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Experimental study on properties of pervious concrete pavement materials

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Abstract

In this paper, a pervious concrete pavement material used for roadway is introduced. Using the common material and method, the strength of the pervious concrete is low. Using smaller sized aggregate, silica fume (SF), and superplasticizer (SP) in the pervious concrete can enhance the strength of pervious concrete greatly. The pervious pavement materials that composed of a surface layer and a base layer were made. The compressive strength of the composite can reach 50 MPa and the flexural strength 6 MPa. The water penetration, abrasion resistance, and freezing and thawing durability of the materials are also very good. It can be applied to both the footpath and the vehicle road. It is an environment-friendly pavement material.

Keywords: Concrete; Permeability; Mechanical properties; Durability

1. Introduction

Our cities are being covered with building and the air-proof concrete road more and more. In addition, the environment of city is far from natural. Because of the lack of water permeability and air permeability of the common concrete pavement, the rainwater is not filtered underground. Without constant supply of water to the soil, plants are difficult to grow normally. In addition, it is difficult for soil to exchange heat and moisture with air; therefore, the temperature and humidity of the Earth's surface in large cities cannot be adjusted. This brings the phenomenon of hot island in city. At the same time, the plash on the road during a rainy day reduces the safety of traffic of vehicle and foot passenger. The pervious concrete pavement possesses many advantages that improves city environment as follows:

1. The rainwater can quickly filter into ground, so the groundwater resources can renew in time.
2. As the pavement is air permeable and water permeable, the soil underneath can be kept wet. It improves the environment of road surface.
3. The pervious concrete pavement can absorb the noise of vehicles, which creates quiet and comfortable environment. In rainy days, the pervious concrete pavement has no plash on the surface and does not glisten at night. This improves the comfort and safety of drivers.
4. The pervious concrete pavement materials have holes that can cumulate heat. Such pavement can adjust the temperature and humidity of the Earth's surface and eliminates the phenomenon of hot island in cities.

The research on pervious pavement materials has begun in developed countries such as the US and Japan since 1980s. However, the strength of the material is relatively low because of its porosity. The compressive strength of the material can only reach about 20–30 MPa. Such materials cannot be used as pavement due to low strength. The pervious concrete can only be applied to squares, footpaths, parking lots, and paths in parks [1–3]. Using selected aggregates, fine mineral admixtures, and organic intensifiers and by adjusting the concrete mix proportion, strength, and abrasion resistance can improve the pervious concrete greatly.

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2. The pervious concrete model and measures for improving strength

A model of the pervious concrete is shown in Fig. 1. The pervious concrete is a porous composite material. The single-diameter aggregate forms the concrete framework. The cement paste or mortar binds the aggregate together. There are many pores with diameters above 1 mm in the pervious concrete, so water can penetrate through the concrete quickly, but the strength of the pervious concrete is relatively low due to the pores.

Based on the model of the pervious concrete, when the concrete is subjected to loading, the load is transferred through the cement paste between aggregates. The strength of aggregate is high, whereas the strength of cement paste and the interface between the cement paste and the aggregate is relatively weak. In addition, the cement paste binder layer is very thin. Therefore, the pervious concrete always fails at the binder layer between the aggregates. Therefore, increasing the cement paste binder area and enhancing the strength of cement binder are the keys in improving the pervious concrete strength. In this study, two methods were used to improve the strength and other mechanical properties of the pervious concrete.

2.1. Increasing the cement paste binder area

Since the material must be permeable, the voids between aggregate particles cannot be entirely filled by cement paste. Using smaller size aggregate can increase the number of aggregate particles per unit volume of concrete. As the aggregate particles increase, the specific surface of the aggregate and the binding area increases. This results in an improvement in the strength of concrete.

2.2. Enhancing the strength of the cement binder

Because the hardened cement paste is thin, the strength of the cement binder is low. There exist some pores and microcracks in the hardened cement paste, which influences the cement paste strength greatly. The quantity of pores and microcracks in the transition zone is even more, which also reduces the strength of the concrete greatly.

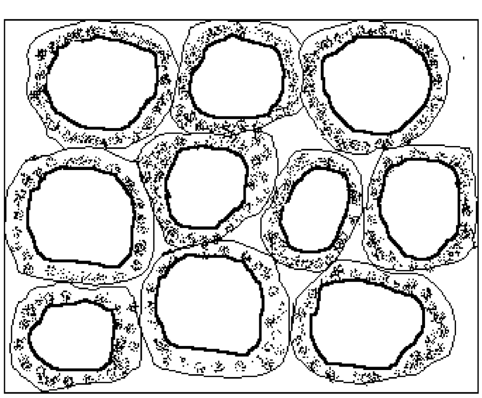

Fig. 1. A schematic model of pervious concrete.

In this study, fine mineral admixture and organic intensifier were incorporated in concrete to improve the microstructure and strength of the cement paste binder. The diameter of the pores in the cement paste is mostly between 5 and 50 μm. After incorporating the fine mineral admixture, that diameter is reduced to about 0.1–0.2 μm, these superfine particles can fill in the pores and increase the density of cement paste binder. It also reduced the thickness of the transition zone between the aggregate and cement paste. Therefore, the strength of cement paste binder can be enhanced.

The organic intensifier is mostly polymer that has good bond property. It is mixed into concrete to improve the bond property of cement paste and aggregate. Due to its good filling property, the organic intensifier can fill the pores of the cement paste to enhance its strength.

Table 1
Mineralogical composition and mechanical properties of Portland cement used

Mineralogical composition (%)				Physical properties			28-Day strength (MPa)	
C_3S	C_2S	C_3A	C_4AF	Initial setting time (h:min)	Final setting time (h:min)	Specific surface area (m^2/kg)	Compressive strength	Flexural strength
52.6	24.4	7.9	10.6	2:04	2:58	300	63.9	10.5

3. Experimental method

3.1. Materials

Ordinary Portland cement: The mineralogical composition and physical properties of the cement used are shown in Table 1.

Aggregate: As shown in Table 2, four size ranges of gravel were used as coarse aggregate (G) and the sand with diameter of less than 2.5 mm was used as fine aggregate (S).

Silica fume (SF): The SiO_2 content is 92.45%. The specific surface area is about 18,000 m2/kg.

Superplasticizer (SP): The SP is liquor of the phenolic aldehyde. Its density is 1.1 g/cm^3 and has 31% solid content.

Table 2
Diameter ranges of aggregates used (mm)

	Sample				
	G1	G2	G3	G4	S
Diameter range	15–30	10–20	5–10	3–5	<2.5

Vinyl acetate–ethylene emulsion (VAE): The VAE emulsion is fluid, milk-white dispersions of copolymers of vinyl acetate and ethylene in water. The solid content of the emulsion is 55%. Its pH value is 4.5 and density is 1.07 g/cm^3.

Polyvinyl alcohol formaldehyde hydrosol (PAF): The PAF hydrosol is a limpid solution of polyvinyl alcohol formaldehyde. The solid content of the hydrosol is 8% and the density is 1.04 g/cm^3.

3.2. Preparation and conservation of sample

The samples were pressed under the 1.5-MPa compressive stress. The workability of mixture was measured with the V. Bahrner denseness mensuration. The V. Bahrner value was controlled to be 20–25 s. When the samples were composite of base and surface layers, the mixtures must be paved twice and be pressed once. After molding, the sample must be covered with plastic membrane to hold the moisture in concrete. After 24 h, the sample was removed out of the mold and put into conversation room for 28 days. The temperature in the conversation room was 20 °C and the relative humidity was above 95%.

The samples had three sizes. The sample, whose size was 100 × 200 × 60 mm, was used to measure the restricted compressive strength. The sample, whose size was 100 × 300 × 60 mm, was used to measure the flexural strength. The sample, whose size was 100 × 100 × 60 mm, was used to measure water penetration coefficient.

3.3. Property testing method

3.3.1. Compressive strength

Referring to the standard of JC446-91 [4], which was published by the Chinese building material industry, the sample was restricted to be pressed to wreck. The outside force was loaded under the rate of 0.3–0.5 MPa/s. As shown in Fig. 2, the pressing area is 120 × 60 mm. The strength values were acquired from five samples from each group.

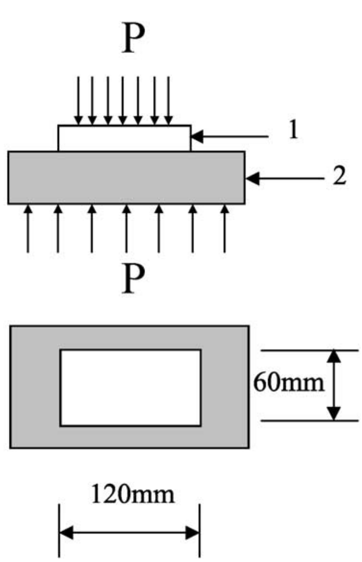

Fig. 2. Compressive strength measuring sketch (1 = pad, 2 = specimen).

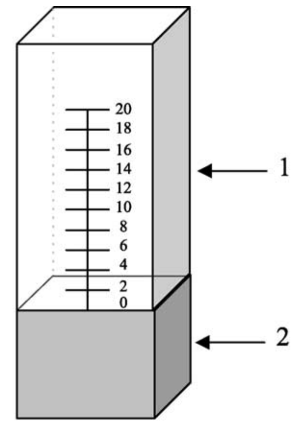

Fig. 3. Water penetration coefficient measuring sketch (1 = device, 2 = specimen).

3.3.2. Flexural strength

The flexural strength was measured with the three-points method. The fulcrum span was 240 mm and the load rate was about 0.1–0.2 MPa/s. The flexural strength values were acquired from five samples from each group.

3.3.3. Water penetration coefficient

The water penetration coefficient was measured with the device that was designed by us. As shown in Fig. 3, the device size is 100 × 100 × 300 mm. It is an organic glass pane and is ringent in both ends. The surface of sample was

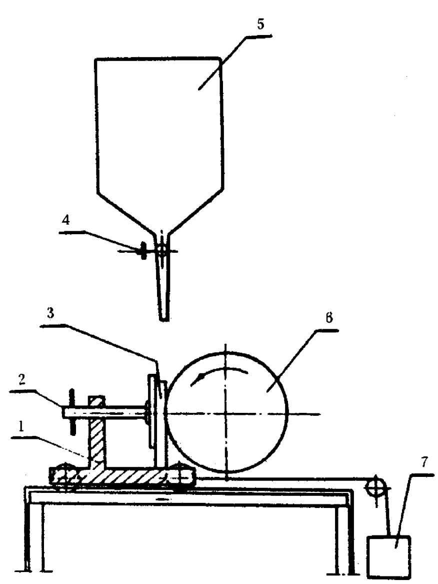

Fig. 4. Sketch of the grinding device (1 = sample bracket, 2 = lock bolt, 3 = sample, 4 = adjustable valve, 5 = hopper, 6 = steel wheel, 7 = plummet).

Table 3
Properties of pervious concrete made with aggregate of different sizes

Mixture number	Aggregate size (mm)	Percentage of fine aggregate (%)	Water-to-cement ratio	28-Day compressive strength (MPa)	Water penetration coefficient (mm/s)	Unit weight (kg/m^3)
T1	15–30	15	0.33	7.1	7.8	1839
T2	10–20	15	0.35	9.8	8.3	1947
T3	5–10	20	0.35	13.8	8.9	1851

air-proofed with wax before measuring. The device was put on the sample. The warm wax was used to air-proof the space between the device and sample. After the wax became cold and hard, water was injected into the device. When the water line reached 200 mm, the injection of water was stopped. When the water line decreased to 160 mm, the timer was started. When the water line reached 140 mm, the timer was stopped. The water penetration coefficient (V) can be calculated out by next equation.

$$V = H/t$$

where V is the water penetration coefficient (mm/s), H is the height of the water line from 160 to 140 mm (20 mm), and t is the time (s) when the water line fell from 160 to 140 mm.

3.3.4. Abrasion resistance of concrete surface

Referring to the standard of JC446-91 [4], the test set-up is shown in Fig. 4. The width of the grind wheel is 70 mm. The wheel was kept contact to the sample surface, and the wheel was turned with a rate of 75 rpm. At the same time, the standard sand was dropped between the wheel and the sample surface. The grinding continued for 1 min, and the length of grinding trace on the sample surface was measured.

3.3.5. Freezing and thawing durability

After 28 days of curing, the specimens were soaked in water with a temperature of 10–30 °C for 48 h. The freezing and thawing durability test was then started. After freezing in air with a temperature of − 15 °C for 5 h, the specimens was put into water to thaw. The temperature of the water was 10–30 °C. After 25 cycles of freezing and thawing, the mass and strength loss were measured. The results of the strength were compared to those of the specimens not exposed to freezing and thawing, and the strength loss was then calculated. For each concrete mixture, five specimens were used for the freezing and thawing test and another five were used as controls [4].

4. Results and discussion

4.1. Effect of the aggregate size on the properties of pervious concrete

As shown in Table 3, three different sizes of the aggregate were used to the pervious concrete. The strength, apparent density, and water penetration coefficient of the concrete were measured. It is obvious that the pervious concrete strength is relatively low due to its high porosity. When the mix proportion and the apparent density of the concrete are approximately same, reducing the aggregate size seems to increase the concrete strength. This may be attributed to the fact that the smaller aggregate size may improve the strength of the interface between the aggregate and cement paste.

4.2. Effect of SF and SP on the properties of pervious concrete

The results are given in Table 4, and the smaller aggregate of G3 and G4 were used for the part of the study on the effect of SF and SP on the strength and water penetration coefficient of pervious concrete.

The mixture T4 used the aggregate with the diameter of 5–10 mm. When 6% SF was used but without SP, the strength was higher than that of mixture T3 in Table 3, but it was still at a low level of 20 MPa because of the poor dispersion of the SF particles. Both SF and SP were used in mixture of T5. Its strength increased to 35 MPa,

Table 4
Effect of SF and SP on the properties of pervious concrete

Mixture number	Aggregate size (mm)	Percentage of fine aggregate (%)	Water-to-cement ratio	Percentage of SF[a] (%)	Percentage of SP[a] (%)	28-Day compressive strength (MPa)	Water penetration coefficient (mm/s)	Unit weight (kg/m^3)
T3	5–10	20	0.35	0	0	13.8	8.9	1851
T4	5–10	20	0.28	6	0	20.1	1.9	2100
T5	5–10	20	0.22	6	0.8	35.5	2.9	2050
T6	3–5	0	0.2	6	0.8	26.7	20.0	1880
T7	3–5	0	0.2	6	0.8	57.2	1.7	2155

[a] The SF and SP dosage is the percentage of the binder.

Table 5
Results of the properties of pervious concrete that different intensifiers were used

Mixture number	Type of additives	Dosage[a] (%)	Percentage of SP[a] (%)	Water-to-cement ratio[b]	28-Day compressive strength (MPa)	Unit weight (kg/m^3)	Length of abrasion trace (mm)	Water penetration coefficient (mm/s)
T7	SF	6	0.8	0.20	57.2	2155	29.2	1.7
T8	VAE	15	–	0.28	61.2	2315	31.3	0.30
T9	PAF	30	–	0.35	52.1	2210	34.7	2.29

[a] The dosage of additives and SP is the percentage of the binder.
[b] The water-to-cement ratio included the water in VAE or PAF.

and the water penetration coefficient was 2.9 mm/s. It seemed that the use of both SF and SP could gain good effect.

The mixtures T6 and T7 used the smaller sized aggregate with diameter of 3–5 mm and a combination of SF and SP. The mixture T6 was controlled to have more voids by decreasing molding pressure to 1.0 MPa. Its unit weight is lower and the water penetration coefficient is higher. The molding pressure to mixture T7 was increased to 2.0 MPa and its strength was increased to 57 MPa and its water penetration coefficient was reduced to 1.7 mm/s. The results indicated that by using smaller aggregate, SF, and SP, pervious concrete of both high strength and good water penetration could be produced.

4.3. Comparison of the effect of a combination of SF and SP and of polymer

As shown in Table 5, mixtures T7–T9 used the aggregate with the diameter of 3–5 mm. The sample of T7 used SF and SP, the mixture T8 used the VAE emulsion, and the mixture T9 used the PAF hydrosol. The properties of each pervious concrete sample are given in Table 5. It is obvious that the use of organic additives improved the strength of pervious concrete greatly. However, the VAE emulsion appeared to fill more voids in concrete. The concrete became close-grained and the water penetration coefficient decreased to 0.3 mm/s, which is too low for water to penetrate. The effect of the PAF hydrosol was not as good as that of SF and VAE. As its dosage was 30%, the cost was very high. The surface abrasion resistance of the concrete that used PAF was worse than the one that used SF and SP. After comparing the effect of these three additives, we can conclude that the SF is the best intensifier for improving the properties of the pervious concrete when used with SP.

4.4. Properties of pervious concrete pavement materials with a surface and a base layer

Based on the experimental study, considering the smooth pavement surface and the permanence of water penetration, we decided that the pervious pavement materials could be made with a base layer and a surface layer. The composite materials properties such as strength, water penetration, abrasion resistance, and freezing and thawing durability have been all measured. The thickness of the surface layer was about 10 mm, with maximum aggregate size of 3–5 mm. The proportion of the mixture T7 was used as the surface layer. The thickness of the base layer was about 50 mm with maximum aggregate size of 5–10 mm. The proportion of the mixture T5 was used as the base layer. The composite specimens were prepared in accordance with the technique that the mixture must be paved twice (once is for the base layer and the other is for the surface layer) and were compacted by pressing and vibration. Two methods were used for curing. One is standard curing at a temperature of 20 ± 2 °C and a relative humidity of above 95%. The other is putting the specimens outside and watering them once everyday. The air temperature outside was 10–20 °C. The specimens were cured for 28 days, and the properties of the materials are shown in Table 6.

In Table 6, it can be seen that by incorporating SF and SP and by compacting the surface layer and base layer with pressing and vibration, the pervious pavement materials with excellent properties can be produced. The compressive strength of the composite can reach 50 MPa and the flexural strength 6 MPa. The water penetration,

Table 6
Results of the properties of the composite pervious concrete pavement materials

Mixture number	Curing method	28-Day compressive strength (MPa)	28-Day flexural strength (MPa)	Water penetration coefficient (mm/s)	Length of abrasion trace (mm)	Unit weight (kg/m^3)	25 cycles of freezing and thawing	
							Mass loss (%)	Strength loss (%)
TM1	standard	56.2	8.5	2.9	31	2250	0.25	15
TM2	outdoor	58.9	6.9	2.9	31	2170	0.15	23

abrasion resistance, and freezing and thawing durability of the materials were also very good. The properties exceeded those of the common pavement materials such as Portland cement concrete and asphalt concrete. Such pervious concrete pavement materials can apply to the motor vehicle road. One of the most significant advantages of such pavement materials is good water and air permeability. It reduces the plash on pavement, which is favorable to driving. It eliminates the glisten of road surface at night, which improves the safety of traffic. It also reduces traffic noise. The rainwater can penetrate into the underground through the pervious pavement. All of these are favorable to the natural balance of underground soil and city space. The pervious concrete is a promising, ecotypic, and environment-friendly pavement material.

5. Summary and conclusions

From the results obtained, the following conclusions may be drawn:

1. Due to voids in pervious concrete, it is difficult to obtain high-strength materials by using the common material and proportion of mixture.

2. Using smaller sized aggregate can enhance the strength of the pervious concrete. However, the cement quantity must be adjusted accordingly.

3. Using SF and SP in the pervious concrete can enhance the strength of pervious concrete greatly. Controlling the pressing force to keep the unit weight of 1900–2100 kg/m^3 can ensure good water penetration. The organic polymer also can enhance the strength of the pervious concrete greatly. However, it is difficult to ensure water penetration due to the polymer-filling property. Its cost is also high due to its high dosage.

4. The pervious pavement materials are composed of a surface layer and a base layer. The compressive strength of the composite can reach 50 MPa and the flexural strength 6 MPa. The water penetration, abrasion resistance, and freezing and thawing durability of the materials are also very good. It can be applied to both the footpath and the vehicle road. It is an environment-friendly pavement material.

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