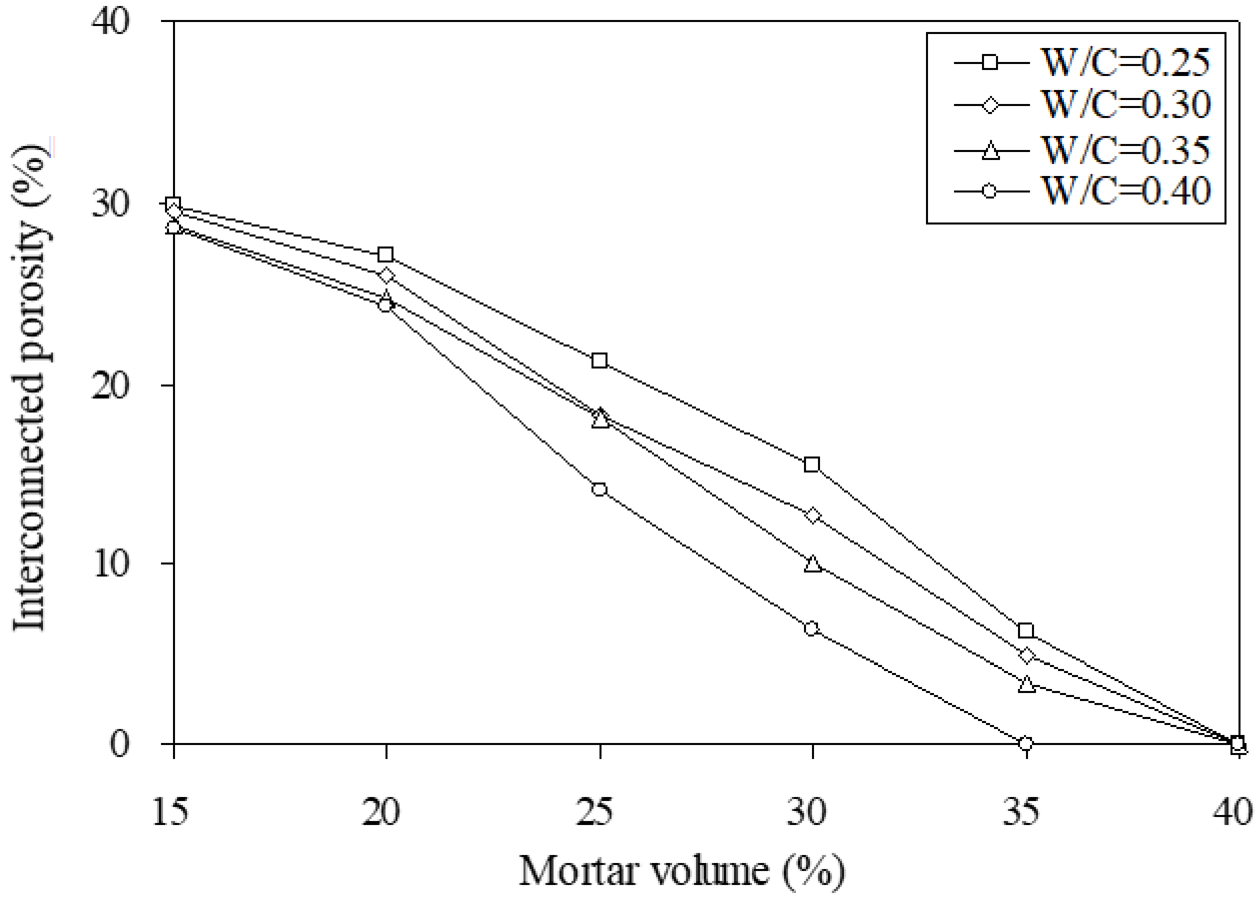

Figure 4

Interconnected porosity versus mortar volume for different W/C ratios

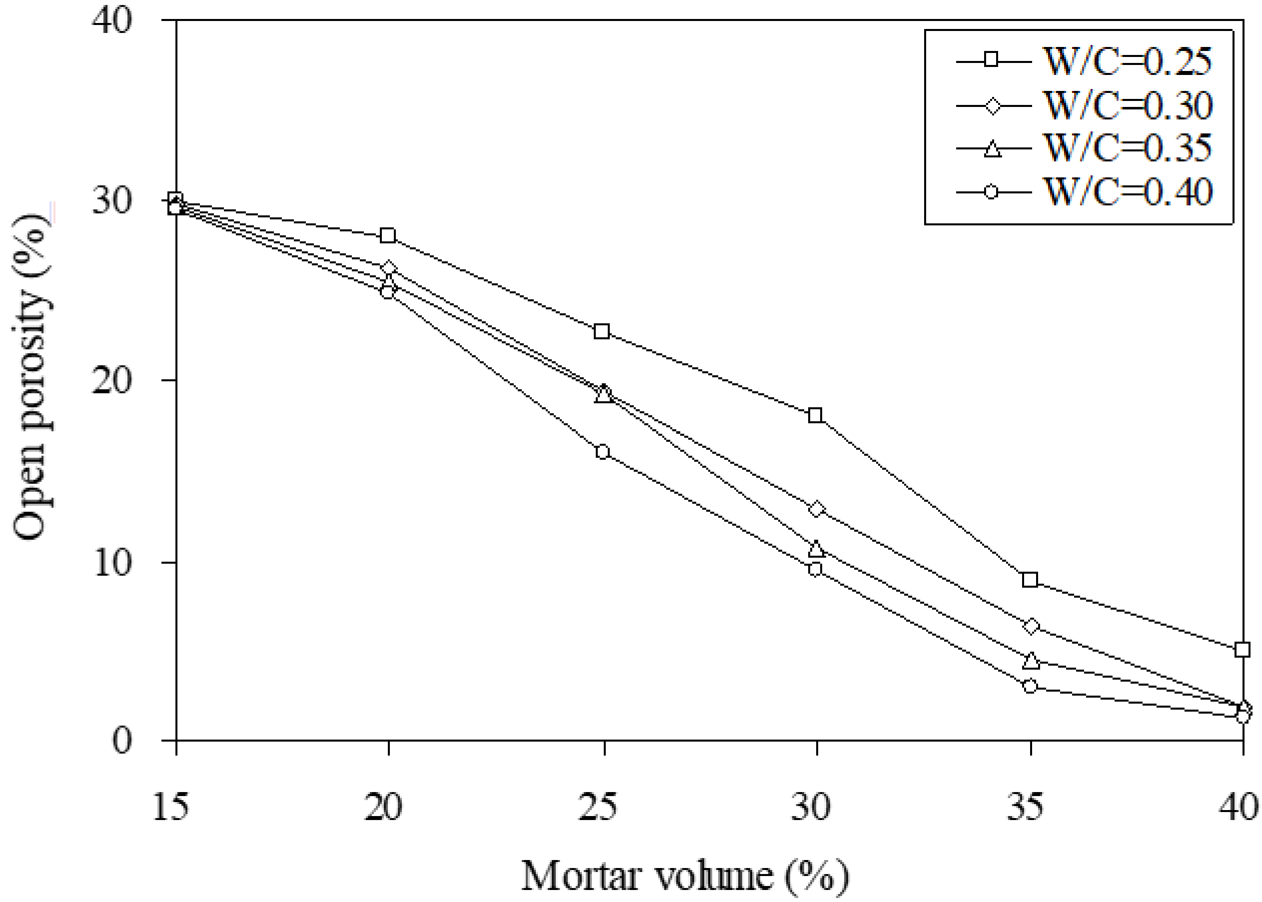

Figure 5

Open porosity versus mortar volume for different W/C ratios

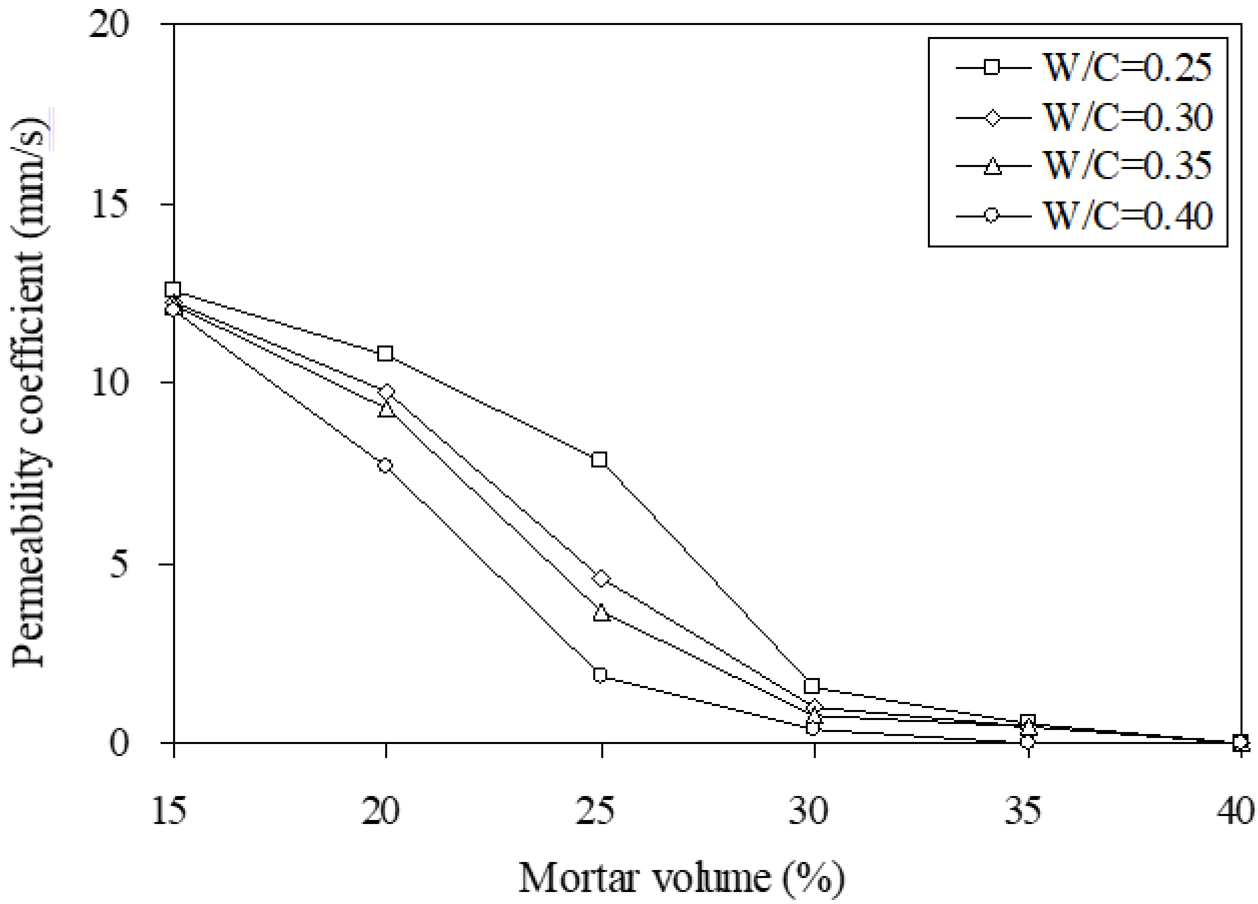

Figure 6

Un-submerged permeability coefficient versus mortar volume for different W/C ratios

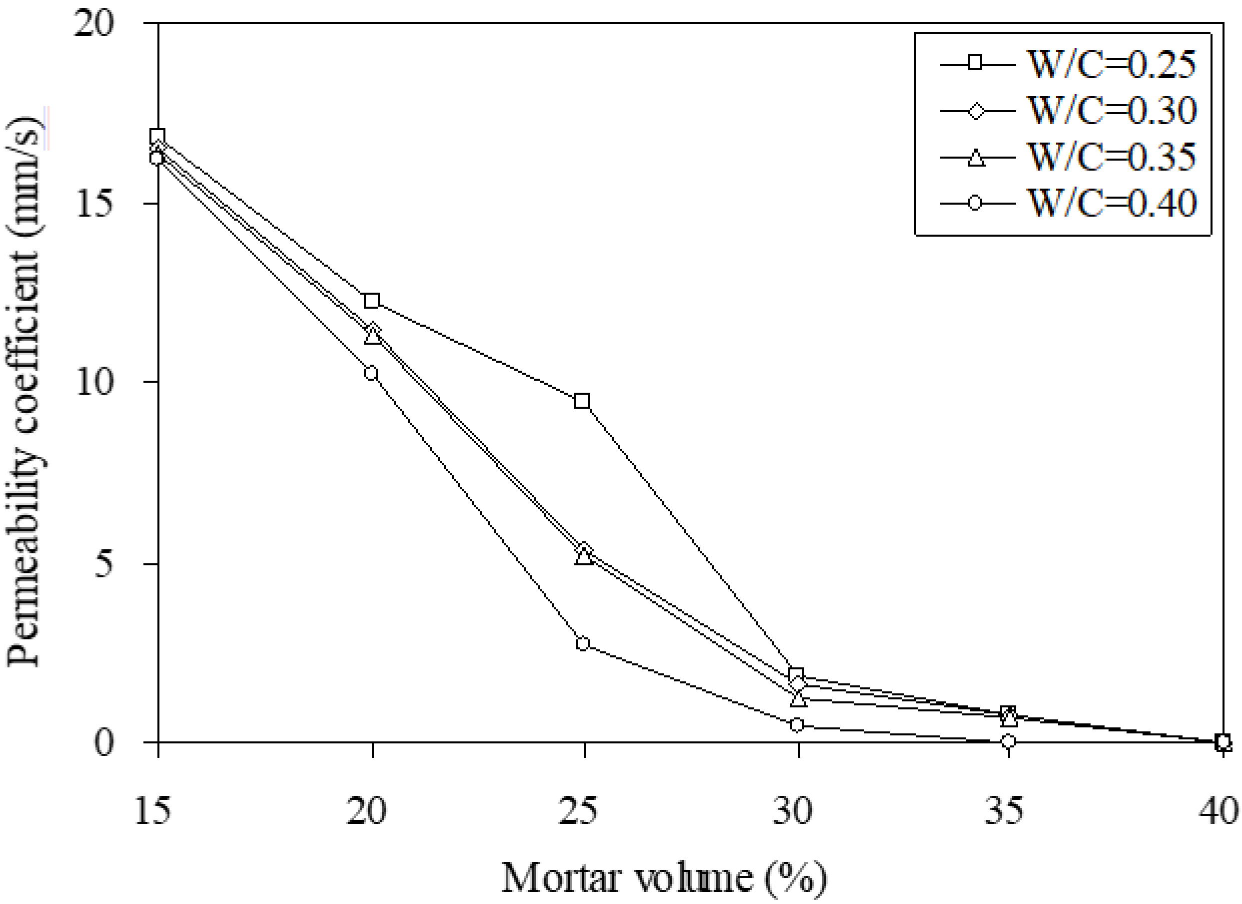

Figure 7

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

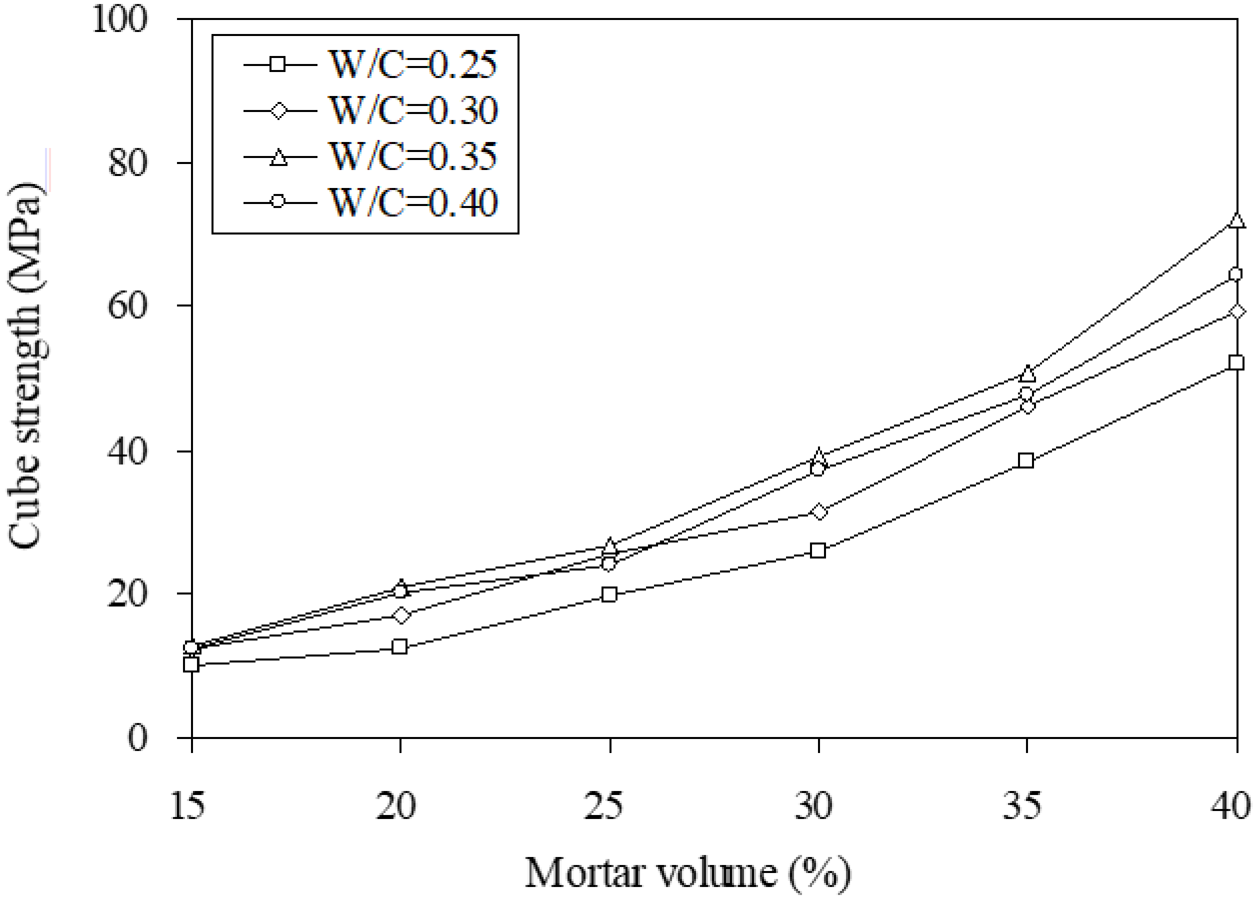

Figure 8

Cube strength versus mortar volume for different W/C ratios

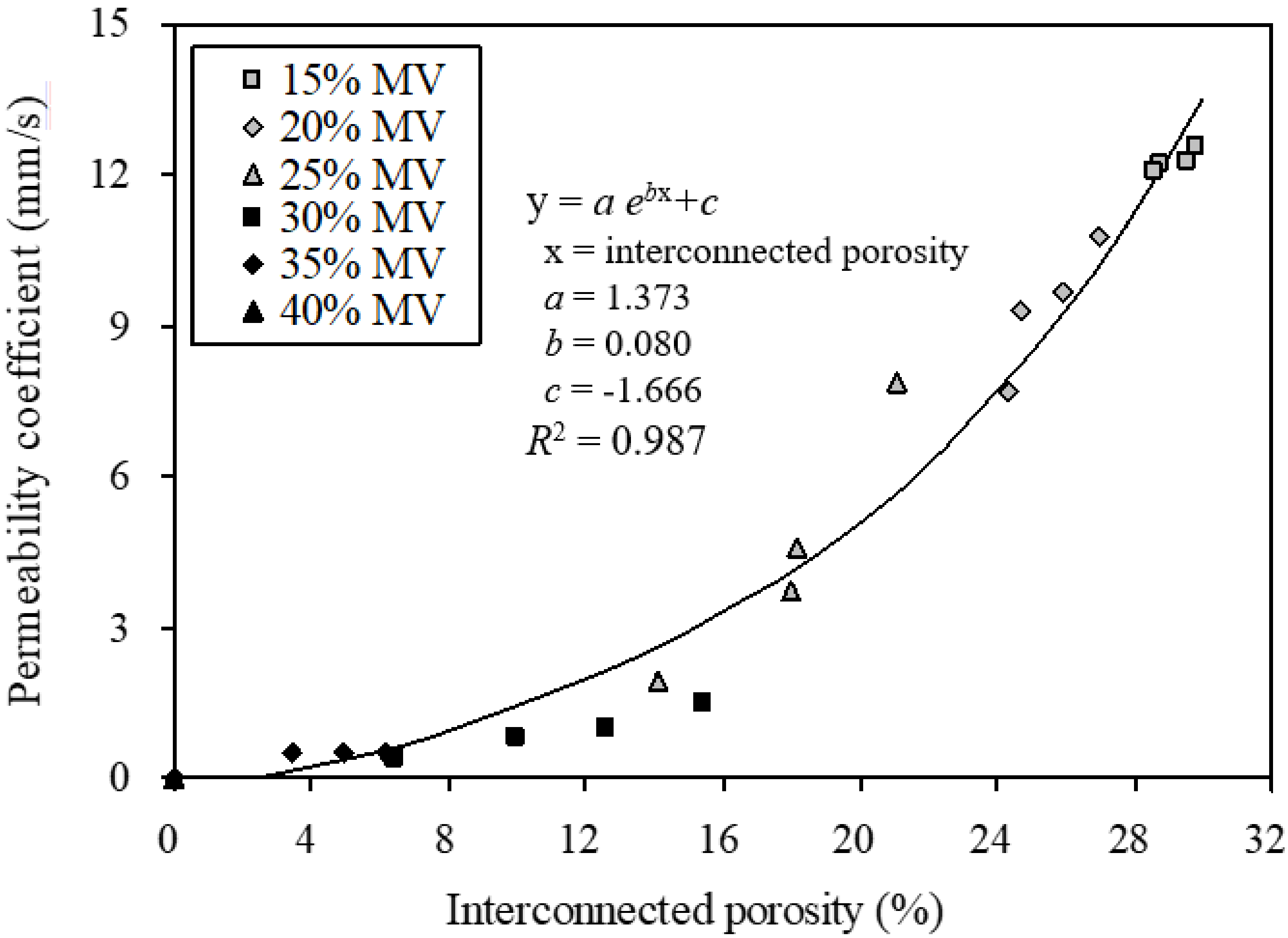

Figure 9

Effect of interconnected porosity on un-submerged permeability coefficient

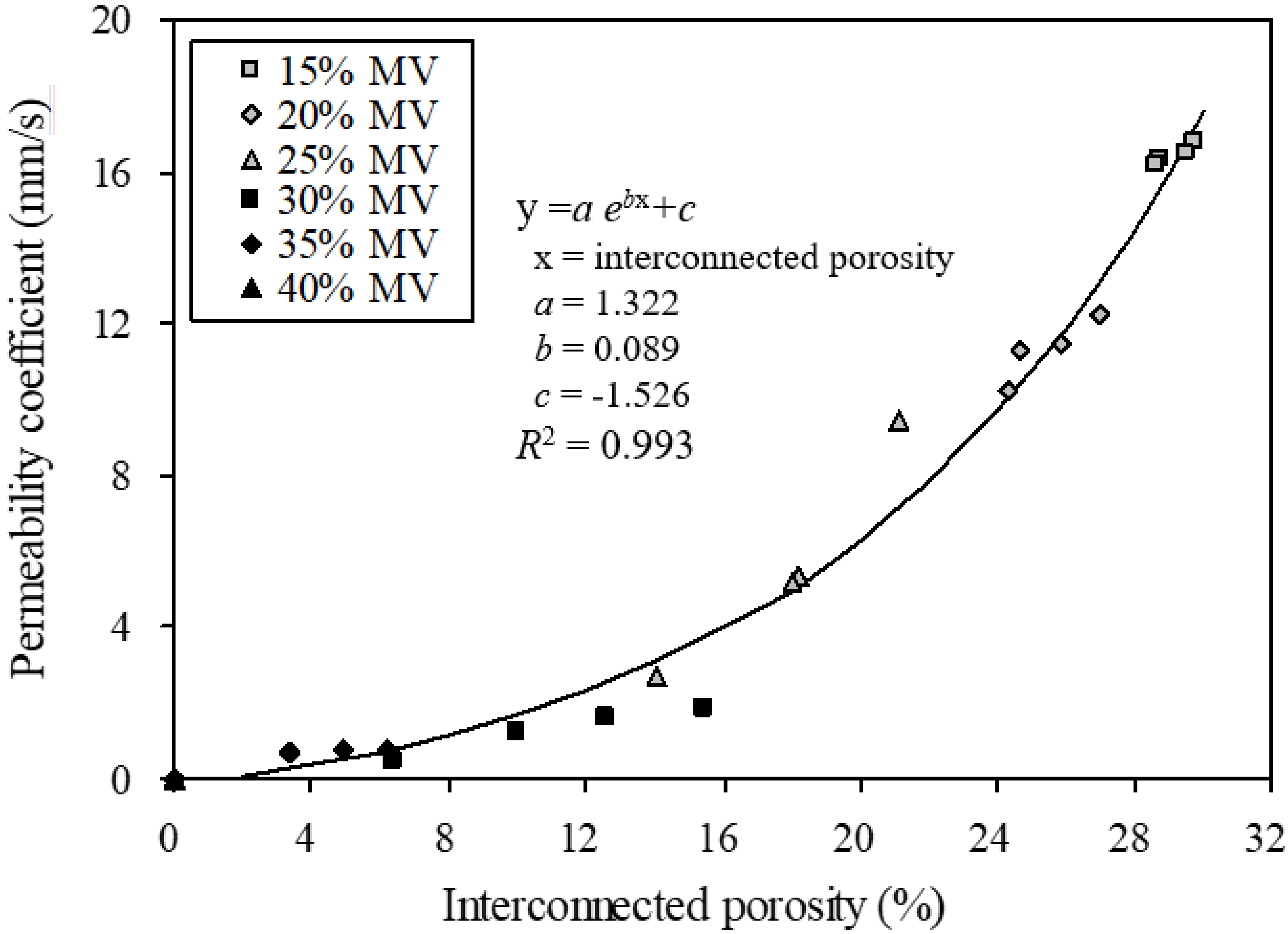

Figure 10

Effect of interconnected porosity on submerged permeability coefficient

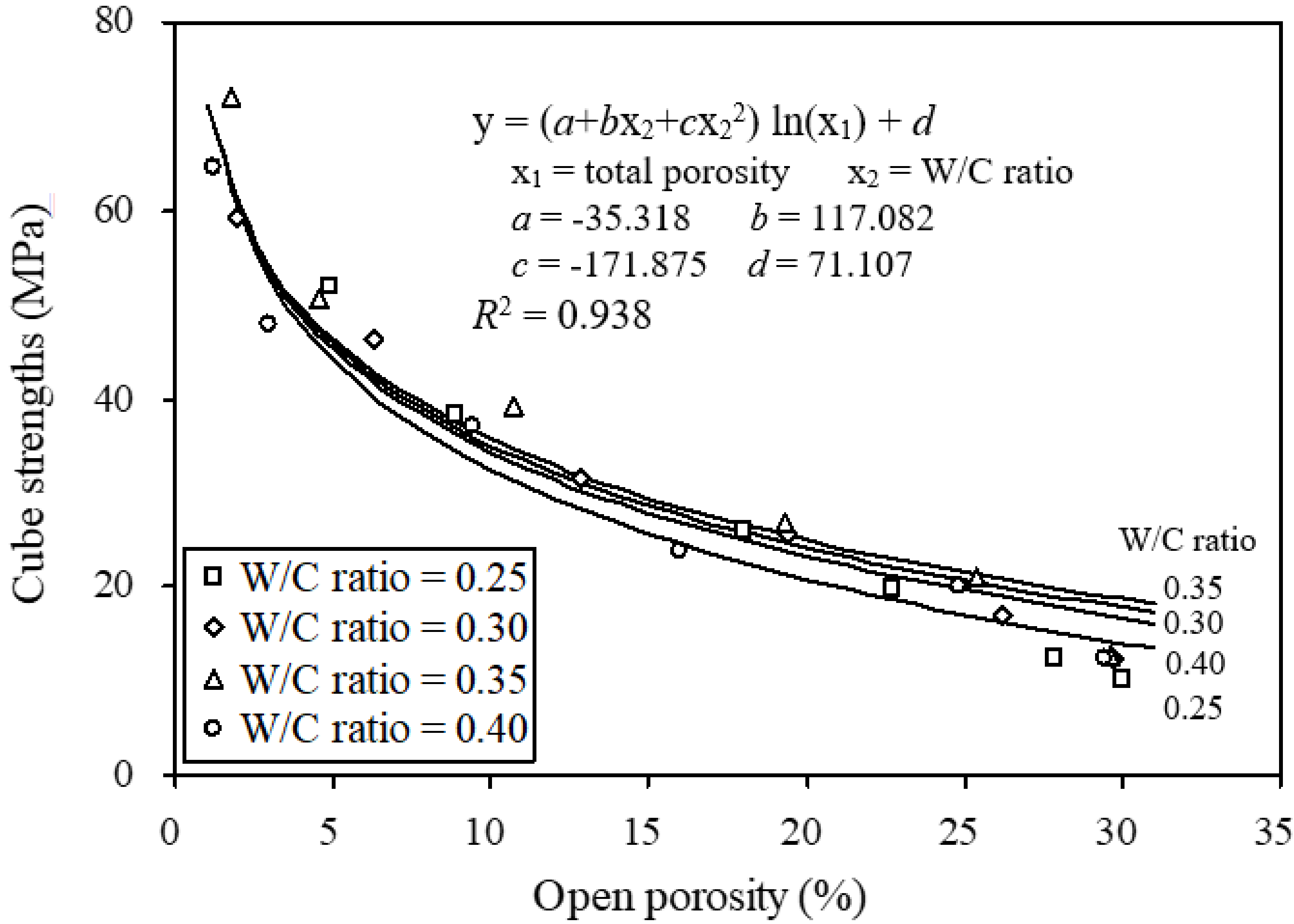

Figure 11

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

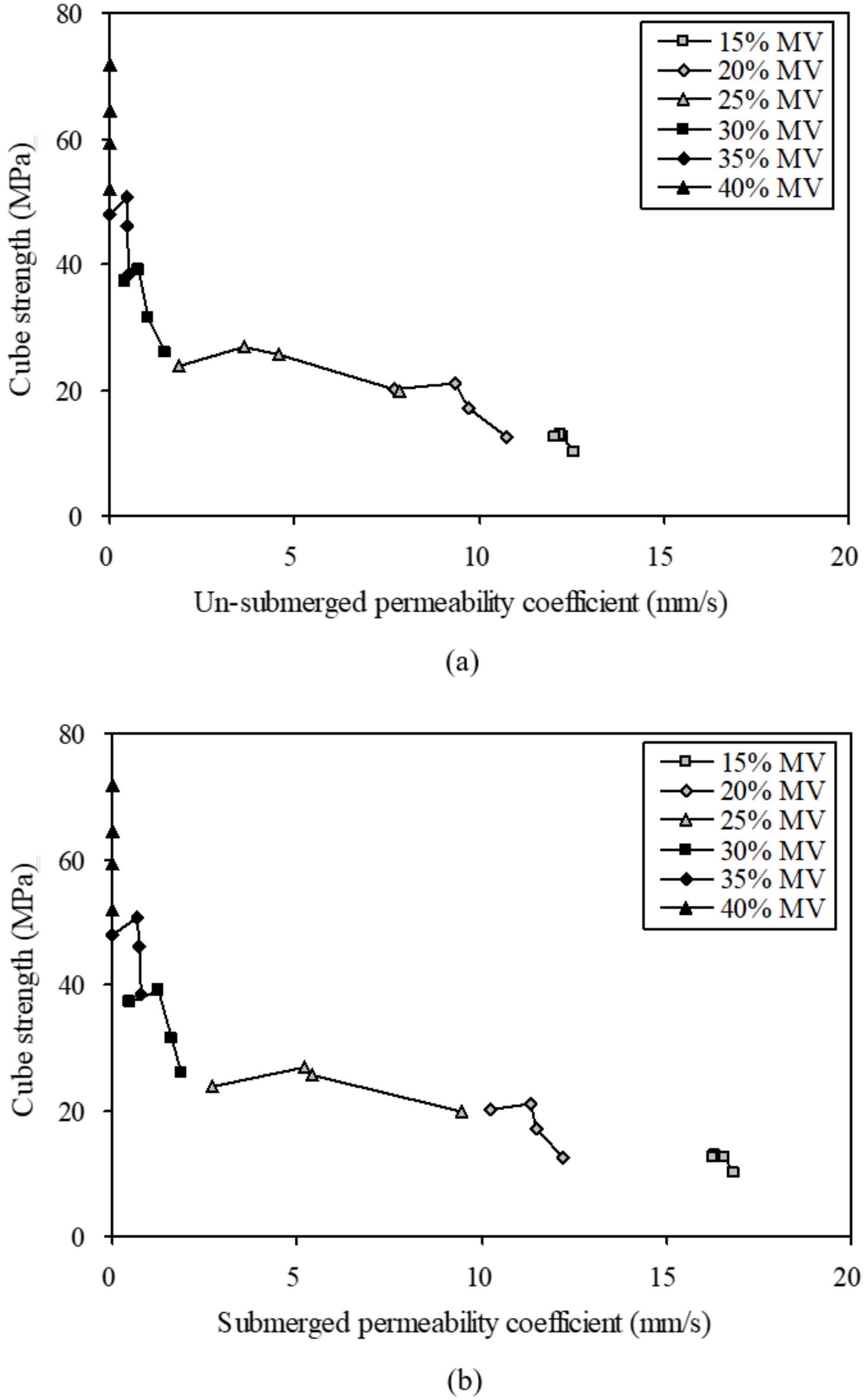

Figure 12

Cube strength versus permeability coefficient