Experimental Study on Pervious Concrete

Bing Chen[1], Juanyu Liu[2], Member, ISCP, and Peng Li[3]

ABSTRACT

Due to its excellent air and water permeability, pervious concrete has become an environmental friendly material in paving application, providing its benefits in reducing the runoff water, enhancing pavement skid resistance by rapid drainage of water, and reducing pavement noise. However, its high porosity and low strength limit its popularity. Based on the concept of pervious concrete, a mix design approach especially for pervious concrete was proposed and an experimental study was undertaken to produce high performance pervious concrete by using gap-graded coarse aggregates and adjusting cement content. The results indicated that pervious concrete with compressive strength up to 33.5 MPa and permeability coefficient of 6 ml/min can be obtained by using this mix design approach. The results also showed that for pervious concrete made with gap-graded aggregates, the strength increases, and the permeability coefficient decreases with the decrease of the aggregate size. There is an optimum content of cement used to coat the coarse aggregates, enhancing the cement-aggregate interface bonding and overall performance of pervious concrete.

Key words: Pervious concrete, gap-graded coarse aggregates, penetration coefficient

Introduction

Pervious concrete began its earliest application in Europe in the 19th century because it uses less cement than conventional concrete. Especially after World War II, cement became scarce and pervious concrete became the best material for housing construction in the world except America. Until the 1970's, pervious concrete was introduced to the United States. Its use began not as a cheaper substitute for conventional concrete, although that was an advantage, but for its permeability characteristics. The problem encountered in America was that of excessive runoff from newly constructed areas. Because of the lack of water permeability and air permeability of the conventional concrete pavement, the rainwater is not filtered underground. This had a negative impact on environment, causing some problem such as the phenomenon of hot island in city, water erosion and degradation in the quality of water.

[1] Associate Professor, Department of Civil Engineering, Shanghai Jiaotong University, Shanghai, P. R. China, 200240, Phone: 86-21-54744255, Fax: 86-21-54744255, E-mail: hntchen@sjtu.edu.cn

[2] Assistant Professor, Department of Civil and Environmental Engineering, University of Alaska, Fairbanks, AK 99775-5900, Phone: 907-474-5764, Fax: 907-474-6030, Email: ffjl@uaf.edu

[3] Graduate Research Assistant, Department of Civil and Environmental Engineering, University of Alaska, Fairbanks, AK 99775-5900, Phone: 907-474-5054, Email: fspl4@uaf.edu

Even though pervious concrete is the cost and complexity of it compared to conventional pavements, it is being used more frequently due to its benefits in reducing the runoff water, improving water quality, enhancing pavement skid resistance during storm events by rapid drainage of water, and reducing pavement noise (Chopra et al. 2007, Schaefer et al. 2006, Ghafoori 1995, Haselbach and Freeman 1996).

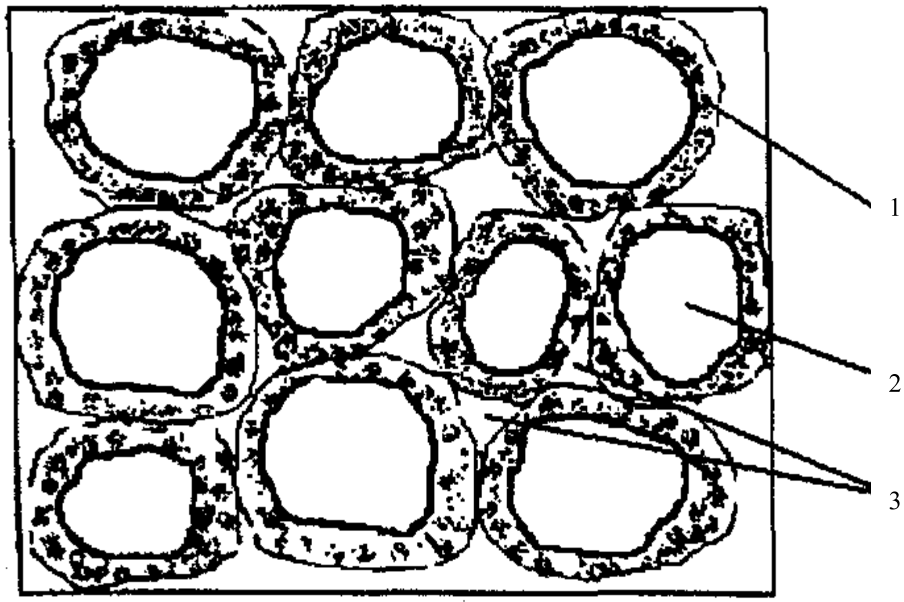
The advantages of pervious concrete relate to its permeability, which depends on the connected voids inside concrete. Since voids are supposed to reduce the strength, many researches have been taken to find a balance between water, aggregate, and cement in order to increase strength and permeability, two characteristic which tend to counteract one another. In 1976, Malhotra (1976) conducted multiple experiments on the effects of various materials properties on the strength of pervious concrete. Later, similar research was conducted by Meininger (1988), apart from the relationship between materials properties and compressive strength of pervious concrete, the relationship between air content and compressive strength was studied. Recently extensive studies were conducted by Ghafoori (1995) and Crouch et al. (2003), focusing on the correlation between compressive strength and compositions of the materials, such as the amount of water, amount of cement, type and size of aggregate. The similar conclusions that the compressive strength of pervious concrete was strongly dependent on the water cement ratio (w/c), the aggregate cement ratio, aggregate size, compaction, and curing were drawn by those researchers in the past 30 years.

Research significance

The strength of pervious concrete made is relatively low, and the pervious concrete can only be applied squares, footpaths, parking lots, and paths in parks. Most of studies are limited on discussing the affecting factors on compressive strength and there were few references on the mix design method by using the normal materials and the strength of pervious concretes, and concrete strength generally limits within 20 MPa. Hence, in this paper, based on the assumption that the single-diameter aggregate forms the concrete strength framework, a mix design approach specifically for pervious concrete was proposed. The effects of unit amount of paste, w/c and aggregate size on the compressive strength and penetration coefficient were discussed based on the experimental results.

Development of mix design approach for pervious concrete

Compared with traditional concrete, pervious concrete has less or no fine aggregates, which provides high porosity of concrete and allows water and air to pass through it. The coarse aggregate usually consists of a single size and is bonded together at its contact points with paste, as shown in Fig. 1 (Yang and Jiang 2003). It results in a concrete with a high percentage of interconnected voids that permits the rapid percolation of water and air through it. Unlike traditional concrete, pervious concrete can have void ratios ranging from 15 to 30% depending on its application. Therefore, pervious concrete has a lower compressive strength, higher permeability, and a lower unit weight (approximately 70% of conventional concrete). In order to produce a pervious concrete with optimum permeability and compressive strength, the amount of paste and aggregate size should be the concerns. On this basis, a mix design approach was proposed as followings:



1-covered coarse aggregate cement paste, 2-coarse aggregate, 3-pore

Fig. 1 Schematic model of pervious concrete

1) Determining the unit amount of aggregate. The first step is to determine the bulk density of coarse aggregate in compacted condition according to ASTM C29. Based on the assumption that coarse aggregate forms the strength framework of pervious concrete, the unit amount of coarse aggregate is the bulk density of aggregate in compacted condition.
2) Calculating the unit amount of cement paste. The unit amount of cement paste has to be optimum. The aggregate can not bind together when there is not adequate cement paste. If the amount of cement paste is too much, the permeability of pervious concrete will be reduced. A 1.0 mm thick of cement paste layer surrounding the aggregate surface is assumed to meet the above requirement. The unit amount of cement paste was calculated according to the equation:

$$M = k\frac{6h\rho_{cp}}{d\rho_g} \tag{1}$$

where,
M − the unit amount of cement paste,
h − the thickness of the cement paste surrounding the coarse aggregate,
ρ_{cp} − the density of cement paste,
ρ_g − the density of coarse aggregate,
d − the average radio of coarse aggregate; and

k − the correction coefficient, which normally ranges in 0.65-0.75 according to the size distribution and surface properties of coarse aggregate.

Experimental methods

Materials The cement used in this study was ordinary portland cement produced by Shanghai cement factory, with a 28-day compressive strength of 58.0 MPa. The fly ash (FA) was provided by Shanghai Wujing power plants. The chemical composition and physical properties of the cement and FA are given in Table 1. Crushed gravel with three size ranges were used as coarse aggregate, as shown in Table 2. A sulphonated naphthalene formaldehyde superplasticizer was used. Its density is 1.2 g/cm^3 and has 35% solid content.

Table 1 Chemical composition of mineral admixture

Chemical composition (%)	OPC	FA
Silicon dioxide (SiO_2)	21.6	54.9
Aluminum oxide (Al_2O_3)	4.13	25.8
Ferric oxide (Fe_2O_3)	4.57	6.9
Calcium oxide (CaO)	64.44	8.7
Magnesium oxide (MgO)	1.06	1.8
Sodium oxide (Na_2O)	0.11	0.3
Potassium oxide (K_2O)	0.56	0.1
Sulfur trioxide (SO_3)	1.74	0.6
Loss on ignition	0.76	0.2

Based on the mix design approach, the unit amount aggregate was determined according to the bulk density of aggregate in compacted condition, and the unit amount of cement paste calculated according to equation 1 ranges from 375 kg/m^3 to 540 kg/m^3. However, the amount of water and the w/c were adjusted according to the workability and strength of pervious concrete. The detailed mix proportion is shown in Table 3.

Table 2 Size ranges of aggregates used

	Sample		
	G_1	G_2	G_3
Size range (mm)	5-10	10-16	16-21
Bulk density in compacted condition (kg/m^3)	1560	1500	1445

Specimens fabrication, curing and testing Instead of following normal mixing sequencing based on ASTM C 192/C, a modified mixing method was applied. Ingredients used to fabricate concretes in Table 3 were mixed in a drum mixer, according to the following steps:

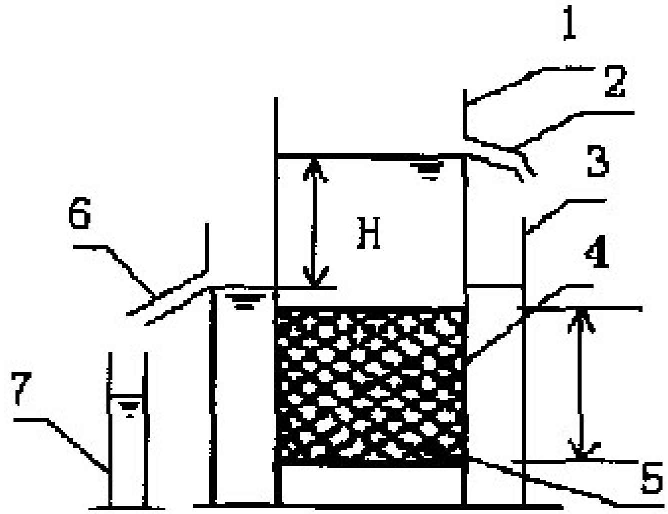
1) Adding coarse aggregates and half of total water to the mixer and mixing for 60 seconds,
2) Adding total cementitious materials to the mixer, and mixing for 90 seconds; and
3) Adding another half of the water and superplasticizer to the mixer, and mixing for another

120 seconds.

Two types of specimens were cast. The cubes with sizes of 150× 150 × 150 mm were used to measure compressive strength. The cylindrical specimens with diameters of 100 mm and heights of 150 mm were used for penetration coefficient test. After molding, specimens were pressed under the 1.0MPa of compressive stress. And the specimens were covered with plastic membrane to hold the moisture in concrete for 24 hours. Then specimens were demolded and keep in the curing room until the testing days. The temperature in the curing room ranged from 20 ^{o}C to 23 ^{o}C and the relative humidity was above 95%. Three specimens were cast for each type of test.

Table 3 Mix Proportion of concrete series

Series	Unit mass (kg/m^3)							Compressive strength /MPa	permeability coefficient cm/s
	Gravel			Cement	Fly ash	water	W/c		
	5~10 mm	10~16 mm	16~21 mm						
1	1560	/	/	270	30	75	0.25	24.0	2.02
2	1560	/	/	270	30	90	0.30	26.0	2.00
3	1560	/	/	270	30	105	0.35	24.5	2.15
4	1560	/	/	315	35	87.5	0.25	26.0	1.75
5	1560	/	/	315	35	87.5	0.30	27.5	1.80
6	1560	/	/	315	35	87.5	0.35	25.0	1.80
7	1560	/	/	360	40	100	0.25	33.5	1.45
8	1560	/	/	360	40	120	0.30	31.0	1.46
9	1560	/	/	360	40	140	0.35	28.6	1.50
10	/	1500	/	270	30	75	0.25	22.0	3.05
11	/	1500	/	270	30	90	0.30	23.0	3.11
12	/	1500	/	270	30	105	0.35	21.0	3.10
13	/	1500	/	315	35	87.5	0.25	24.0	2.72
14	/	1500	/	315	35	87.5	0.30	25.5	2.80
15	/	1500	/	315	35	87.5	0.35	23.5	2.85
16	/	1500	/	360	40	100	0.25	26.5	2.05
17	/	1500	/	360	40	120	0.30	26.0	2.10
18	/	1500	/	360	40	140	0.35	24.0	2.11
19	/	/	1445	270	30	75	0.25	19.0	3.25
20	/	/	1445	270	30	90	0.30	18.5	3.30
21	/	/	1445	270	30	105	0.35	17.0	3.33
22	/	/	1445	315	35	87.5	0.25	22.0	2.9
23	/	/	1445	315	35	87.5	0.30	21.5	2.95
24	/	/	1445	315	35	87.5	0.35	20.5	3.0
25	/	/	1445	360	40	100	0.25	23.0	2.76
26	/	/	1445	360	40	120	0.30	22.0	2.80
27	/	/	1445	360	40	140	0.35	21.5	2.85



1-columnar sheath, 2-overfall pipe, 3-orientation barrel, 4-permeable global barrel, 5-porous concrete, 6-pipe for water out, 7-measuring cylinder

Fig.2 Permeability testing equipment

Compressive strength test was carried out in a testing machine of 2000kN capacity at a loading rate of 2.5 KN/s. The water penetration coefficient (k_r) was measured with the device that was designed by authors. As shown in Fig.2, the cylindrical specimen has a diameter of 100 mm and a height of 150 mm. Above the specimen, the stable water level is kept at 12 cm high and k_r can be calculated by equation 2:

$$K_r = QD \Big/ AH(t_2 - t_1) \tag{2}$$

where,

k_r − the water penetration coefficient (cm/s),

Q − the amount water penetrate the pervious concrete during the time from t_2 to t_1,

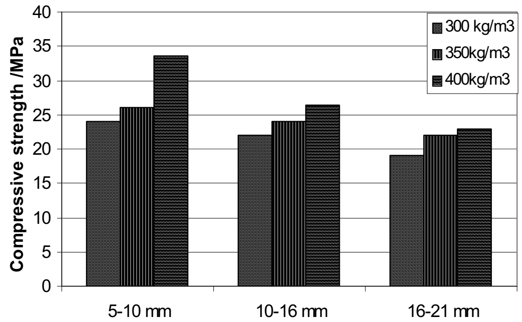
D − the thickness of the sample, and A is the surface area of the specimen,

H − the height of water level determined and here H is 12 cm, and

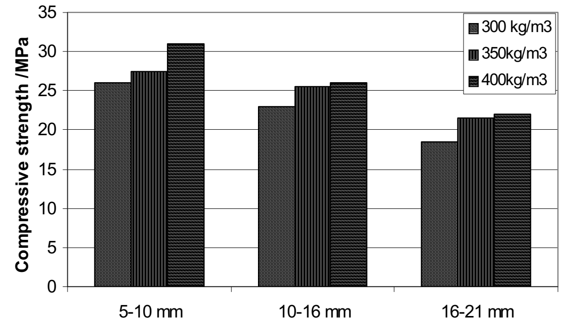
$t_2 - t_1$ − the testing time.

Results and Discussion

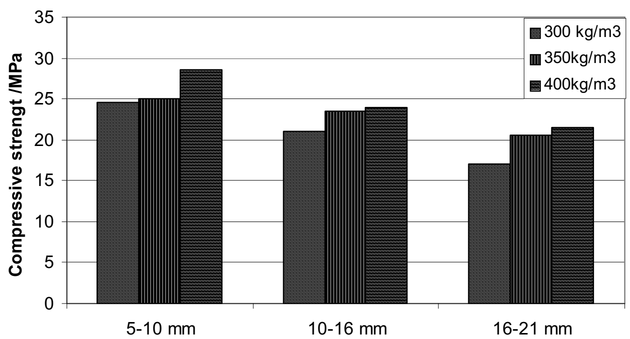
A comprehensive summary of testing results is presented in Table 3. From the table 3, it can be found that it is easy and economic to produce pervious concrete with compressive strength over 20 MPa and permeability coefficient over 2.0 cm/s by the proposed mix design approach, which can meet the requirement of engineering.



(a) w/c =0.25



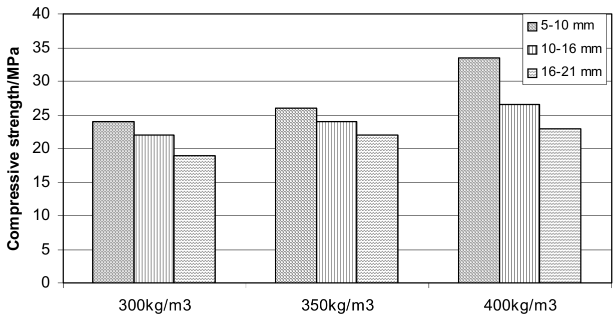
(b) w/c =0.30



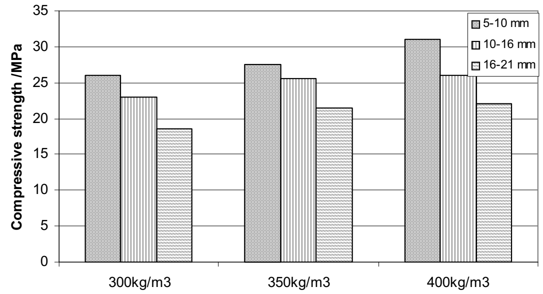
(c) w/c =0.35

Fig. 3 Effect of unit amount cement paste on the compressive strength of pervious concrete

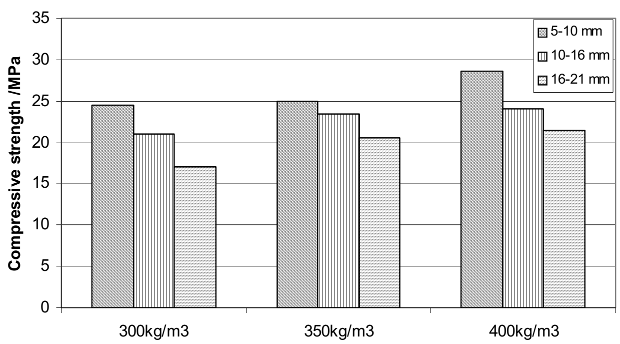
Compressive strength Fig. 3 shows the effect of unit amount of cement paste on the compressive strength of pervious concrete. It can be seen that the compressive strength of pervious concrete increases with the increase of amount of cement paste under the same w/c. The increment becomes small when w/c becomes large. The effect of w/c on compressive strength is related to the aggregate size when the unit amount of cement paste is same. The compressive strength increases with the increase of w/c when the aggregate size ranges in 5~10 mm and the unit amount of cement paste are 300 kg/m^3 and 350 kg/m^3. The compressive strength decreases with the increase of w/c when the amount of cement paste reaches 400kg/m^3. For the pervious concrete with larger coarse aggregate size, the increasing w/c results in the decrease of compressive strength. The main reason is that the total surface area of coarse aggregate is large when the aggregate size is small and it needs more cement paste to coat the aggregate. Therefore, the compressive strength increases with the increase of w/c when the unit amount of cement paste is small. The experimental results indicate that there exists an optimal amount of cement paste for a given w/c. Gap-size coarse aggregate forms strength framework of the pervious concrete and the contribution of cement paste is to bind the coarse aggregate together as an integer. As a consequence, the unit amount of the cement paste needed is the appropriate amount sufficient for coating the coarse aggregate surface.



(a) w/c =0.25



(b) w/c =0.30

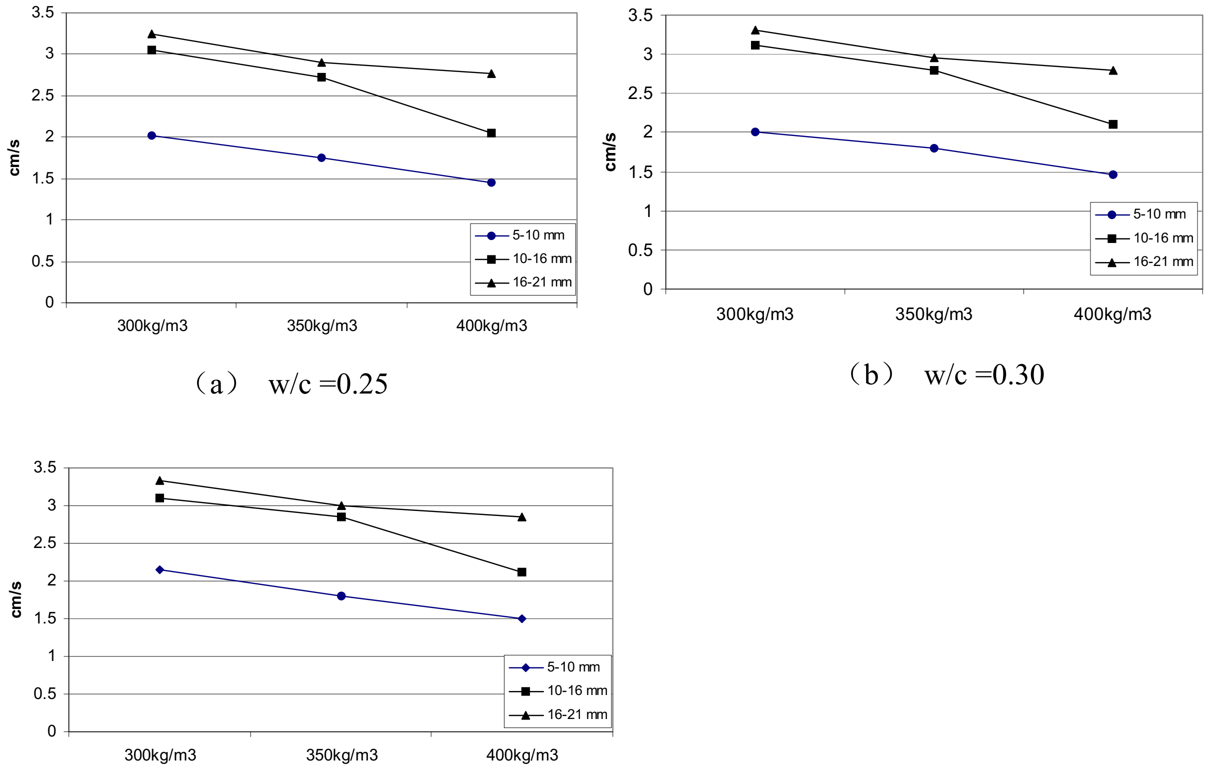


(c) w/c =0.35

Fig. 4 Effect of aggregate size on the compressive strength of pervious concrete

The effect of aggregate size on the compressive strength of pervious concrete is shown in Fig. 4. It can be seen that the compressive strength of pervious concrete increases with the decrease of aggregate size under the same unit amount of cement paste and w/c. For pervious concrete with 400kg/m^3 of unit amount of cement paste and 0.25 of w/c, the compressive strength of pervious concrete with aggregate size of 5-10 mm is 45% higher than concrete with aggregate size of 16-21 mm. It indicates that the aggregate size has an important effect on the strength of pervious concrete. For pervious concrete, the smaller the aggregate size, the more dense compacted concrete and the higher the compressive strength. Therefore, in order to get high strength pervious concrete, the aggregate size should be controlled in a certain range.

Water penetration coefficient Fig. 5 illustrates the effects of aggregate size and unit amount of cement paste on the water penetration coefficient of pervious concrete. From Fig. 5, it can be seen that the aggregate size affects the water penetration coefficient greatly. When the mix proportion is approximately same, reducing the aggregate size seems to decrease the water penetration coefficient. This may be attributed to the fact that the larger aggregate has



（a） w/c =0.25

（b） w/c =0.30

（c） w/c =0.35

Fig. 5 Effects of aggregate size on the water penetration coefficient

smaller unit surface area and the contact point between each other is less and the pore formed is large. For the concrete with same size of aggregate, the water penetration coefficient decreases greatly with the increase of unit amount of cement paste. When continually increasing the unit amount of cement paste, the rest cement paste will fill the void and block the pores. It is obvious that the water penetration coefficient increases with the increase of w/c, same as normal concrete.

Conclusions

Within the scope of this experimental research, the following conclusions can be drawn:

1) Based on the proposed mix design approach, pervious concrete with 28 days compressive strength 33.5 MPa and 1.45 cm/s of water penetration coefficient can be made by using gap-graded aggregate and common raw materials, which can meet the need of pavement engineering.

2) There exists an optimal unit amount of cement paste for suitable pervious concrete, which is enough for coating coarse aggregate surface with a thin layer of 1.0 mm.

3) For pervious concrete with gap-graded aggregate, using smaller size aggregate can enhance the strength, but reduce the water penetration coefficient. In order to benefit both, an

appropriate aggregate size range should be considered.

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