Technical Paper

ISSN 1997-1400 Int. J. Pavement Res. Technol.5(2):102-107

Mix Design Method for Permeable Base of Porous Concrete

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Abstract: As a new material type for permeable base, porous concrete should be designed to maintain both porosity and the structural strength. Based on Talbot's formula and experience, four gradation compositions of porous concrete are designed with consideration of effective particle size and uniform coefficient as effective descriptive targets for the aggregate gradation. Three factors, including cement dosage, water cement ratio and aggregate gradation, are considered in an orthogonal test. Statistical variance analysis of the tests results showed that, at a confidence probability of 95%, the factors that significantly influence the 7-day compressive strength are gradation and cement aggregate ratio while the factor that significantly influences effective porosity at the same confidence probability is the cement aggregate ratio. In addition, when the confidence probability is 90%, gradation, cement dose and water cement ratio all have significant influence on the 7-day compressive strength and the effective porosity. Based on the test results, a series of regression relationships of 7-day compressive strength and effective porosity of porous concrete are derived. Finally, an empirical equation for mixture design of porous concrete is proposed.

***Key words**: Permeable base; Porous concrete; Porosity; Effective particle size; Orthogonality test; Mixture ratio design*

Introduction

Most of the water falling on pavement runs off the road along the transverse and longitudinal slopes of the pavement surface. However, there is still a portion of water that penetrates into the pavement structure through joints, cracks and surface voids in the pavement causing pavement structure to deteriorate. At locations where the geography of the land is flat, water can penetrate into pavement structure from the side slope of the road. Furthermore, the capillary action and evaporating movement of ground water can also cause water to enter the interior of the pavement structure, which is released gradually by seepage flow to the subgrade and roadside. If water trapped in the pavement structure is not released quickly enough, it will soak both the pavement materials and subgrade resulting in decreased strength and increased amount of deformation. More seriously, high water pressure develops when the roadway is under traffic loads, which leads to many structural and functional damages of the pavement.

For the reasons mentioned above, many studies have been focused on finding a way of decreasing or even eliminating pavement water damage through the design of permeable base materials and effective internal drainage systems.

Researches have shown that a permeable base layer must meet three requirements [1-8]. First, it must have enough permeability to quickly free itself from any water that has entered and then is trapped in the pavement structure. Secondly, it must have sufficient strength to serve as a pavement construction platform. Finally, the design should meet the strength requirements to carry the traffic loads of the pavement structure. Presently, there are three ways of addressing this problem. The first is to remove part of fine grains from close-graded aggregate to enable it meet the required permeability and form an open-graded aggregate permeable base. The second is to apply cement or asphalt to stabilize open - graded aggregate to form binder stabilized permeable base. The last technique is to increase porosity and cement dose to achieve higher permeability, strength and stability so as to form a porous concrete permeable base.

The mix design of porous concrete is different from that of regular concrete, and it has some special requirements for aggregate gradation, cement dose and water cement ratio in order to ensure the porosity and structural strength of a pavement structure layer. However, high permeability and strength restricts each other hence every aspect of these factors should be taken into account when designing the mixture.

Raw Materials

Cement

Firstly, cement with a long initial setting time should be adopted, and the other characteristics of the cement should meet the requirements of their corresponding technical specifications. The 32.5 P. O. Cement of Qinling brand is used in the test for this research, and the test results are listed in Table 1, along with standard requirements.

Coarse Aggregate

Coarse aggregate used in porous concrete should be clean, hard and from durable crushed stone. Crushed lime stone from Xi’an is used in the test and the test results are listed in Table 2.

Others

There should be enough water for porous concrete to fulfill the demands of cement hydration and compaction. In this paper potable

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Note: Submitted August 3, 2010; Revised October 8, 2011; Accepted October 12, 2011.

Table 1. Technical Targets of Cement.

Test Items	Initial Setting time /min	final setting time /h	Fineness /%	3-day Strength /MPa		28-d Strength /MPa	
				Bending	Compression	Bending	Compression
Standard Requirements	⩾45	⩽10	⩽10.0	⩾2.5	⩾11.0	⩾5.5	⩾32.5
Test Results	218	5.72	3.8	4.5	23.4	8.6	47.7

Table 2. Technical Targets of Crushed Stone.

Test Items	Apparent Relative Density	Bulk Density /g·cm^{-3}	Mud Content /%	Flat and Elongated Particle Content /%	Crushed Value /%
Standard Requirements	——	——	⩽1	⩽15	⩽30
Test Results	2.7	1.5	0.9	8.9	6.3

Table 3. Aggregate Gradation of Porous Concrete.

Sieve Size /mm	Passing percentage of quality /%			
	Gradation 1	Gradation 2	Gradation 3	Gradation 4
31.5	100	100		
25			100	100
20	76-87	76-87	90-100	
16				25-60
10	0-5	50-71	20-55	
5		0-5	0-10	0-10
2.5			0-5	0-5

drinking water was used in the mixing and curing of the porous concrete.

Aggregate Gradations

Gradation Design Principle

Aggregate component design of porous concrete should meet the requirements of porosity and must form high strength after it is mixed with the cement paste. A desirable porous concrete is one in which the coarse aggregates are interlocked but not interfered with each other after compaction. It should also have high friction to form a space framework structure. In accordance with Talbot's formula [1] and experience [9], the authors designed four kinds of gradation, as listed in Table 3.

$$P = 100\left(\frac{d}{D}\right)^n \tag{1}$$

In the equation, P represents the passing percentage of quality material through every sieve size; d for the sieve size, mm; D for the maximum particle size, mm, and n for the test index with the value from 0.3 to 0.6.

Description of aggregate gradation

Since aggregate gradation is a kind of distribution there should be effective parameters to describe it when designing the composition of the porous concrete. Practices have shown [1] that the effective particle size and homogeneity coefficient are effective target parameters. Furthermore, since porosity is one of the design targets of porous concretes, the percent voids in aggregates can also be used to evaluate the gradation indirectly.

1. Effective particle size

Effective particle size, D_x, is a particle size for which the mass passing ratio for sizes less than it is x% in sieve curve. When x equals 10, it is called Hazen effective size.

Effective size D_{10} can characterize the permeability of materials. When there are more grains with diameter exceeding effective size, D_{10}, the material permeability is better.

2. Homogeneity coefficient

Homogeneity coefficient (C_u) is the particle size ratio of the passing percentage of 60% to 10%. That is

$$C_u = D_{60} / D_{10} \tag{2}$$

The homogeneity coefficient characterizes the expanding degree of grain size. It shows the density of material gradation and indicates material permeability indirectly. A study[1)] has shown that the combination of big effective particle size and small homogeneity coefficient can get high permeability coefficient. The effective particle size and coefficient of homogeneity of the four kinds of aggregate gradation in Table 3 are shown in Table 4.

Orthogonality Test of Mixture Ratio Design

Method of Preparing Test Specimen

Porous concrete is a material from cement stabilized open-graded crushed stone and common lean concrete and different preparation methods will affect its strength and porosity evidently.

Presently, cement - stabilized crushed stone permeable material is formed by a static pressure method in accordance with common cement-stabilized crushed stone. However, open-graded crushed stone has little fine aggregate which causes coarse aggregates to make contact at points and be easily crushed resulting in decreased strength and porosity. Although the static pressure method can sufficiently simulate actual construction, the compaction standard to determine the maximum dry density is difficult to control and the operation of the test is more complex.

One research [10] reported an improved compaction method, with the compaction time being completely determined by the standards of compacting and the stones remained uncrushed. This method attempts to attain the maximum dry density, but it is difficult to determine the compaction time and make the mixture surface of every layer easy to crush.

To attain a skeleton void structure such as porous concrete, the

Table 4. Effective Size and Homogeneity Coefficient of Aggregate.

Gradation	Gradation 1	Gradation 2	Gradation 3	Gradation 4
Effective Size D_{10} /mm	10.68	5.47	5.56	5.84
Effective Size D_{60} /mm	16.56	9.94	13.12	18.33
Homogeneity Coefficient C_u	1.551	1.636	2.360	3.139

static pressure method is not suitable. Since many characters of porous concrete are similar to common concrete, it can be looked as a special kind of common concrete. At present, vibration method is the common preparation method for common concrete, and previous tests show it is also appropriate for porous concrete.

For the above reasons, the authors adopted the vibration method of common cement concrete to prepare the porous concrete and cured the test pieces with the standard curing method.

Orthogonality Test Design

There are many factors, such as cement dose, water cement ratio, aggregate gradation and cement strength, etc, that influence the mechanical behavior and permeability of porous concrete, with the cement dose expressed as the cement aggregate ratio. Since the cement used widely in actual base construction is strength level of 32.5, the tests mainly take into account three factors; cement dose, water cement ratio and aggregate gradation, with each factor taking four levels according to experience, which are shown in Table 5. According to Table 5**,** and the orthogonality design table $L_{16}(4^5)$, the mixture ratios are arranged in Table 6, in which the aggregate content is the product of aggregate bulk density under the condition of vibrating compaction and the reduction coefficient of 0.98 [11].

Analysis of Test Results

According to the mixture ratio in Table 6, the test pieces with size of 15×15×15 cm^3 were cast by the vibration method with each one vibrated for approximately 20 seconds. After standard curing of 7 days, the compressive strength and effective porosity were tested and the test results are shown in Table 7.

Variance analysis results listed in Table 8 [1] show that when the confidence probability is 95%, the factors that significantly influence the 7-day compressive strength are gradation and cement aggregate ratio; and the factor that significantly influences the effective porosity is the cement aggregate ratio. Furthermore, when the confidence probability is 90%, gradation, cement dose and water cement ratio all have significant influence on the 7-day compressive strength and effective porosity.

Among the factors influencing the strength and the porosity of porous concrete, the effective particle size D_{10} is found to represent aggregate gradation effectively when regression analysis is conducted. Therefore, it is taken as the independent variable during the regression process. From the test results shown in Table 7, the regression equations for the 7-day compressive strength and effective porosity are obtained and shown in Table 9 [1].

In the equations, $f_{c,7}$ is the 7-day compressive strength of porous concrete, MPa; n_e is the effective porosity of porous concrete, ％; D_{10} is the effective particle size, mm; C is the cement dose, kg • m^{-3}; W/C is the water cement ratio.

Mixture Design Method

Design Standard

The composition design of porous concrete should fulfill the demands of porosity, permeability coefficient and strength according to the material characteristics with the minimum cement dose. The design effective porosity should be 20％~30％ [12-14], the coefficient of permeability shouldn't be less than 1.05 cm/s [15], and the strength should fulfill the demands in Table 10 [16, 17].

Empirical Equation Method of Mixture Ratio Design

According to the above orthogonality test results, the authors put forward the following empirical equation method for mixture ratio design of porous concrete.

Determination of target strength and design porosity

1. Target strength

According to the preceding mixture ratio design standards, the 7-day compressive strength of porous concrete is determined from Table 9 and the target strength is determined using Eq. (7).

$$f_{c,o} = 1.15 \cdot f_{c,d} \tag{7}$$

In the equation, $f_{c,o}$ means the 7-day target compressive strength, MPa, $f_{c,d}$ means the 7-day design compressive strength, MPa.

2. Design porosity

The design effective porosity of porous concrete is 20％～30％.

Determination of aggregate dose

Table 5. Factors and Levels Table of Orthogonality Test Design.

Levels	Factors		
	A Gradation	B Cement Aggregate Ratio	C Water Cement Ratio
1	Gradation 1	1/8	0.33
2	Gradation 2	1/9	0.36
3	Gradation 3	1/10	0.39
4	Gradation 4	1/11	0.42

Table 6. Orthogonality Design and Mixture Ratio Arrangement Table.

No.	Test No.	A	B	C	D	E	Mixture ratio /kg • m^{-3} Aggregate	Cement	Water	Water Cement Ratio	Calculating Density /kg • m^{-3}
1-1	1	1	1	1	1	1	1668.0	208.5	68.8	0.33	1945.3
1-2	2	1	2	2	2	2	1668.0	185.3	66.7	0.36	1920.0
1-3	3	1	3	3	3	3	1668.0	166.8	65.1	0.39	1899.9
1-4	4	1	4	4	4	4	1668.0	151.6	63.7	0.42	1883.3
2-1	5	2	1	2	3	4	1720.0	215.0	77.4	0.36	2012.4
2-2	6	2	2	1	4	3	1720.0	191.1	63.1	0.33	1974.2
2-3	7	2	3	4	1	2	1720.0	172.0	72.2	0.42	1964.2
2-4	8	2	4	3	2	1	1720.0	156.4	61.0	0.39	1937.4
3-1	9	3	1	3	4	2	1757.0	219.6	85.6	0.39	2062.2
3-2	10	3	2	4	3	1	1757.0	195.2	82.0	0.42	2034.2
3-3	11	3	3	1	2	4	1757.0	175.7	58.0	0.33	1990.7
3-4	12	3	4	2	1	3	1757.0	159.7	57.5	0.36	1974.2
4-1	13	4	1	4	2	3	1781.6	222.7	93.5	0.42	2097.8
4-2	14	4	2	3	1	4	1781.6	198.0	77.2	0.39	2056.8
4-3	15	4	3	2	4	1	1781.6	178.2	64.2	0.36	2024.0
4-4	16	4	4	1	3	2	1781.6	162.0	53.5	0.33	1997.1

Table 7. Orthogonality Test Results.

No.	7-day Compressive Strength / MPa	Effective Porosity / %	Density / kg • m^{-3}	No.	7-day Compressive Strength / MPa	Effective Porosity / %	Density / kg • m^{-3}
1-1	5.59	31.80	1917.05	3-1	7.50	25.95	1954.05
1-2	4.36	32.97	1903.70	3-2	6.10	28.23	1939.30
1-3	4.61	33.37	1908.15	3-3	4.61	33.57	1844.46
1-4	3.30	33.64	1866.65	3-4	4.67	34.06	1885.95
2-1	6.77	28.14	1970.35	4-1	7.58	24.28	1991.15
2-2	5.60	30.96	1921.50	4-2	5.92	30.31	1920.00
2-3	5.03	31.70	1911.10	4-3	4.49	32.27	1872.60
2-4	4.16	33.00	1866.65	4-4	3.35	33.12	1857.85

Table 8. Variance analysis of orthogonality test results

Targets	Variance Sources	Sum of Squares of Deviations	Degree of Freedom	variance	F Value	Critical Value	Significance
7-day Design Compressive Strength	A Gradation	3.45	3	1.149	8.146	F0.95(3,6)= 4.76	significant
	B Cement Aggregate Ratio	19.49	3	6.498	46.083		significant
	C Water Cement Ratio	1.58	3	0.527	3.737		
	D Empty Column	0.03	6	0.141	——		
	E Empty Column	0.82					
effective porosity	A Gradation	20.26	3	6.754	3.519		
	B Cement Aggregate Ratio	84.33	3	28.109	14.648		significant
	C Water Cement Ratio	20.19	3	6.730	3.507		
	D Empty Column	4.31	6	1.919	——		
	E Empty Column	1.45					

Table 9. Regression Equations of Porous Concrete Formed by Vibrating.

Dependence variable	Regression Equations	Correlation coefficient	Equation No.
$f_{c,7}$	$f_{c,7} = -3.133 - 0.118 D_{10} + 0.050 C$	0.945	(3)
	$f_{c,7} = -6.131 - 0.118 D_{10} + 0.049 C + 8.116 W/C$	0.969	(4)
n_e	$n_e = 51.313 - 0.109 C$	0.863	(5)
	$n_e = 60.283 + 0.316 D_{10} - 0.094 C - 37.181 W/C$	0.936	(6)

Firstly, aggregate gradation in Table 3 should be selected according to the materials as well as porosity and strength demands. Then, the bulk density of the selected aggregate is obtained using the vibration method.

Table 10. Design Compressive Strength and Flexural Tensile Strength for Porous Concrete Base.

Traffic Grade	Extra Heavy-duty	Heavy-duty
7-day Design Compressive Strength /MPa	5-8	3-5
28-day Design Flexural Tensile Strength /MPa	1.5-2.5	1.0-2.0

The aggregate dose of the porous concrete is then determined from Eq. (8).

$$G = 0.98 \cdot \rho \tag{8}$$

In the equation, G means aggregate dose of unit volume of porous concrete, kg • m^{-3}, ρ means bulk density of the aggregate, kg • m^{-3}.

Determination of cement dose

1. Determination of cement dose C_1 (kg • m^{-3}) based on the target strength

According to Eq. (3) which precedes the orthogonality test, the cement dose is shown as Eq. (9).

$$C_1 = 62.660 + 2.360 D_{10} + 20.000 f_{c,o} \tag{9}$$

To reduce test factors, this paper only studied the relationship between the strength, porosity and material composition for porous concrete of the cement with strength level of 32.5. When cement of strength level of 42.5 is adopted, the strength can be converted using the relationship between the porous concrete of cement with strength level of 32.5 and 42.5.

2. Determination of cement dose C_2 (kg •m^{-3}) according to porosity

According to Eq. (5), Eq. (10) can be deduced as follows.

$$C_2 = 470.761 - 9.174 n_e \tag{10}$$

Comparing the value of C_1 and C_2, if $C_1 > C_2$, the target strength and porosity should be adjusted, and the cement dose should be calculated again according to Eqs. (9) and (10) until $C_2 > C_1$ is satisfied and then the cement dose C (kg • m^{-3}) is determined as C_1.

Determination of reasonable water cement ratio and water dose

Since the effective size, D_{10}, and the cement dose, C, have been determined, the water cement ratio, W/C, can be found from Eq. (11) as follows.

$$W / C = 0.755 + 0.123 f_{c,o} + 0.015 D_{10} - 6.037 \times 10^{-3} C \tag{11}$$

In actual operation, whether the water cement ratio is reasonable or not can also be judged by experience. If the quantity of water is less, the aggregates will not be parceled by cement paste. However, if there is too much water, the cement paste would be too thin to deposit at the bottom hence would not parcel the aggregate, which would affect the overall strength and homogeneity of the porous concrete. Suitable water content will make cement paste parcel aggregates evenly, with no cement paste dropping, and the presence of metal luster on the concrete surface. From experience, the suitable range of water cement ratio is from 0.33 to 0.42.

With the water cement ratio W/C calculated, the unit water dose, W, (kg • m^{-3}) can be obtained from Eq. (12).

$$W = C \cdot (W / C) \tag{12}$$

Conclusions

The following conclusions were drawn based upon the study:

1. Porous concrete should have certain porosity to fully drain water and in addition to a particular structural strength. According to the Talbot's formula and previous experience, four gradation compositions were designed with the effective size and the homogeneity coefficient being the effective targets.
2. The orthogonality test was designed with consideration of three factors - cement dose, water cement ratio and aggregate gradation - with each having four levels. According to the statistical variance analysis of the test results, the significantly effective factors at the design targets and under different confidence probabilities were proposed. A series of regression relationships of the 7-day compressive strength and effective porosity of porous concrete were derived.
3. The empirical equation method of mixture ratio design for porous concrete was proposed based on the orthogonality test.

Acknowledgements

This research paper is supported by National Natural Science Foundation of China (Number: 51008033) and Natural Science Foundation of Shaanxi Province (Number: 2005E$_2$07).

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