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Recycling Old Concrete as Waste Concrete Powder for Use in Pervious Concrete: Effects on Permeability, Strength and Eco-Friendliness

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Abstract: The fine portion of crushed old concrete is difficult to be recycled for use in new concrete because it contains old cement paste, which generally has high porosity and low strength. Hence, in practice, the coarse portion is recycled as coarse aggregate and the fine portion is mostly not recycled. Nevertheless, attempts have been made in recent years to recycle the fine portion as waste concrete powder (WCP) by grinding before use. In this research, WCP was used to make pervious concrete. The WCP was added using the paste replacement method (PR method) of replacing an equal volume of cementitious paste. A series of pervious concrete mixes containing 100% recycled coarse aggregate and having different amounts of WCP added were produced for testing of interconnected porosity, water permeability and strength. The results showed that the addition of WCP using the PR method can improve the interconnected porosity by 9% and water permeability by 18%, greatly enhance the strength by 86%, as well as decrease the cement consumption by 10% at the same time. Therefore, the addition of WCP as paste replacement has great potential to be applied to the production of eco-friendly high-performance pervious concrete.

Keywords: eco-friendly concrete; paste replacement method; pervious concrete; recycled aggregate; waste concrete powder; waste reutilization

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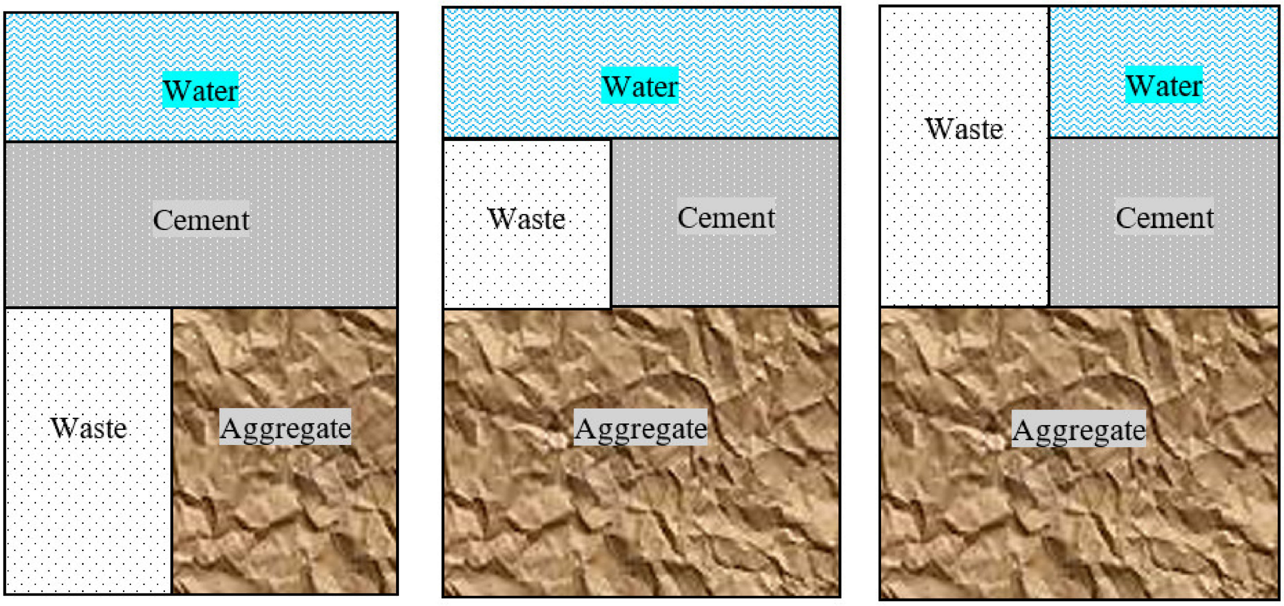
1. Introduction

1.1. Background

All over the world, more than 10 billion tons of construction and demolition (C&D) waste are being generated annually [1], causing serious environmental problems [2–6]. On the other hand, the indiscriminate exploitation of the natural aggregate for concrete production has led to dramatic reduction in sand and gravel resources [7–12]. At the same time, cement manufacturing results in 7% of the world's total CO_2 emission [13]. Therefore, the construction industry is under heavy pressure to deal with the disposal or reutilization of C&D waste, shortage of natural aggregate, and reduction in carbon footprint. In this regard, if the old concrete, which is a major component of C&D waste, can be reused for new concrete production to reduce waste disposal and consumptions of cement and natural aggregate, it will bring substantial environmental and economic benefits [14–19].

By crushing and processing the old concrete, two portions, a coarse portion containing mainly the coarse aggregate and a small amount of old cement paste, and a fine portion containing mainly the fine aggregate and a large amount of old cement paste, are produced. The coarse portion may be recycled as coarse aggregate replacement, as shown in Figure 1a, though the old cement paste adhered onto the aggregate particles would slightly lower the strength of the new concrete produced [20–23]. However, the fine portion is mostly not recycled because its direct use as fine aggregate replacement would substantially lower the strength [24–27]. In recent years, in order to better utilize the unhydrated cement embedded in the old cement paste and break open the pores in the old cement paste so as to improve the performance of the new concrete produced and enable a higher degree of recycling, attempts have been made to grind the fine portion to become waste concrete powder (WCP) before its use in production of new concrete [28–33]. In previous attempts, the WCP was mostly added as cement replacement, as shown in Figure 1b. Somehow, the performance of the new concrete so produced is highly dependent on the fineness of the WCP and such cement replacement would still generally lower the strength because of the relatively low cementing efficiency of the WCP compared to the cement replaced.



(**a**) Aggregate replacement method (**b**) Cement replacement method (**c**) Paste replacement method

Figure 1. Schematic diagram of replacement methods.

Previous research on the possible uses of recycled aggregate and ground powder from C&D waste (such as WCP) are mainly on ordinary concrete. Relatively, there has been little research on pervious concrete made of recycled aggregate and/or ground powder of C&D waste [34]. Both the aggregate replacement and cement replacement methods have been employed. Zaetang et al. [35] found that the use of recycled concrete blocks as coarse aggregate replacement would increase the strength except at the high replacement level of 100%. Liu et al. [36] advocated that whilst the use of recycled aggregate would significantly reduce the strength of pervious concrete, silane polymer emulsion treatment could more than compensate for the reduction in strength. El-Hassan et al. [37] revealed that the use of recycled concrete aggregate would reduce the permeability, mechanical and durability performance of pervious concrete. Lu et al. [38] demonstrated that the addition of silica fume can compensate for the strength reduction due to the uses of waste glass cullet and/or recycled concrete aggregate. Li et al. [39] tried the addition of waste glass powder as cement replacement and observed decreases in 28-day strength and water permeability. Zeng et al. [40] used recycled C&D waste as coarse aggregate and added ground brick powder as cement replacement, and showed that the pervious concrete so produced has lower strength but higher water permeability.

Apart from the aggregate replacement and cement replacement methods, there is also a relatively new paste replacement method (PR method), by which an industrial byproduct or a solid waste is first ground to a fine powder (sometimes called dust to emphasize its fine size) and then added to replace an equal volume of cementitious paste (water + cementitious materials) without changing the water/cementitious materials ratio, as shown in Figure 1c. This method was proposed by Kwan's research team [41,42] about 10 years ago. It has been successfully applied by a number of researchers to the utilizations of limestone powder [43,44], granite dust [45], marble dust [46], ground clay brick waste [47,48], pumice powder and glass microspheres [49], blast furnace ferronickel slag [50], ceramic polishing waste [51] and molybdenum tailing [52] to produce eco-friendly, low-cement, high-performance mortar and concrete. Basically, with this PR method employed, the cement consumption would be reduced; the microstructure would be densified; and the strength, durability and dimensional stability of the mortar and concrete produced would be significantly increased, regardless of the cementing efficiency of the powder added. However, the PR method has not yet been applied to the production of pervious concrete and the possible use of WCP in normal concrete and pervious concrete.

1.2. Research Significance

In order to recycle the fine portion of crushed old concrete as well as to reduce carbon footprint and natural resource consumption, it is proposed herein to investigate the possibility of using WCP to produce pervious concrete. However, the use of WCP following the traditional practice of adding WCP to replace an equal mass of cementitious materials would in general adversely affect the concrete performance. To overcome this long-standing problem, the new PR method of replacing an equal volume of cementitious paste, which has been demonstrated to have great advantages in recycling waste powders for the production of eco-friendly, low-cement and high-performance concrete, is employed to produce pervious concrete. This is the first attempt at employing the PR method to produce pervious concrete using WCP. The results are positive, indicating that the PR method may also be used to produce eco-friendly high-performance pervious concrete.

2. Experimental Programme

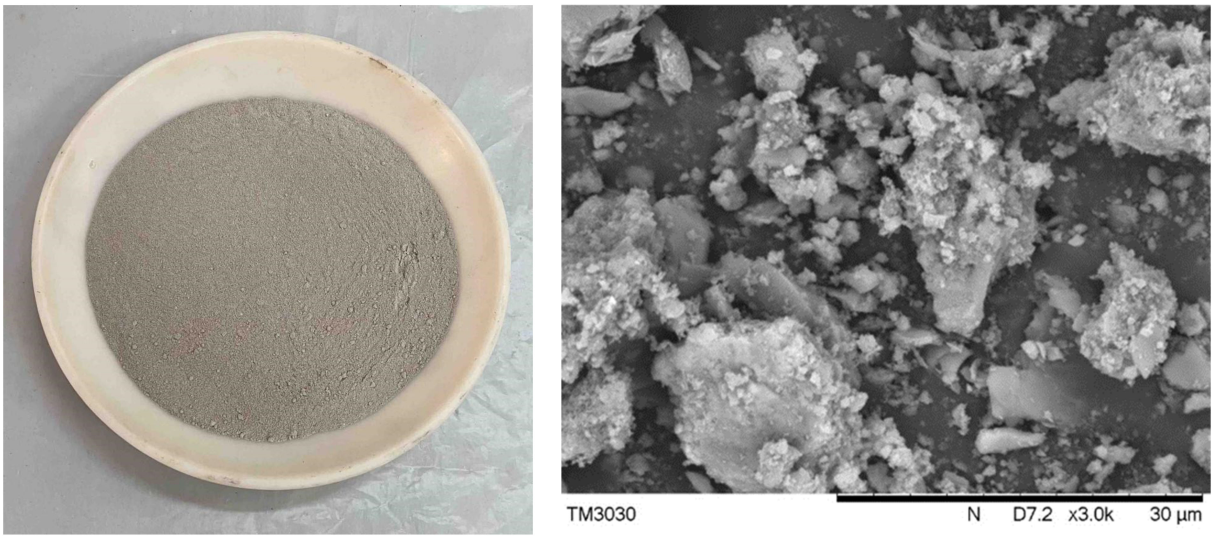
2.1. Materials

The production of the pervious concrete mixes to be tested utilized the following raw materials: cement, recycled coarse aggregate (RCA), waste concrete powder (WCP), water, and water reducer (WR). The cement employed was an ordinary Portland cement of grade 42.5R complying with Chinese Standard GB 175-2020 [53]. It was added as the only cementitious material (i.e., no other cementitious material was added). Its relative density was 3.10 and chemical compositions are listed in Table 1. The RCA was supplied by a recycled aggregate production plant located in Shenzhen city. It had maximum particle size of 20 mm as suggested by Chinese Standard CJJ/T 135-2009 [54], relative density of 2.58, moisture content of 2.00%, water absorption of 4.20% and crushing index of 20.0%.

Table 1. The chemical composition of cement.

Chemical Composition	CaO	SiO_2	Al_2O_3	MgO	Fe_2O_3	SO_3	Alkali	LOI
Content (%)	62.92	23.22	4.35	0.98	3.11	2.81	0.43	1.78

The WCP was made by the authors themselves. To produce the WCP, the RCA was first ground by a small tumbling ball mill in the laboratory and then mechanically sieved to remove the particles larger than 0.15 mm so as to obtain the powder content of the ground RCA. To control the moisture content, the powder was placed into an oven at 105 °C for 8 h of drying. This dried powder was the finished WCP to be used in this research. The WCP was measured to have a relative density of 2.56. A photograph of the WCP was taken and shown in Figure 2a. It can be seen that the WCP used was a grey color dry powder. In addition, a SEM image of the WCP was exhibited in Figure 2b. From the figure, it can be observed that the WCP has an angular shape and no pores on the surfaces, and the size range is large. This is attributed to the grinding action of the tumbling ball mill. The water utilized was local tap water, and the WR utilized was a commonly used 3rd generation polycarboxylate-based superplasticizer with solid content of 20% and relative density of 1.03.



(**a**) Photograph of WCP (**b**) SEM image of WCP

Figure 2. Photograph and SEM image of WCP.

The particle size distributions of the cement and WCP had been determined by a laser diffraction particle size analyzer while the particle size distribution of the RCA had been measured by mechanical sieving, as plotted in Figure 3. From the figure, it is noted that the median particle sizes of the cement, WCP and RCA were 10.3 μm, 111.4 μm and 2.3 mm, respectively. Hence, the WCP was coarser than the cement and finer than the RCA.

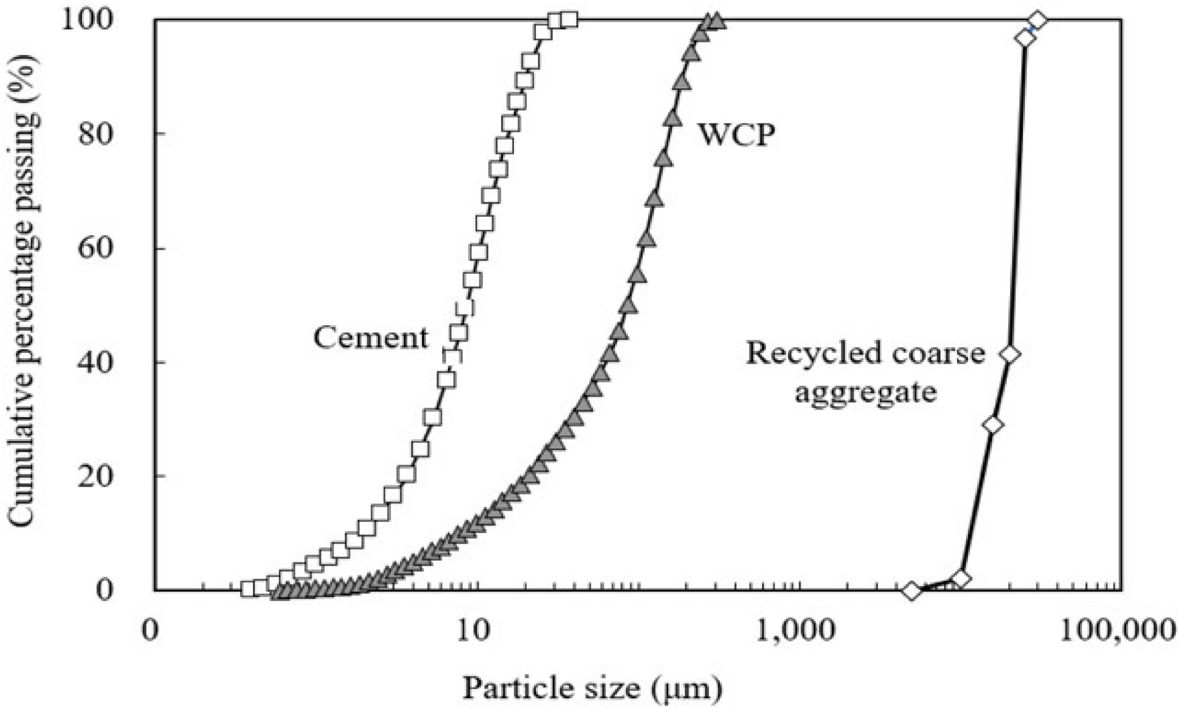


Figure 3. Particle size distributions of cement, WCP and recycled coarse aggregate.

2.2. Mix Designs and Mixing Procedure

In this study, the pervious concretes made were no-fine pervious concretes, each consisting of two portions: the coarse aggregate portion and the paste portion. For the coarse aggregate portion, only RCA was added. For the paste portion, the water/cement (W/C) ratios by mass were set at 0.30 and 0.35 (corresponding W/C ratios by volume were 0.9 and 1.1, respectively). The main reason for choosing these two W/C ratios is that if the W/C ratio is lower than 0.30, the paste portion would be too dry to adhere to the aggregate particles, whereas if the W/C ratio is higher than 0.35, the paste portion would drip downwards to cause blockage at the bottom. As per the PR method [41,55,56], the WCP was added to replace an equal volume of cementitious paste (water + cementitious materials) at volumetric replacement rates of 5% and 10%. The reason for not adopting a higher replacement rate than 10% is that a replacement rate of higher than 10% had been found in preliminary trials to render the paste too dry and the WR dosage too high. In this particular case, since only cement was added as the cementitious material, the cementitious paste was just a cement paste. After adding WCP, the paste becomes a powder paste comprising of water, cement and WCP. It should be noted that because the water content and cement content were decreased proportionally and simultaneously, the W/C ratio was not changed. Due to the increase in powder content (cement + WCP) and the decrease in water content, the powder paste (i.e., water + cement + WCP) would have a lower water/powder ratio, and therefore, the WR dosage was adjusted upwards after adding WCP to maintain a more or less constant and suitable paste rheology.

To develop the mix designs of the pervious concretes, numerous concrete mixing trials were carried out and it was decided to set the target slump of the paste portion, measured using a mini slump cone test, as 20 to 40 mm. For each paste portion, the optimum WR dosage (expressed as a percentage by mass of cement and WCP) to attain such target slump was determined by paste mixing trials. Regarding the paste and aggregate contents, the paste/aggregate (P/A) ratios by volume were set at 0.4 and 0.5. The reason for choosing these two P/A ratios is that in previous studies [57], it was found that the range of P/A ratio between 0.4 and 0.5 would provide a good balance between strength and water permeability. In total, 12 pervious concrete mixes were designed and produced for testing. For identification, each pervious concrete mix was assigned a mix number in the form of A-B-C, in which A is the P/A ratio by volume, B is the W/C ratio by mass, and C is the WCP volumetric replacement ratio (%), as listed in the 1st column of Table 2. As can be seen from the mix nos., the P/A ratio ranged from 0.4 to 0.5, the W/C ratio ranged from 0.30 to 0.35, and the WCP volume ranged from 0% to 10%.

Table 2. Test results of paste portions.

Mix No.	Slump (mm)	WR Dosage (%)
0.4-0.30-0	25	0.20
0.4-0.30-5	25	0.27
0.4-0.30-10	35	0.50
0.4-0.35-0	28	0.12
0.4-0.35-5	32	0.15
0.4-0.35-10	26	0.22
0.5-0.30-0	25	0.20
0.5-0.30-5	25	0.27
0.5-0.30-10	35	0.50
0.5-0.35-0	28	0.12
0.5-0.35-5	32	0.15
0.5-0.35-10	26	0.22

For preparing the pervious concretes, the mixing procedures were as follows.

1. The cement and WCP were added to the mixer and the mixture was dry-mixed for 30 s.
2. The water and WR were added to the mixer and the (water + WR + cement + WCP) mixture was wet-mixed for 90 s.
3. The RCA was added to the mixer and the pervious concrete mixture was mixed for 90 s.

After thorough mixing, six 150 mm cubes were cast, according to Chinese Standards GB/T 50081-2002 [58] and CJJ/T 135-2009 [54], for interconnected porosity test, water permeability test and cube strength test. To avoid downward flow and uneven distribution of paste, no vibration was applied during casting. Instead, a heavy metal roller was applied at the top surface to compact the fresh pervious concrete after filling up the moulds. At 24 h after casting, the cubes were demoulded and then placed in a curing room until the time of testing. At 28 days after casting, three of the cubes were subjected to interconnected porosity test and water permeability test, and the other three cubes were subjected to compression test.

2.3. Testing Methods

To assess the workability of the paste portion, the mini slump cone test, as suggested by Okamura and Ouchi [59], was conducted in this study. The mini slump cone used has a top diameter of 70 mm, a base diameter of 100 mm, and a height of 60 mm. Details of the test procedures have been given before [59,60]. During the test, the slump was measured as the reduction in height of the paste patty formed after lifting of the mini slump cone. The photograph of this test is presented in Figure 4.

Figure 4. Photograph of mini slump cone test.

To measure the porosity of the pervious concrete, an interconnected porosity test was carried out, as shown in Figure 5. Details of the test procedures have been presented before [57]. Basically, the weights of the pervious concrete specimen in air and in water were measured and the buoyancy was determined as the reduction in weight after immersion in water. The volume of interconnected pores was calculated by applying Archimedes' principle of buoyancy, and the interconnected porosity was then evaluated as the ratio of the volume of interconnected pores to the bulk volume of the pervious concrete, expressed as a percentage.

For evaluating the water permeability of the pervious concrete, a water permeability test developed by the authors' research group was performed, as depicted in Figures 6 and 7. The test procedures have been presented before in previous publications [61,62]. Basically, the flow rate of water through the pervious concrete specimen was measured under both the un-submerged condition, as shown in Figure 6a, and the submerged condition, as shown in Figure 6b, and the un-submerged and submerged permeability coefficients were calculated from the respective measured flow rates using Darcy's law of permeability.

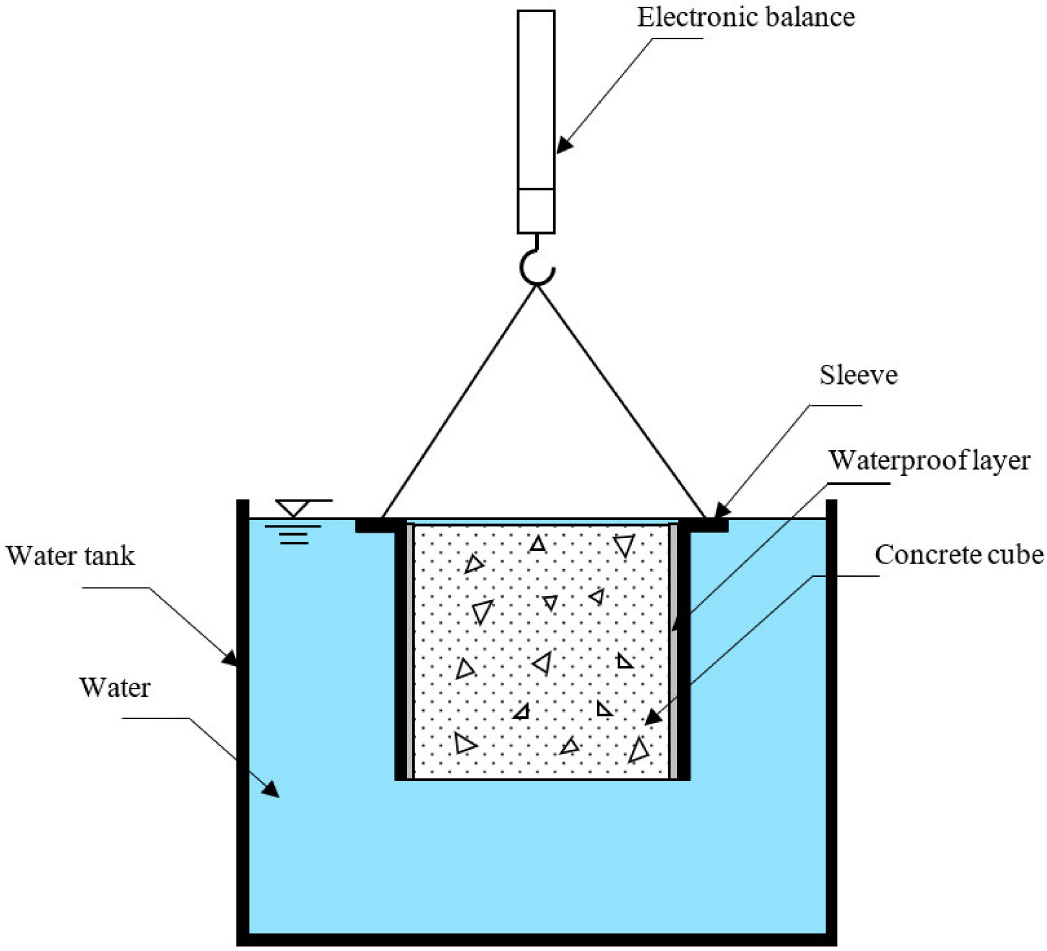
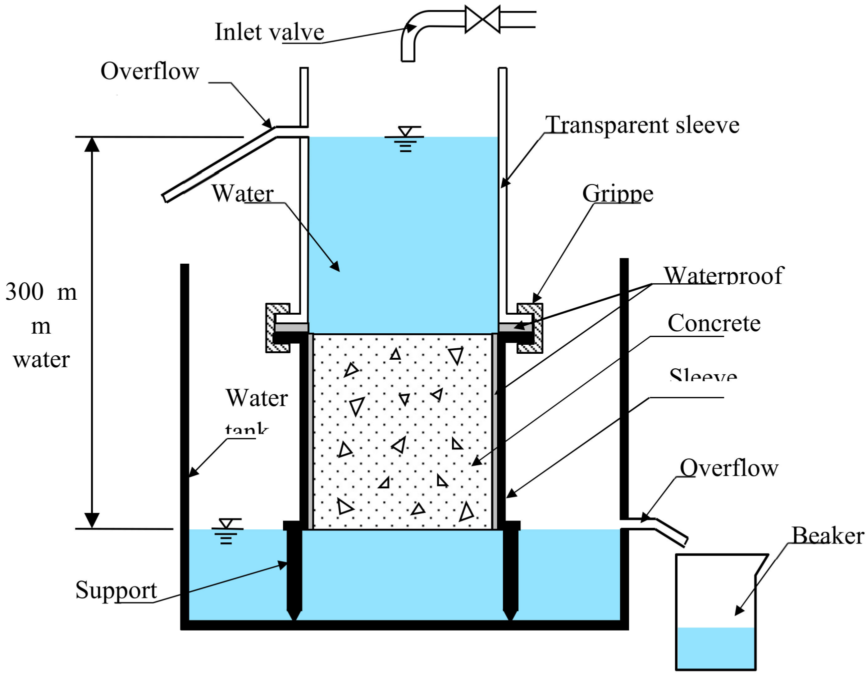
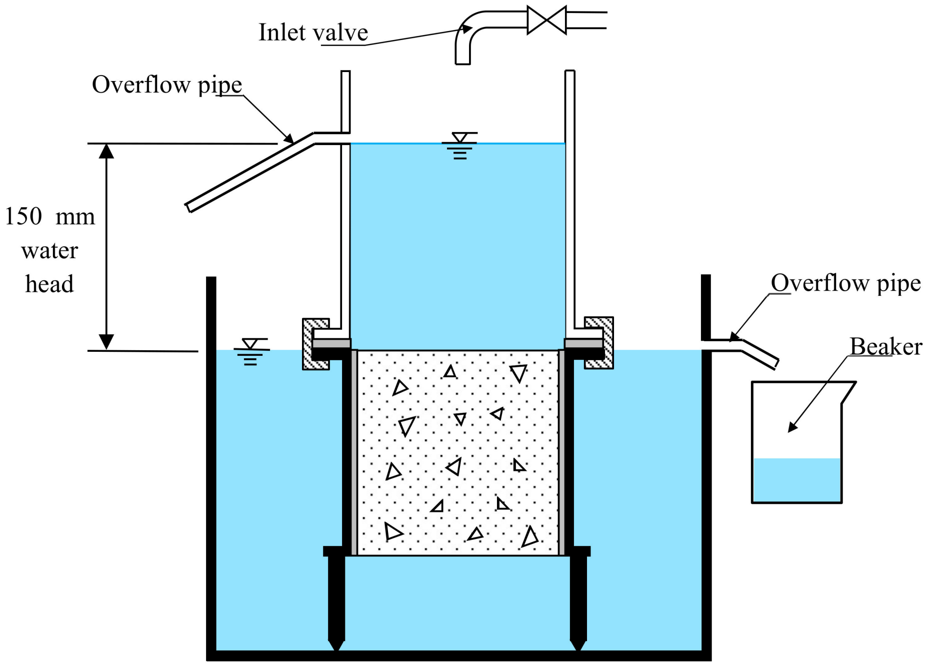


Figure 5. Schematic diagram of interconnected porosity test.



(**a**) Un-submerged condition (300 mm water head)

Figure 6. *Cont.*



(**b**) Submerged condition (150 mm water head)

Figure 6. Schematic diagram of permeability test.

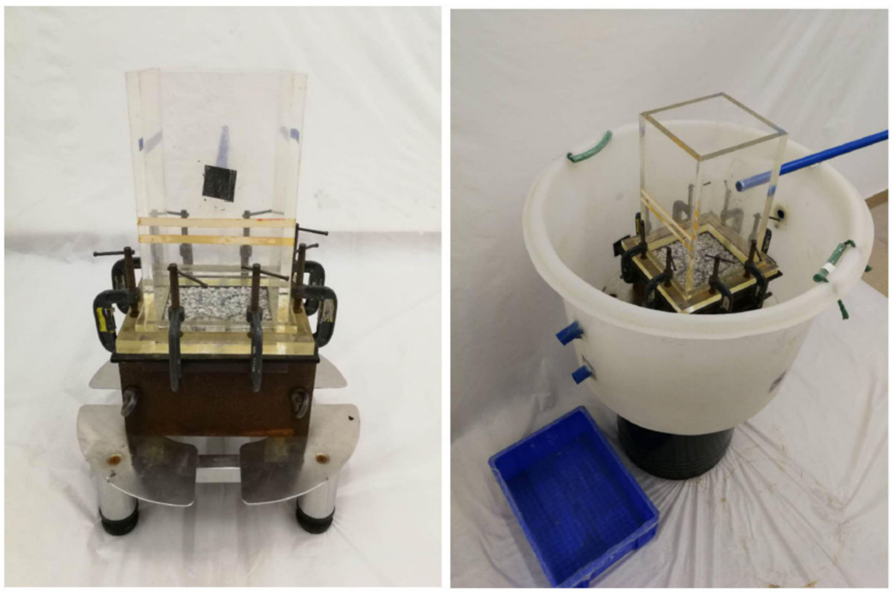


Figure 7. Photograph of permeability test.

To determine the cube compressive strength of the pervious concrete, the three 150 mm cubes cast from the previous concrete were tested by a servo-controlled compression testing machine, as shown in Figure 8. The mean value of the cube compressive strength results of the three cubes tested was taken as the cube compressive strength of the pervious concrete.

(**a**) Compression testing machine

(**b**) Specimen after failure

Figure 8. Photograph of compressive strength test.

3. Experimental Results

3.1. Slump of Paste Portion and WR Dosage

The workability results of the paste portions and the WR dosages required are presented in the 2nd and 3rd columns of Table 2. It can be seen that all the paste portions had attained slump values of 25 to 38 mm, which were well within the target range of 20 to 40 mm for the production of the pervious concrete. As expected, the WR dosage was generally higher at lower W/C ratio and/or higher WCP volume. Hence, the addition of WCP by the PR method would increase the WR dosage.

3.2. Interconnected Porosity Results

The interconnected porosity results of the pervious concrete specimens are presented in the 2nd column of Table 3 and plotted against the WCP volume in Figure 9. From these results, it is evident that at a given WCP volume, as the P/A ratio or W/C ratio increased, the interconnected porosity decreased. These results are as expected because an increase in P/A ratio would increase the paste volume and an increase in W/C ratio would increase the water content, and both would cause downward flow of the paste to block the pores in the pervious concrete at the bottom [57,63,64].

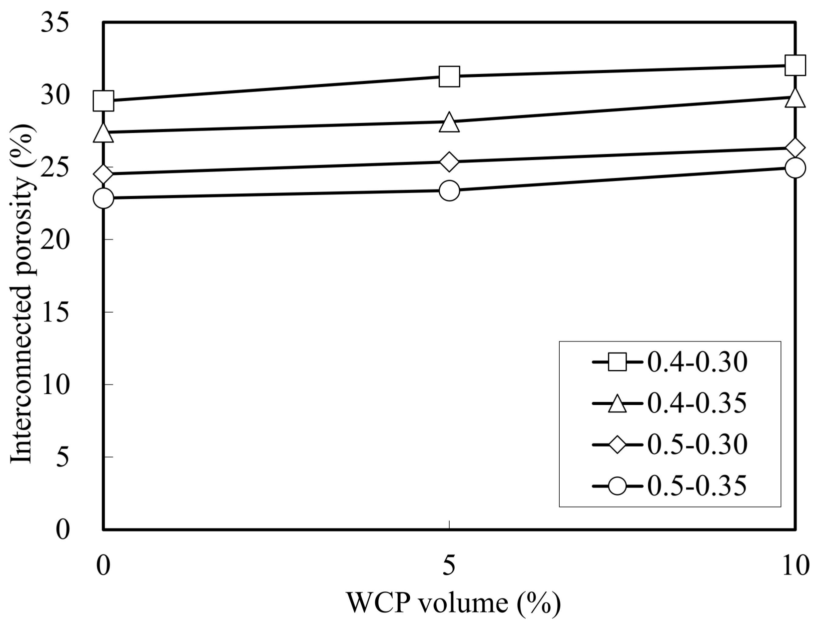


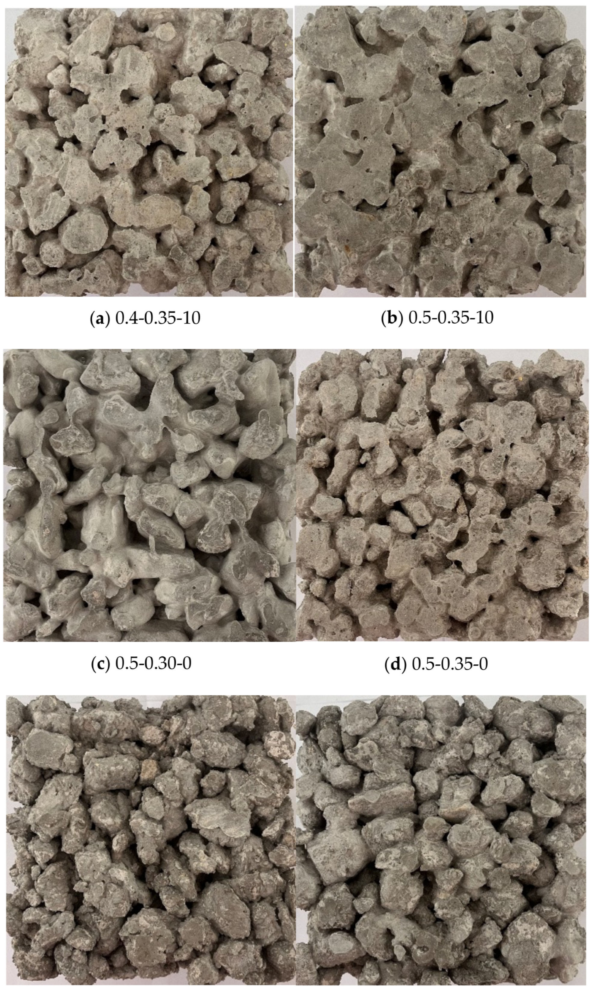
Figure 9. Variation in interconnected porosity.

More importantly, at given P/A ratio and W/C ratio, the increase in WCP volume from 0% to 10% had generally led to gradual increase in interconnected porosity. For instance, at a P/A ratio of 0.5 and W/C ratio of 0.35, as the WCP volume increased from 0% to 10%, the interconnected porosity increased from 22.87% to 24.97%, or in other words, increased by a relatively proportion of 9.2%. The reason may be that the addition of WCP had increased the powder content and simultaneously decreased the water content, so that the paste became more cohesive [65] to be able to resist the downward flow of the paste and thus reducing the pore blockage at the bottom of the pervious concrete.

The variation in interconnected porosity with the various mix parameters can be explained more directly from the photographs of the underside of the pervious concrete specimens presented in Figure 10. Comparing Figure 10a (for concrete mix 0.4-0.35-10) and Figure 10b (for concrete mix 0.5-0.35-10), it is obvious that an increase in the P/A ratio had significantly reduced the pores at the underside of the specimen. Comparing Figure 10c (for concrete mix 0.5-0.30-0) and Figure 10d (for concrete mix 0.5-0.35-0), it is clear that an increase in the W/C ratio had also significantly reduced the pores at the underside of the specimen. Comparing Figure 10e (for concrete mix 0.4-0.30-0) and Figure 10f (for concrete mix 0.4-0.30-10), it is seen that adding WCP had not reduced the pores at the underside and had even rendered the paste better distributed to cover more uniformly the surfaces of coarse aggregate particles, which was conducive to the formation of an unblocked pore system.

Table 3. Test results of pervious concretes.

Mix No.	Interconnected Porosity (%)	Un-Submerged Permeability Coefficient (mm/s)	Submerged Permeability Coefficient (mm/s)	Cube Strength (MPa)	Cement Content (kg/m^3)
0.4-0.30-0	29.57	12.60	16.26	6.34	466.2
0.4-0.30-5	31.26	14.13	18.18	8.90	442.9
0.4-0.30-10	32.03	14.91	19.23	11.82	419.5
0.4-0.35-0	27.41	11.17	14.57	5.91	421.8
0.4-0.35-5	28.12	12.13	15.88	7.69	400.7
0.4-0.35-10	29.84	13.12	16.98	10.42	379.6
0.5-0.30-0	24.53	9.99	12.53	8.87	543.9
0.5-0.30-5	25.36	10.23	13.13	12.20	516.7
0.5-0.30-10	26.34	10.84	14.18	16.38	489.5
0.5-0.35-0	22.87	9.01	11.93	8.28	492.1
0.5-0.35-5	23.38	9.35	12.08	10.47	467.5
0.5-0.35-10	24.97	10.22	13.53	13.84	442.9



(**a**) 0.4-0.35-10 (**b**) 0.5-0.35-10

(**c**) 0.5-0.30-0 (**d**) 0.5-0.35-0

(**e**) 0.4-0.30-0 (**f**) 0.4-0.30-10

Figure 10. Photographs of underside of pervious concrete.

3.3. Water Permeability Results

The measured un-submerged and submerged permeability coefficients are tabulated in the 3rd and 4th columns of Table 3 and plotted against the WCP volume in Figure 11a,b, respectively. From the tabulated results, it can be seen that the un-submerged permeability coefficients were within the range of 9.01 to 14.91 mm/s, whereas the submerged permeability coefficients were within the range of 11.93 to 19.23 mm/s. Evidently, the submerged permeability coefficient was generally larger than the respective un-submerged permeability coefficient. The reason may be that under un-submerged condition, the water channels inside the pervious concrete were not fully filled or saturated, whereas under submerged condition, the water channels inside the pervious concrete were fully filled and saturated, thus allowing a larger water flow through the water channels [57,61].

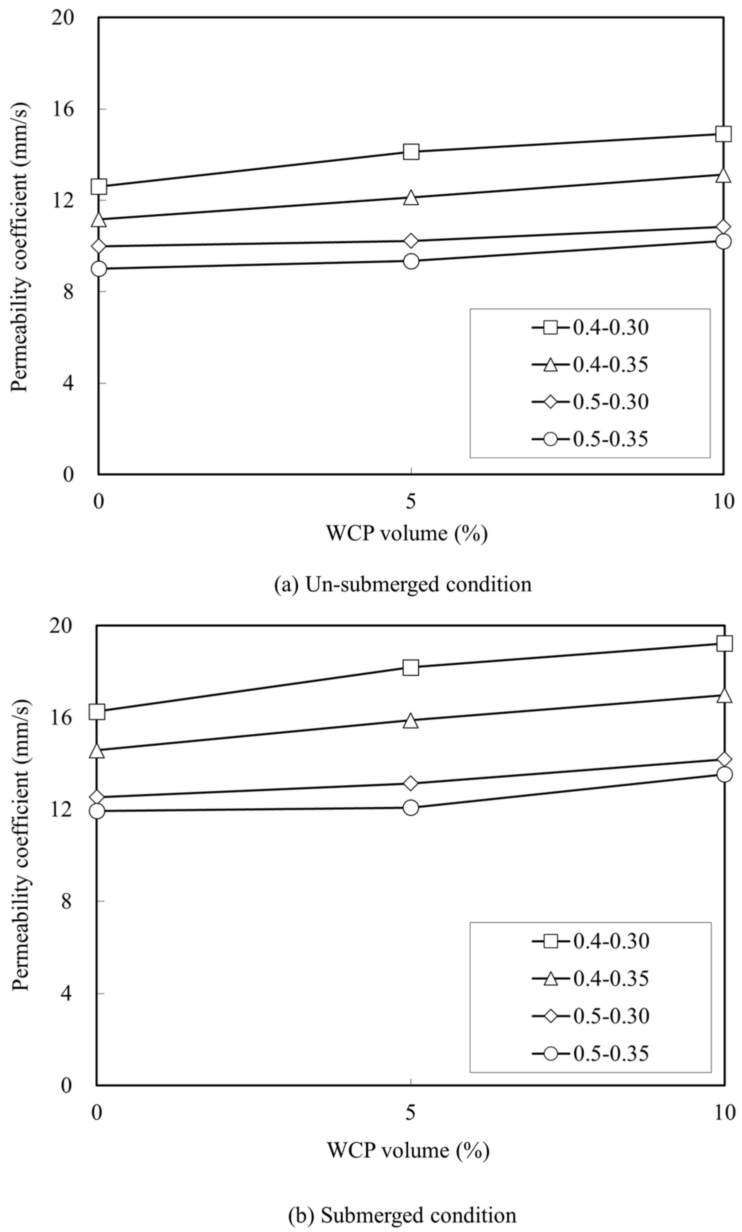


Figure 11. Variation in permeability coefficient.

From the plotted results, it can be seen that at a fixed WCP volume, when the P/A ratio or W/C ratio increased, both the un-submerged and submerged permeability coefficients decreased. The reason should be similar to that for the decrease in interconnected porosity;

that is, the increase in paste volume caused by a higher P/A ratio and the increase of water content caused by a higher W/C ratio both tended to cause more paste downward flow and more pore blockage near the bottom, thus resulting in the gradual decrease in water permeability as the P/A ratio and/or W/C ratio increased [66,67].

More importantly, at a fixed P/A ratio and W/C ratio, increasing the WCP volume significantly increased both the un-submerged and submerged permeability coefficients. For examples, at a P/A ratio of 0.4 and W/C ratio of 0.30, as the WCP volume increased from 0% to 10%, the un-submerged permeability coefficient increased from 12.60 mm/s to 14.91 mm/s, or in other words, increased by a relative proportion of 18.3%; and the submerged permeability coefficient increased from 16.26 mm/s to 19.23 mm/s, or in other words, increased by a relative proportion of 18.3%. The reason should be similar to that of the increase in interconnected porosity; that is, the incorporation of WCP had rendered the paste to become more cohesive [65], and thus reduced the paste downward flow and pore blockage at the bottom, which enhanced the water permeability.

3.4. Failure Mode and Cube Compressive Strength Results

The typical failure mode of the specimens was presented in the Figure 8. It can be seen that major and diagonal cracks went throughout both ends, showing that the specimen was collapsed mainly under shear failure. Similar phenomena can be found in other studies [68,69].

The cube strength results, listed in the 5th column of Table 3, reveal that the cube strength ranged between 5.91 MPa and 16.38 MPa. To graphically depict how the cube strength varied with the various mix parameters, the cube strength is plotted against the WCP volume at various P/A and W/C ratios in Figure 12. From the curves plotted, it is clear that regardless of the WCP volume, as the P/A ratio increased or the W/C ratio decreased, the cube strength increased. These phenomena are as expected because it is well known that increasing the P/A ratio would provide more paste to fill the gaps between aggregate particles to reduce the volume of voids, improve the compactness and finally increase the strength of pervious concrete [57,61] and decreasing the W/C ratio would generally increase the strength of pervious concrete, provided of course the paste portion still has suitable rheology [70].

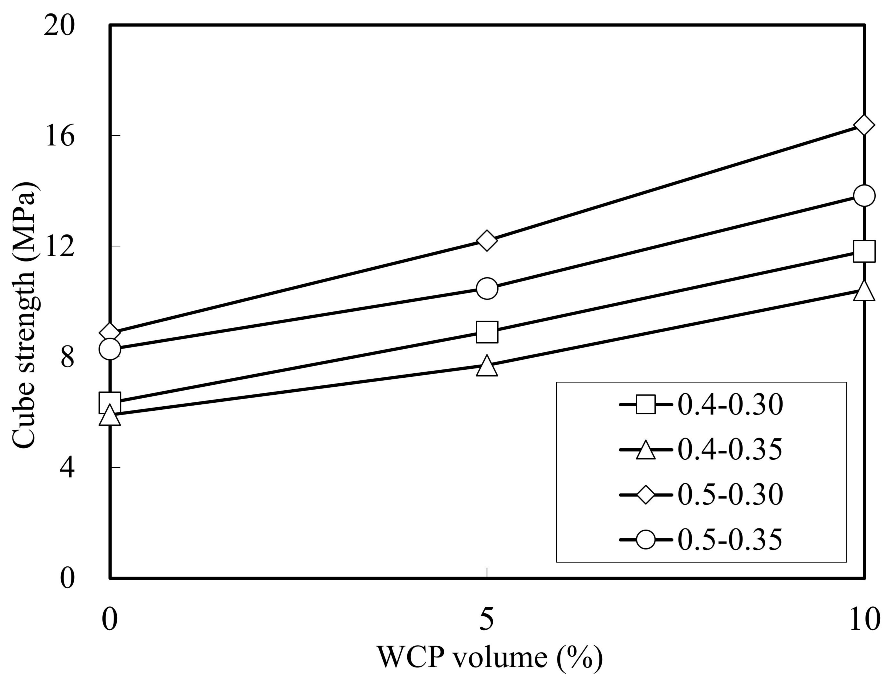


Figure 12. Variation in cube strength.

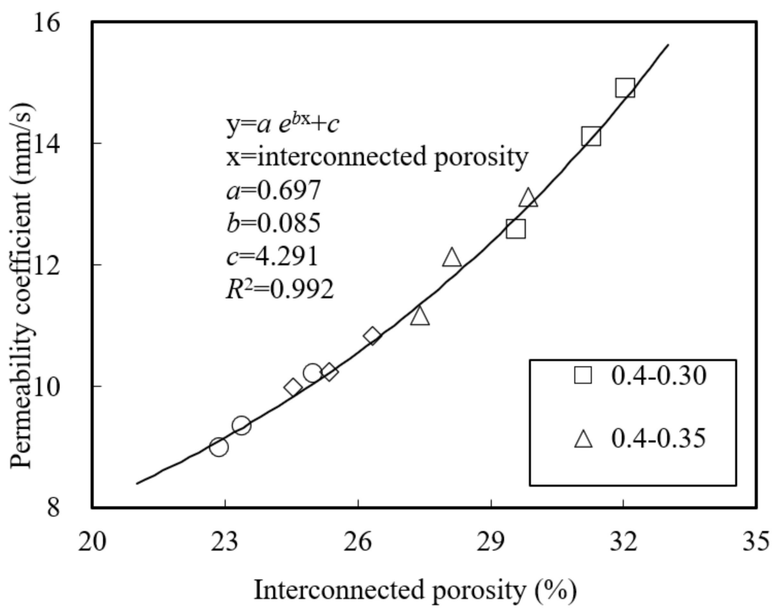
Most importantly, it is noted that regardless of the P/A ratio and W/C ratio, the addition of WCP had substantially enhanced the cube strength. For example, at P/A ratio of 0.4 and W/C ratio of 0.30, increasing the WCP volume from 0% to 10% improved the cube strength from 6.34 MPa to 11.82 MPa by as much as 86.4%. The underlying mechanism of such strength improvement due to addition of WCP as paste replacement may be explained as follows.

1. Unlike the cement replacement method, which increases the effective W/C ratio after cement replacement, the paste replacement method would not change the W/C ratio and thus at least would not reduce the strength [41,42].
2. As shown in Figure 3, the WCP has a median particle size intermediate between those of the cement and the coarse aggregate, and thus when added would form part of the paste and fill into the voids between coarse aggregate particles to increase the packing density, which would then improve the strength [71–73].
3. The WCP may contain some unreacted cement or supplementary cementitious materials from the old concrete, which could act in hydration reaction to increase the strength [30,74].

4. Comprehensive Analysis of Experimental Results

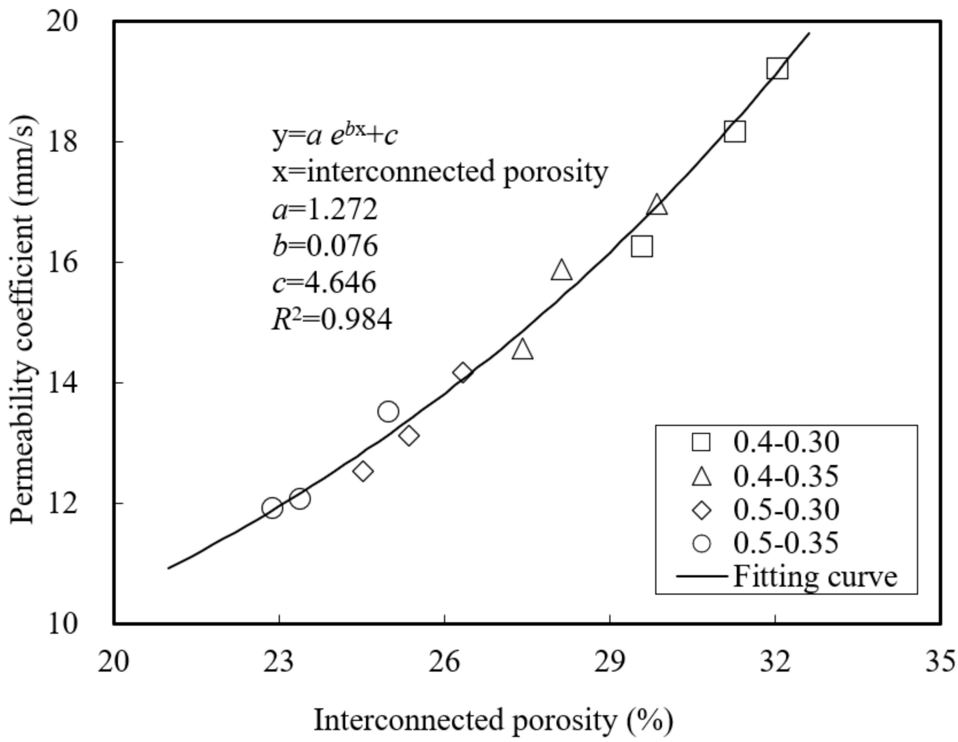
4.1. Correlation between Interconnected Porosity and Water Permeability

It is envisaged that an increase in interconnected porosity would allow more water to flow through and thus improve the water permeability. Hence, there should be a certain relation between the interconnected porosity and water permeability [57]. To study their relations, the un-submerged and submerged permeability coefficients are plotted against the interconnected porosity in Figure 13a,b, respectively. From the figures, it is clear that the un-submerged and submerged permeability coefficients both increased with the interconnected porosity. More interestingly, the data points in each graph lie closely to a certain curve indicating that in each graph there is a well-defined relation between the interconnected porosity and permeability coefficient. To determine the actual correlation, regression analysis has been carried out, and the best-fit curve so obtained is plotted in the graph to demonstrate how well it fits the data points. Very high R^2 values of 0.992 and 0.984 have been achieved, implying that there are very strong correlations between the interconnected porosity and un-submerged/submerged permeability coefficients of pervious concrete.



(**a**) Un-submerged condition

Figure 13. *Cont.*



(**b**) Submerged condition

Figure 13. Interconnected porosity versus permeability coefficient.

4.2. Improved Strength at Increased Permeability

It is not easy for a pervious concrete to attain both high strength and high water permeability at the same time because increasing the amount of pores in the concrete to increase the water permeability would reduce the strength whereas decreasing the amount of pores in the concrete to increase the strength would reduce the water permeability [75,76]. To illustrate the concurrent strength and permeability that had been attained by the pervious concrete produced herein, the cube strength and water permeability under the un-submerged and submerged conditions are plotted together in Figure 14a,b, respectively. As can be seen from these figures, when the P/A ratio increased from 0.4 to 0.5, the strength-permeability curve moved upwards and to the left, indicating that the increase in P/A ratio had increased the cube strength, but simultaneously decreased the water permeability. When the W/C ratio increased from 0.30 to 0.35, the strength-permeability curve moved downwards and to the left, showing that the increase in W/C ratio had decreased both the cube strength and water permeability. On the contrary, the grey arrow in each figure, which reveals the direction of movement of the strength-permeability curve when the WCP volume increased, points to the upwards-right direction, indicating that the increase in WCP volume had enhanced both the cube strength and water permeability of the pervious concrete. Hence, the addition of WCP as paste replacement is a particularly good method for the production of high-performance pervious concrete.

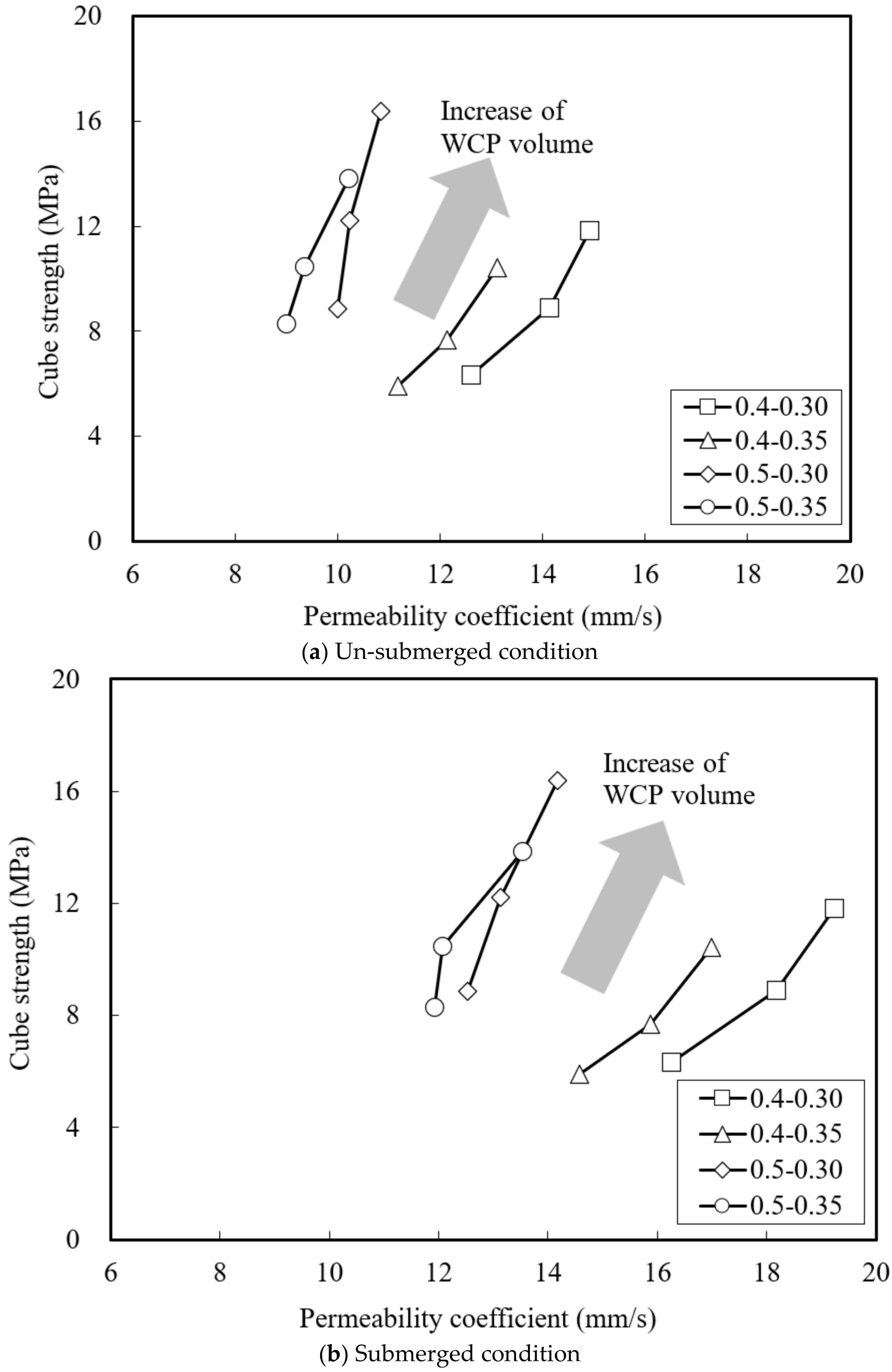


Figure 14. Cube strength versus permeability coefficient.

4.3. Improved Strength at Reduced Cement Content

For eco-friendliness, the cement content, which has a large carbon footprint, should be as low as possible. However, in most cases, lowering the cement content would adversely affect the strength and therefore it is not easy for a pervious concrete to attain both high strength and low cement content at the same time [77,78]. To evaluate the eco-friendliness of the pervious concretes produced herein, the cement contents of the pervious concrete mixes are presented in the last column of Table 3, and, to present graphically the concurrent increase in strength and decrease in cement content due to the addition of WCP as paste replacement, the cube strength and cement content at different P/A ratios and W/C ratios are plotted together in Figure 15. As shown in the figure, when the P/A ratio increased from 0.4 to 0.5, the strength-cement content curve moved upwards and to the right, indicating that the increase in P/A ratio had enhanced the cube strength, but increased the cement consumption. When the W/C ratio increased from 0.30 to 0.35, the strength-cement content curve moved downwards and to the left, showing that the increase in W/C ratio had decreased both the cube strength and cement consumption. More importantly, the grey arrow in the figure, which reveals the direction of movement of the strength-cement content curve when the WCP volume increased, points to the upwards-left direction, indicating that the increase in WCP volume had enhanced the cube strength and at the same time reduced the cement consumption. Hence, the addition of WCP as paste replacement is a particularly good method for the production of eco-friendly pervious concrete.

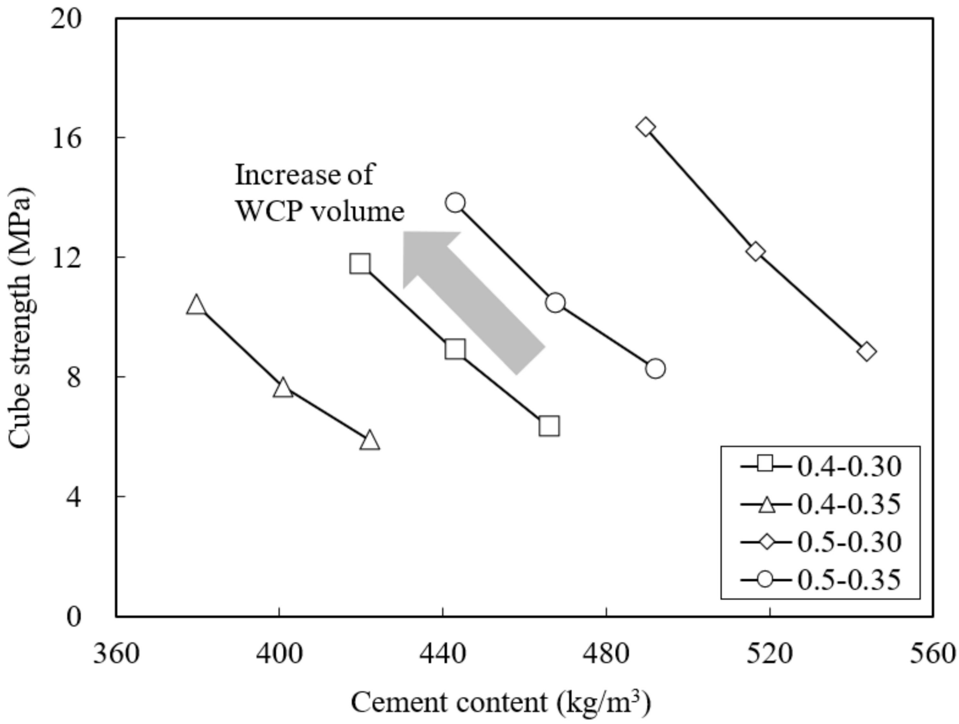


Figure 15. Cube strength versus cement content.

4.4. Proposed Mix Design for WCP Pervious Concrete

By considering permeability, strength and eco-friendliness together, some concrete mixes are proposed. From the permeability priority point of view, the concrete mix 0.4-0.30-10 (with P/A ratio of 0.4, W/C ratio of 0.30 and WCP replacement rate of 10%) is proposed, since it has the highest permeability coefficient as well as reasonably good strength and cement consumption. From the strength priority point of view, the concrete mix 0.5-0.30-10 (with P/A ratio of 0.5, W/C ratio of 0.30 and WCP replacement rate of 10%) is recommended, because it has the highest strength and reasonably good permeability coefficient and cement consumption.

5. Conclusions

To explore the feasibility of recycling waste concrete powder (WCP) using the paste replacement method (PR method), a series of pervious concrete mixes with 100% recycled coarse aggregate, various amounts of WCP added as paste replacement, and different paste/aggregate (P/A) ratios and water/cement (W/C) ratios have been produced and tested for the evaluation of their porosity, water permeability, cube strength and cement consumption. Based on the test results, the conclusions are drawn as follows:

1. By adjusting the water reducer dosage such that the paste portion of the concrete has the target slump of 20 to 40 mm, all the concrete mixes designed have achieved the suitable rheology for the production of pervious concrete.
2. Regression analysis showed that there are good correlations between the interconnected porosity and un-submerged/submerged water permeability.
3. The decrease in P/A ratio improved the interconnected porosity and water permeability, and reduced the cement consumption, but it diminished the cube strength.
4. The decrease in W/C ratio improved the interconnected porosity and water permeability and enhanced the cube strength, but it increased the cement consumption.
5. The addition of WCP as paste replacement can slightly improve the interconnected porosity and un-submerged/submerged water permeability, substantially enhance the cube strength and simultaneously reduce the cement consumption, carbon footprint and waste disposal.
6. From the permeability priority point of view, the concrete mix 0.4-0.30-10 is proposed, while from the strength priority point of view, the concrete mix 0.5-0.30-10 is recommended.
7. The proposed method of adding WCP by the PR method has great potential to be applied to the production of eco-friendly high-performance pervious concrete.

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