

Research on the performance of sand-based environmental-friendly water permeable bricks

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Abstract. This paper examines the effects of the amount of admixture, the water cement ratio, the aggregate grading, and the cement aggregate ratio on the mechanical service properties and of porous concrete pavement bricks including strength, water permeability, frost resistance, and wear resistance. The admixture can enhance the performance of water permeable brick, and optimize the design mix. Experiments are conducted to determine the optimal mixing ratios which are given as; (1) the admixture (self-developed) within the content of 5% of the cement quality; (2) water-cement ratio equal to 0.34; (3) cement-aggregate ratio equal to 0.25; (4) fine aggregate of 70% (particle size 0.6-2.36mm); and coarse aggregate of 30% (particle size: 2.36-4.75mm). The experimental results that the sand-based permeable concrete pavement brick has a strength of 35.6MPa and that the water permeability coefficient is equal to 3.5×10^{-2} cm/s. In addition, it was found that the concrete water permeable brick has good frost resistance and surface wear resistance, and that its production costs are much lower than the similar sand-based water permeable bricks in China.

1. Introduction

Permeable concrete pavement brick is a kind of concrete pavement brick that can not only bear a large load, but also allow water to penetrate into the ground through the concrete surface[1]. Water permeable brick mainly consists of cement, special aggregate grading and water, after mixing admixture and through the processes of mixing, molding and curing technique, it has good water permeability as well as high strength. Compared with common concrete pavement brick, the water permeable brick can achieve the environmental benefits such as rainwater utilization, supplement of groundwater level and air circulation natural balance[2]. Water permeable brick is mainly used for the urban sidewalks, pedestrian streets, squares residential areas and parking lots[3]. Due to the superior ecological environment function of the permeable bricks, in recent years, it's especially recommended to be used by water permeable paving material in sponge city construction.

In China, there are few researches on sand-based water permeable concrete bricks, especially in the northern special climate the literature is on environmentally-friendly water permeable concrete bricks with sand as the main material is rare. In this paper, the characteristics of the material and the optimal mixture ratio as well as its economic and social benefits are analyzed through laboratory experiments. The application of sand-based environmentally-friendly water permeable concrete for pavement in cold regions as urban sidewalks, pedestrian streets, squares, residential areas and parking lots pavement tiles is developed, and it can play an important role in sponge city construction and eco-green construction, as well as providing corresponding basis and reference for future scientific research and engineering practice.



2. Raw materials and test methods

2.1. Raw materials

The raw materials used in this test mainly include cement, aggregate, admixture and water. The specific properties and parameters of the material are as follows:

Cement: Tangshan Jidong Cement Plant shield P • O 42.5R, performance index as shown in Tab.1.

Aggregate: The local sand and stone chips of Hohhot, the apparent density of fine aggregate is 2.65g/cm^3 , the moisture content is 0.38%, the apparent density of coarse aggregate is 2.85g/cm^3 , the crush value is 6.10%. Aggregate grading design, as shown in Tab. 2.

Admixture: Self-developed admixture (hereinafter referred to as admixture) is mainly composed of three functional components powder: Effectively enhance the physical strength of water permeable brick, to improve its bond strength and cohesion; Improve the water permeable brick water retention and density, Thereby enhancing its strength, wear resistance and frost resistance; reduce the water-cement ratio, increase strength and resistance to freeze-thaw damage.

Water: Drinking tap water.

Table 1. Cement performance index

Cement varieties	Standard thick water (%)	Initial setting Time (min)	Final condensate Time (min)	Compressive strength (MPa)			Flexural strength (MPa)		
				3d	7d	28d	3d	7d	28d
				P•O42.5R	137.5	163	198	28.2	46.2

Table 2. Aggregate grading design

Particle size range / mm	Particle size within the mass ratio of the total mass /%
0~0.6	38.9
0.6~2.36	38.1
2.36~4.75	12.1
>4.75	10.9

2.2. Test methods

The test includes three stages: the first stage is the admixture mortar mix test which aims to determine the appropriate dosage of admixture; the second stage is analyzing the effects of water-cement ratio, aggregate particle size and cement-aggregate ratio of sand-based water permeable brick on the brick's strength, water permeability, and to determine the most suitable ratio; the third stage is the tests about physical performance and road performance of the optimal ratio of the sand-based pervious concrete pavement brick based on the "Permeable paving bricks and permeable paving flags" (GB/T 25993-2010) [4].

2.2.1. Sample preparation. Prepare the material based on volume ratio. An electronic balance with precision of 0.1g is used to weighed aggregate, cement and admixture. Then the mixture are put into HJW-60 concrete mixer for 1min, and then add in water and continue mixing for 4min. After mixing, the mixture was divided into two layers and put into the two samples whose the size is $200 \times 100 \times 60\text{mm}$. While installing the first layer, put about 1200g mortar in per mold, with a sow feeder sowing, and then vibrated with a vibration table for 15 seconds, and then loaded the second layer, vibrate for 15 seconds after sowing, use the hammer thrash 40 times and tamping corner after the vibration molding. Demoulding and put the bricks into the standard curing room maintenance to the required age after 24h.

2.2.2. *Permeability brick strength test method.* According to the compressive strength test method of "Permeable Brick" (JC/T 945-2005) [5], the YAW-2000D automatic pressure testing machine is adopted in the testing machine and 120×60×30mm steel is selected as press plate, After soaking in room temperature water for 24 hours, wipe the wet surface with wet towel which is wring out and place it in the center of the lower platen of the testing machine. Then put the press plate on the center of the upper surface of the specimen symmetrically and start the testing machine. Set the loading speed of 0.5MPa/s, record the load when the sample is damaged. Compressive strength can be calculated according to equation (1) .

$$R_c = \frac{P}{A} \quad (1)$$

Where: R_c - Compressive strength, unit for MPa;

P - Failure load, unit for N;

A - The upper surface area of the test-piece, unit for mm²;

Test take the average compressive strength of five samples.

2.2.3. *Permeability coefficient test method.* According to " Permeable paving bricks and permeable paving flags " (GB/T 25993-2010) [4], three cylinders of diameter Φ75mm are drilled on the sand-based water permeable bricks respectively, as shown in Fig.1, The samples are sealed with tape and putted into vacuum plant, pump to 90kPa vacuum for 30min, add tap water until the water layer is 10cm higher than the sample, then stop pumping vacuum, soaking for 20min, remove it into the permeability meter, as shown 2, use plasticine to seal the sample to the water-permeable cylinder. Open the water supply valve, the airless water (90kPa under vacuum pumping to bubble-free) poured into the container, the water-permeable cylinder maintain the water level of 150mm, when the overflow port and water-permeable cylinder's overflow out of steady water flow, using the measuring cylinder collects the airless water overflowing from the outlet, records the water yield (Q) for five minutes, measures three times averaged. Fig.1 and Fig. 2 show the core sample and the permeability meter. Water permeability coefficient can be calculated according to equation (2) :

$$k_T = \frac{QL}{AHt} \quad (2)$$

Where: k_T - Water permeation coefficient of the sample when the water temperature is T°C, unit for cm/s;

Q - Water yield in seconds t , unit for mL;

L - The thickness of the sample, unit for cm;

A - The upper surface area of the test-piece, unit for mm².

t - Time, unit for s.

The experiment to 15°C water temperature as the standard temperature, the standard temperature of the water permeability coefficient according equation (3) to calculate:

$$k_{15} = k_T \frac{\eta_T}{\eta_{15}} \quad (3)$$

Where: k_{15} - The standard temperature of the water permeability coefficient of the sample, unit for cm/s;

η_T - The dynamic viscosity coefficient of water at T°C, unit for kPa·s;

η_{15} - The dynamic viscosity coefficient of water at 15°C, unit for kPa·s

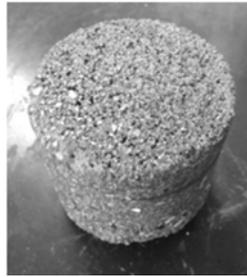


Figure.1 Core sample

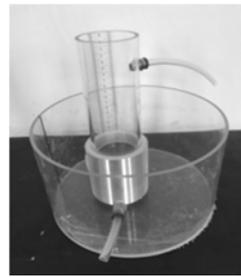


Figure.2 Permeability meter

2.2.4. Water retention test method. The three pieces of water permeable bricks are dried in a drum wind dryer at a temperature of 110°C and the qualities are weighed once every 24 hours until the difference between two consecutive tests are less than 0.1%. The mass m_1 is recorded and the sample are cooled to room temperature and then inject 20°C airless water until 20mm above the sample surface. Remove the sample after 24 hours, wipe the surface water with a wet towel, immediately weighed, record the quality of m_2 , water retention according equation (4) to calculate, take the average of three samples and record.

$$B = \frac{m_2 - m_1}{A_1} \quad (4)$$

Where: B - water retention, unit for g/cm²;

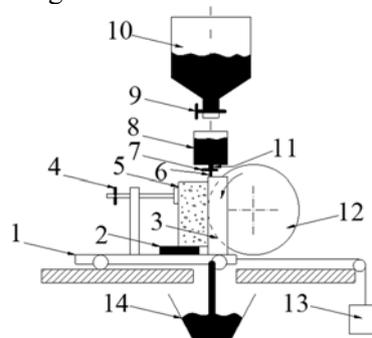
A - The upper surface area of the test-piece, unit for mm².

2.2.5. Frost resistance test method. 10 water permeable bricks are divided into two groups equally. Put one group into the water of temperature of 20°C for 24 hours, as -18 °C in the antifreeze test machine, after 25 freeze-thaw cycles record the compressive strength of R_D , the other group into the standard room, until the end of the freeze-thaw cycle and measure compressive strength R . Compressive strength loss rate according equation (5) to calculate:

$$B = \frac{R - R_D}{R} \times 100\% \quad (5)$$

Where: B - loss rate of compressive strength after freeze-thaw cycles, unit for %.

2.2.6. Wear resistance test method. Test the pavement performance of optimal mixing ratio water permeable, wear resistance: Use of the GLN-6-type concrete pavement brick wheel wear resistance test machine, as shown in Fig.3, with the 14kg weights wearing 2min, abrasive selection of corundum, use a vernier caliper to measure the length of mill and record it.



1-Clamping block 2-Pad 3-Guide slot 4-Fastening bolt 5-Test piece 6-Abrasive flow
7-Diversion regulating valve 8-Diversion bucket 9-Abrasive hopper control valve 10-Abrasive hopper
11- Rectangular discharge port 12 - Friction steel wheel 13-Counterweight 14 - Abrasive collector;

Figure. 3 GLN-6 steel wheel wear test machine

3. Results and discussion

3.1. Influence of the amount of admixture on cement strength

Addition of admixture cement mortar strength test, admixture mixed with cement quality 0%, 1%, 3%, 5%, 8%, contrast five kinds of mix combination, water-cement ratio is 0.32, based on "Method of testing cements-Determination of strength "(GB/T 17671-1999)[6], the results of compressive strength test are shown in Fig. 4, the flexural strength test results are shown in Fig. 5.

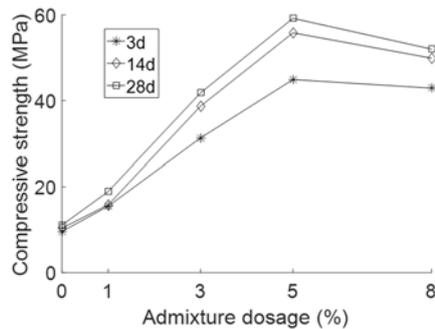


Figure.4 Compressive strength curve of cement mortar

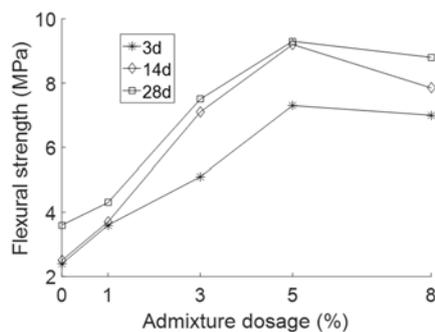


Figure.5 Cement mortar flexural strength curve

From Fig.4 and Fig.5, it can be seen that the admixture can significantly improve the strength of cement, and the strength of cement increases first and then decreases with the increase of admixture. this is due to bleeding and segregation of concrete when the admixture is in excess, thereby reducing its strength. The compressive strength of samples 28d without adding admixture is 11.1MPa and the flexural strength is 3.6MPa. When the quantity of admixture is 5%, the samples compressive strength is 59.2MPa, which is higher than that of pure cement mortar 13.6%; flexural strength is 9.3MPa, higher than pure cement mortar 10.7%, significant enhancement, and can reduce the amount of cement. Through the comparison of the strength which maintenance to 3d, 14d and 28d, it is found that with the increase of the content of admixture, the strength growth rate of cement increases first and then decreases. When the quantity of admixture is 5%, The strength of more than 94% of the 28d intensity, is conducive to improving the actual progress of the project.

3.2. Influence of Water-Cement Ratio on the Performance of Sand-Based Permeable Brick

In order to study the effect of water-cement ratio on the performance of permeable brick designed for fine aggregate gradation, the design water-cement ratios are 0.28, 0.30, 0.32, 0.34, 0.36, 0.38 respectively. Admixture within the content of 5% of the cement quality, when the aggregate grading is 0~0.6mm, the surface of the water permeable brick formed is dense, although the proportion of the particle size in this range is high, because of its poor water permeability, the sand with the particle size of 0.6~2.36mm is selected as the aggregate, the proportion of particle size is 38.1%, and the cement-

aggregate ratio is 0.32. The compressive strength and water permeable coefficient are measured 28 days after standard curing, as shown in Fig.6.

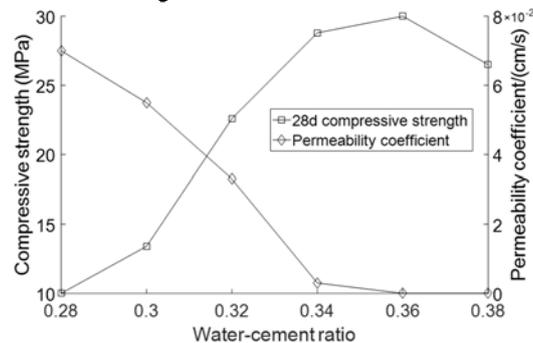


Figure. 6 Influence of water-cement ratio on the performance of sand-based water permeable brick

As shown in Fig.6, the water-cement ratio has a great effect on the compressive strength and water permeability coefficient of fine aggregate grading water permeable brick. The strength of water permeable brick increases first and then decreases with the increase of water-cement ratio. The reason is that when the water-cement ratio is relatively low, the water permeable brick is less coated with the cementitious material and the aggregates are not completely encapsulated by the cementitious material, thereby reduce the adhesion between the particles and lead to reducing the strength of water permeable brick; on the contrary, when the water-cement ratio is relatively high, the gelled slurry wrapped in the outer layer of the aggregate will peel off the aggregate surface due to vibration and gravity, block the internal voids of the water permeable brick and form a slurry layer at the bottom of the sample, making the uneven distribution of the gelled slurry, not only reduce the strength of water permeable brick, but also affect the water permeability. When the water-cement ratio is 0.36, the maximum compressive strength is 30MPa. When the water-cement ratio increases from 0.34 to 0.36, the strength increases slowly, as the water permeability coefficient of water permeable brick decreases with the increase of water-cement ratio, select the water-cement ratio is 0.34. When the permeable brick is only 0.6~2.36mm particle size of the sand as aggregate, while meeting JC/T 945-2005 "Water Permeable Brick" [5] Cc30 water permeable brick compressive strength of 30.0MPa requirement, Its water permeability coefficient is too low.

Admixture within the content of 5% of the cement quality, the water-cement ratio is 0.34 and the cement-aggregate ratio is 0.32. On the basis of sieving fine aggregate with particle size of 0.6~2.26mm, mix particle size 2.36~4.75mm sand, standard curing 28d and measured its compressive strength and water permeability coefficient, as shown in Fig.7.

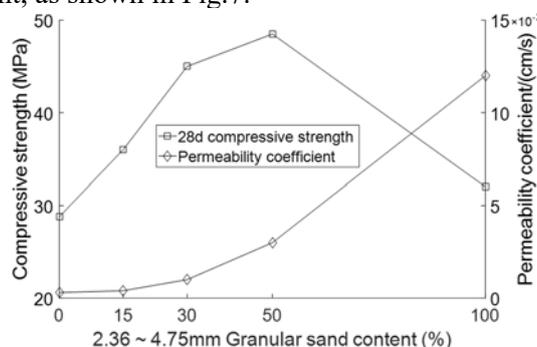


Figure. 7 Influence of gravel grading on the performance of sand-based water permeable brick

It can be seen from Fig.7 that with the increase of 2.36~4.75mm particle size sand, the strength of the permeable brick first increases and then decreases, and the water permeability of the water permeable brick increases gradually, because when the amount of cement is constant, mix the coarse aggregate can increase the volume fraction of aggregates to improve the compressive strength of the

water permeable brick, and the incorporation of 2.36~4.75mm sand can form a continuous grading, the workability of continuous grading is significantly better than the single grading, it's showed in the early stage, and with the increase of age more obvious, thus affecting its compressive strength. Single-particle gradation sinks during forming, making the binder in the permeable brick non-uniform, causing it to reduce its strength. When the dosage is 30%~50%, the compressive strength of the permeable brick can be effectively improved. However, when the content is too high, not only the strength increases slowly, but also the economic cost is increased. Therefore, determine the content of 2.36~4.75mm sand is 30%.

3.3. Cement-aggregate ratio on the performance of sand-based water permeable brick

In order to study the effect of cement-aggregate ratio on the performance of sand-based water permeable brick, the cement-aggregate was designed as follows: 0.23, 0.25, 0.27, 0.29, 0.31, 0.33, the compressive strength and water permeability coefficient as shown in Fig.8.

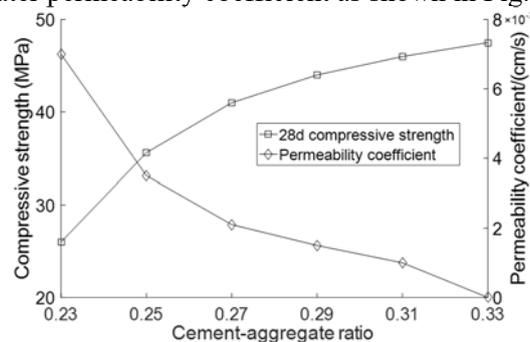


Figure. 8 Influence of cement-aggregate ratio on the performance of sand-based water permeable brick

As can be seen from Fig.8, as the cement-aggregate ratio increases, the strength of the water permeable brick gradually increases, but its water permeability gradually decreases, this is because when the raw materials and manufacture methods are the same, as the amount of sand increases, the water permeable brick's internal bond areas and bonding points decrease, resulting in its strength gradually decreased, increasing the amount of cement will make the contact point between the aggregate into contact with the surface, the strength increases, but too much cement amount will make the gap between the aggregate becomes smaller, as the cement paste with mobility, and even plug the original connectivity of the gap, resulting in a substantial reduction of its permeability. In meeting the requirements of "Water Permeable Brick" (JC/T 945-2005) [5], the compressive strength of water permeable brick should be minimum 30MPa and water permeability coefficient (15°C) $\geq 1.0 \times 10^{-2}$ cm/s, With a view to reducing economic costs. Therefore, the final selected optimal ratio for the admixture within the content of 5% of the cement quality, water-cement ratio is 0.34, aggregate gradation: particle size 0.6~2.36mm accounting for 70% of the total mass of the aggregate, particle size 2.36~4.75mm accounted for 30% of the total mass of the aggregate. The strength of the sand-based water permeable concrete brick is 35.6MPa and the water permeability coefficient is 3.5×10^{-2} cm/s.

3.4. Pavement Practical Performance

The practical performance test of pavement, including water retention, frost resistance and wear resistance, of the selected optimal sand-based water permeable concrete pavement brick is shown in Tab. 3.

Table 3. Pavement practicality test value

project	requirements	Measured value
Wear resistance	Grind pit length not more than 35mm	15mm
Frost resistance	After 25 freeze-thaw cycles, the compressive strength loss rate shall not exceed 20%	The strength loss rate was 7.5%, and the appearance of no significant change
Water retention	Not less than 0.6g/cm ²	1.1g/cm ²

The above analysis shows that spontaneous development of admixture can effectively improve the physical properties of bricks and pavement practical performance, the final selection of the best ratio of sand-based water permeable concrete pavement brick in addition to the compressive strength and water permeability coefficient meet the industry standard Cc35 permeable brick strength and water permeability coefficient ($15\text{ }^{\circ}\text{C}$) $\geq 1.0\times 10^{-2}\text{cm/s}$ requirement, the length of the mill pit is 15mm, much smaller than the standard 35mm requirements, it has good wear resistance. Water retention is 1.1g/cm², higher than the standard 0.6g/cm² requirement, its large-capacity water retention, makes the water-permeable pavement have good water storage capacity to prevent groundwater depletion, while effectively regulating the local surface temperature and humidity, improve vegetation ecological environment, ease the city "heat island effect." The ratio of permeable brick in 25 freeze-thaw cycles, the strength loss rate of 7.5%, less than the standard 20% of the requirement.

4. Economic analysis

Hohhot local prices of mountain sand and stone crushing are 75.00 yuan/m³, 95.00 yuan/m³, according to the size of each particle size ratio of the total mass to calculate the price, Tangshan Jidong cement plant shield P·O 42.5R cement: 410.00 yuan/ton, self-developed admixture: 5816.00 yuan/ton, according to the mix and the number of laying tiles per square meter can calculate the unit pavement area of the material and its cost, then the ratio of cost of production and raw material costs can be seen as 1: 1, it is estimated that the cost of water permeable brick is 35.40 yuan/m², excluding the work cost of sifting sand and shipping. The price of domestic brand sand-based water permeable pavement brick is 140 yuan/m², far less than the price of similar sand-based water permeable brick.

5. Conclusion

(1) Permeability and compressive strength of sand-based water permeable concrete brick are a pair of performance indexes which restrict each other. In this experiment, the optimal ratio of the mixture was designed as follows: admixture within the content of 5% of the cement quality, the water-cement ratio is 0.34, aggregate gradation: particle size 0.6~2.36mm accounting for 70% of the total mass of the aggregate, particle size 2.36~4.75mm accounted for 30% of the total mass of the aggregate. the design of aggregate gradation is 0.6~2.36mm, accounting for the total aggregate mass of 70%, the sand-based permeable brick strength of 35.6MPa, water permeability coefficient is $3.5\times 10^{-2}\text{cm/s}$, respectively, to meet the Cc35 water permeable brick strength and permeability coefficient ($15\text{ }^{\circ}\text{C}$) $\geq 1.0\times 10^{-2}\text{cm/s}$ requirement.

(2) The water permeable brick has better water retention capacity, water retention can reach 1.1g/cm², higher than the standard 0.6g/cm² requirement, it has good water storage capacity and the length of the mill pit is 15mm, far less than the standard 35mm requirement, wear resistance is also better.

(3) After 25 freeze-thaw cycles, the strength loss rate of this sand-based water permeable concrete brick is only 7.5%, which meets the 20% requirement of "Water Permeable Brick" (JC/T 945-2005).

(4) The cost of self-developed admixture is lower than the price of similar products in the market, while it can be used to prepare water permeable concrete bricks that satisfy the standard requirements.

Moreover, the pores on the surface of the brick body are small and not easily clogged with dust, which has high popularization and application value.

Based on the conclusion of the experiment, it is planned to further study the practical durability of sand-based water permeable concrete pavement bricks in terms of wet and dry cycle of sulfate, weathering resistance, forming method, skid resistance, the optimization of admixture itself and other aspects.

Acknowledgments

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