Material Design and Performance Analysis of Porous Cement Stabilized Macadam

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Abstract. In order to use cement stabilized macadam in sponge road engineering, porous cement stabilized macadam was designed based on Bailey method and Taibal method, and theoretical porosity was taken as design index. Effective porosity, permeability coefficient, unconfined compressive strength, splitting strength and COD removal ability were analyzed by experiment. The results show that, effective porosity is proportional to theoretical porosity, ratio of effective porosity is lower while theoretical porosity is smaller. Unconfined compressive strength (UCS) and splitting strength are decreasing with theoretical porosity increasing, and downtrend is more significant while theoretical porosity is less than 20%. The removal ability of COD is enhancing with porosity increasing. So, if strength, water permeable ability, water storage ability, COD removal ability are taken into consideration, 20% is optimum porosity for porous cement stabilized macadam.

1. Introduction
In recent years, there have been frequent waterlogging in urban areas of China. During the period from 2008 to 2010, nearly 62% of the cities have experienced urban waterlogging, which has caused serious impact on the safety of people's lives and property. On the other hand, the utilization rate of rainwater in China is low, the urban water body is heavily polluted, and the groundwater supply is insufficient. In this context, the construction of Sponge City (low impact development) has attracted the attention of the government and researchers (Li Lan et al., 2018). The important features of the sponge city are the functions of “infiltration, storage, stagnation, net, use, and row” of urban infrastructure and natural ground, as a result, peak flow rates are reduced, groundwater is recharged, and the risk of urban waterlogging is reduced (WANG Hao et al., 2017). Roads are an important part of urban infrastructure, traditional roads that are hardened and compacted are not conducive to the accumulation of rainwater and increase the burden on urban drainage facilities. Porous road emerged as the main solution for the construction of sponge roads, the surface layer design uses materials with a certain permeability (large pore asphalt mixture, permeable bricks etc.). China has successively issued the "Technical Specification for Permeable Cement Concrete Pavements" (CJJ/T135-2009) and "Technical Specification for Pervious Bricks and Pavements" (CJJ/T188-2012) and other regulations. The road that the surface layer is the main water-permeable interface, the pores are easily affected by dust and debris, and the resulting blockage affects the permeability of the water. And according to the status quo of road construction in China with "strong base and thin surface", the water-storage capacity of the permeable surface is congenitally insufficient.
(HOU Zichen et al., 2017; XU Shuai et al., 2016). In contrast, the base has a greater thickness, exerts the “sponge” function of the base such as “seepage, accumulation, stagnation, and net”, and will be able to exert its “sponge” function more effectively (YIN Jinming et al., 2017).

The key to the basic sponge function lies in the design and application of the base materials, the premise of exerting functions such as “seepage, accumulation, stagnation, and net” is that the base must have a certain effective pore (connecting pores). Cement stabilized gravel is commonly used in road bases in China, and porous cement stabilized gravel is mainly used in porous bases. The design of the porous cement stabilized macadam uses trial fitting and empirical methods. The existing research focuses on mechanical properties, and there are few reports on the permeability of the cement (XIE Jun et al., 2005; HU Li- qun et al., 2006; CAO Yu-ling et al., 2010; ZHANG Chao, 2014). In this paper, based on the requirements of porosity, the porous cement stabilized macadam is designed based on Bailey method and Taibal method, and through experiments analysis unconfined compressive strength, splitting strength, porosity, permeability coefficient, and COD removal characteristics of typical pollutants in rainwater, these can improve reference for engineering application of porous cement stabilized gravel.

2. DESIGN METHOD OF POROUS CEMENT STABILIZED MACADAM

According to the Bailey method, the aggregate is divided into coarse aggregate and fine aggregate. The demarcation mesh of coarse aggregate and fine aggregate is 0.22 NMPS. Coarse aggregates form skeletons, fine aggregates fill them. Coarse aggregate forms skeleton gap for VCA (PENG Bo et al., 2005; GUO Yin-chuan et al., 2014).

\[
VCA = (1 - \rho_d / \rho_b) \times 100\%
\]  
(Eq. 1)

Where: \( \rho_d \) =design density of coarse aggregate, \( \rho_b \) = bulk density of coarse aggregate.

The Bailey method divides aggregates into coarse aggregates and fine aggregates. In order to meet the detailed mix ratio design requirements, the sieve control at all levels is determined by the Taibal method, and the pass rate of each sieve is calculated as follows (ZHANG Ai-qin et al., 2000).

\[
p = 100 \times \left(\frac{d}{D}\right)^m
\]  
(Eq. 2)

Where: \( D \) =maximum particle size of aggregates, \( d \) = sieve size, \( m \) = gradation index.

Due to the coarse aggregate forming the skeleton, when the volume of the mixture is \( V \), the coarse aggregate usage \( m_c \) could be calculated with Eq. 3.

\[
m_c = \rho_a \cdot V
\]  
(Eq. 3)

Cement hydration requires the combination of 25% of its own mass of water to form a long-lasting substance with a volume that absorbs 75% of the volume of free water (Czernin, W, 1991). Cement mass \( m_c \) could be calculated with Eq. 4.

\[
m_c = (\rho_d \cdot V + m_f) \cdot \gamma_{ce}
\]  
(Eq. 4)

Where: \( m_f \) = mass of fine aggregate, \( \gamma_{ce} \) =mass ratio of cement.

\[
V_{ce} = 0.25 \times 0.75 \times \frac{(\rho_d \cdot V + m_f) \cdot \gamma_{ce}}{\rho_w}
\]  
(Eq. 5)

Where: \( \rho_w \) =design density of water.

The mixture consists of coarse aggregates, fine aggregates, cement hardened products and pores. If the target porosity \( n \) is set as required, the fine aggregate volume \( V_f \) is:

\[
V_f = V \cdot (VCA - n) - 0.25 \times 0.75 \times \frac{(\rho_d \cdot V + m_f) \cdot \gamma_{ce}}{\rho_w}
\]  
(Eq. 6)

Fine aggregate content is:
\[ m_j = \frac{V \cdot (VCA - n) - \frac{3}{16} \times \frac{\rho_d \cdot V \cdot \gamma_c}{\rho_w}}{\frac{1}{\rho_d} + \frac{3}{16} \times \frac{\gamma_c}{\rho_w}} \]  

(Eq. 7)

The specific design steps are as follows:

1. Aggregate screening to determine the maximum particle size and nominal particle size of the aggregate. According to the Bailey method, the definite grain size of the coarse aggregate and the fine aggregate is determined, and the gradation of the coarse aggregate and the fine aggregate is calculated according to the Taibal method.

2. According to the gradation of the coarse aggregates and the fine aggregates, the coarse aggregates and the fine aggregates are respectively mixed to determine the gross bulk density of the coarse aggregates. Determine the design density of coarse aggregates and fine aggregates according to the molding method of the mixture.

3. Estimate the volume of the desired mixture and calculate the amount of coarse aggregate according to Eq. 3.

4. According to equation (1), calculate the skeleton gap rate of the mixture, remove the amount of cement, set the target porosity of the mixture, and determine the amount of fine aggregate according to Eq. 7.

3. Porous Cement Stabilized Gravel Material Test Plan

In this study, the raw material for the design of cement stabilized macadam comes from the Beijing-Shanghai high-speed expansion project, produced from Tongling, where it is supplied in four stages. The specifications of each file are shown in Table 1. All the parameters meet the requirements of the specification. To meet the test requirements, the various pieces of gravel are sieved and the gradation is synthesized as required. Cement uses Taizhou Conch brand 32.5 ordinary portland cement.

| Sieve size (mm) | 31.5 | 19  | 16  | 9.5  | 4.75 | 2.36 | 1.18 | 0.6  | 0.3  | 0.075 |
|-----------------|------|-----|-----|------|------|------|------|------|------|-------|
| Sieve residue   |      |     |     |      |      |      |      |      |      |       |
| A               | 5.9  | 81.3 | 8.5 | 4.3  |      |      |      |      |      |       |
| B               | 0.2  | 59.6 | 38.4 | 1.7 | 0.1  |      |      |      |      |       |
| C               | 0.7  | 4.1  | 77.2 | 10.4 | 5.8 | 1.8  |      |      |      |       |
| D               | 2.9  | 29.1 | 11.8 | 14.4 | 20.8 | 21.0 |      |      |      |       |

The maximum particle size of gravel aggregate is 31.5mm and the nominal particle size (NMPS) is 26.5mm. According to the Bailey method, the demarcation mesh of coarse aggregate and fine aggregate is 0.22 NMPS, which is 4.75mm. According to the aggregate used in the design, the Taibal method calculates the gradation of the mixture in Table 2 and controls the mixing of the mixture according to the screening quality of the sieves at all levels.

| Sieve size (nm) | 31.5 | 26.5 | 19  | 16  | 13.2 | 9.5  | 4.75 | 2.36 | 1.18 | 0.6  | 0.3  | 0.075 |
|-----------------|------|------|-----|-----|------|------|------|------|------|------|------|-------|
| Sieve residue   |      |      |     |     |      |      |      |      |      |      |      |       |
| A               | 5.9  | 81.3 | 8.5 | 4.3 |      |      |      |      |      |      |      |       |
| B               | 0.2  | 59.6 | 38.4 | 1.7 | 0.1  |      |      |      |      |      |      |       |
| C               | 0.7  | 4.1  | 77.2 | 10.4 | 5.8 | 1.8  |      |      |      |      |      |       |
| D               | 2.9  | 29.1 | 11.8 | 14.4 | 20.8 | 21.0 |      |      |      |      |      |       |

According to the grading of coarse aggregates in Table 2, coarse aggregates were blended, and the measured bulk density of the coarse aggregate was 2.753 g/cm³. The vibration was used for molding. The measured density of the coarse aggregate was 1.887 g/cm³, the material skeleton gap is 31.5%.

Due to the design of the porous cement-stabilized gravel, the recommended cement design for Highway Cement Concrete Pavement Design (JTG D40-2011) is 9.5%-11%. In this paper, the cement content rc is taken as 10%. In the design, in order to achieve the maximum porosity, the fine aggregate
content is 0, and the theoretical porosity of the mixture according to Eq(6) is 27.9%; The gradation design was carried out according to the Taibal method, the porosity was the smallest, the theoretical porosity was 4.5%, and the coarse aggregate and fine aggregate mass ratio was 3.14; The theoretical porosity is set at 24%, at this time the coarse aggregate and fine aggregate mass ratio is 18.74; Set the theoretical porosity to 20%, at this time, the mass ratio of coarse aggregate to fine aggregate is 9.27; Set the theoretical porosity to 15%, at this time, the mass ratio of coarse aggregate to fine aggregate is 5.68. The relationship between the mass ratio of coarse aggregate to fine aggregate and the theoretical porosity is shown in Fig. 1. It can be seen from the figure that when the theoretical porosity is less than 20%, the coarse and fine aggregate mass ratio is less affected by the theoretical porosity; when the theoretical porosity exceeds 20%, the mass ratio of coarse aggregates increases sharply, it shows that the amount of coarse aggregates increases significantly.

Fig.1. Relationship between mass ratio(coarse aggregate to fine aggregate) and theoretical porosity

Based on the above porous cement stabilized gravel base material design, mixes were mixed at a theoretical porosity of 27.9%, 24%, 20%, 15%, and 4.5%. The mix types were numbered I, II, III, IV, and V. The five types of mixture grading are shown in Table 3.

| Mixture number | Sieve size (mm) | 31.5 | 26.5 | 19 | 16 | 13.2 | 9.5 | 4.75 | 2.36 | 1.18 |
|----------------|----------------|------|------|----|----|------|-----|------|------|------|
| I              | Pass ratio     |      |      |    |    |      |     |      |      |      |
| II             | Pass ratio     | 100.0| 86.5 | 63.5| 53.0| 42.3 | 26.3| 0     | 0     | 0     |
| III            | Pass ratio     | 100.0| 87.2 | 65.3| 55.4| 45.3 | 30.0| 5.1   | 2.1   | 0     |
| IV             | Pass ratio     | 100.0| 88.5 | 68.9| 60.1| 51.0 | 37.3| 15.0  | 6.2   | 0     |
| V              | Pass ratio     | 100.0| 89.7 | 72.3| 64.4| 56.3 | 44.1| 24.2  | 9.9   | 0     |

The vibration was used for molding. The effective porosity, water permeability coefficient, 7d unconfined compressive strength, and 28 d splitting strength of the five types of mixes were measured. The test method refers to "Test Procedures for Inorganic Binder Materials for Highway Engineering" (JTG E51-2009), "Technical Specification for Permeable Brick and Pavement" (CJJ/T 188-2012).

4. Strength and Permeability Test Results and Analysis

The effective porosity, permeability coefficient, 7d unconfined compressive strength and splitting strength test results are shown in Table 4.

According to the test results, the effective porosity is in direct proportion to the theoretical porosity, and the effective porosity accounts for 52.7% to 70.6% of the theoretical porosity. The relationship between effective porosity and theoretical porosity is shown in Fig. 2. With the theoretical porosity of 20% as the boundary, the slope of the curve is larger than that of the former, indicating that the larger the theoretical porosity is, the larger effective porosity ratio is. This is due to the greater the porosity,
the greater the mass ratio of coarse aggregates and the smaller fine aggregates resulting in the reduction of closed porosity.

Table 4. The experiment results

| Number | Theoretical porosity (%) | Effective porosity (%) | Permeability coefficient (cm/s) | UCS (MPa) | Splitting strength (MPa) |
|--------|--------------------------|------------------------|-------------------------------|-----------|-------------------------|
| I      | 27.9                     | 19.7                   | 2.11                          | 2.062     | 0.357                   |
| II     | 24                       | 15.2                   | 1.42                          | 4.353     | 0.687                   |
| III    | 20                       | 11.3                   | 1.17                          | 6.359     | 1.082                   |
| IV     | 15                       | 7.9                    | 0.84                          | 7.045     | 1.118                   |
| V      | 4.5                      | 3.1                    | 0.45                          | 8.552     | 1.151                   |

According to the test results of water permeability, the permeability coefficient is proportional to the effective porosity of the test piece. It is considered that the effective porosity is the proportion of the connected porosity and the connected porosity is increased. The water permeability of the sample is also increased. The relationship between the two is shown in Figure 3. The curve is slower in the front section and steeper in the back section. This is due to the drastic reduction of the sample fine aggregate in the back section of the curve, resulting in an increase in the effective porosity ratio and an increase in the permeability coefficient.

According to the experimental results, with the increase of the theoretical porosity, the unconfined compressive strength and the splitting strength both decrease. With the increase of the theoretical porosity, the fine aggregate that acts as a filler increases. And with the reduction, the contribution of fillermaterial strength is also reduced, and the splitting strength is positively correlated with the unconfined compressive strength. The splitting strength of the sample is 13.5%-17.3% of the unconfined compressive strength. Theoretical porosity increased from 4.5% to 15%, unconfined compressive strength decreased by 17.6%, splitting strength decreased by 2.9%, theoretical porosity increased from 4.5% to 20%, and unconfined compressive strength decreased by 25.6 %, splitting strength decreased by 6.0%; theoretical porosity increased from 4.5% to 24%; unconfined compressive strength decreased by 49.1%; splitting strength decreased by 40.3%; theoretical porosity increased from 4.5% to 27.9%, unconfined compressive strength decreased by 75.9%, splitting strength decreased by 69.0%; It shows that the theoretical porosity has greater influence on the unconfined compressive strength than the splitting strength. The relationship between theoretical porosity,
unconfined compressive strength, and splitting strength is shown in Figures 4 and 5. It can be seen from the figure that the theoretical porosity has similar influence on the unconfined compressive strength and splitting strength. It is expressed by the theoretical porosity of 20%. The slope of the first half of the curve is smaller than that of the latter half of the curve, indicating the theoretical porosity. After more than 20%, the unconfined compressive strength and the splitting strength of the specimen increase faster. This is because when the theoretical porosity exceeds 20%, the mass ratio of the coarse and fine aggregates increases rapidly, and the fine aggregates rapidly decrease, resulting in no lateral compressive strength and splitting strength also decreased rapidly. The relationship between the coarse and fine aggregate mass ratio and the unconfined compressive strength and splitting strength is shown in Figure 6 and Figure 7. As can be seen from the figure, the effect of the coarse and fine aggregate mass ratio on the two is not the same. Figure 6 shows that the front curve is steeper and the back section is slower. Figure 7 is the opposite. The relationship between the coarse and fine aggregate mass ratio and the unconfined compressive strength is shown in Figure 7.

5. Influence of Porous Cement Stabilized Crushed Stone on Rainfall Pollutant COD

Studies have shown that early rain was contaminated by tire wear, vehicle leakage, discarded waste, pesticides, etc, resulting in high levels of COD and other contaminants in the rain and becoming major pollutants (HEN Li-qin et al., 2009; LI Qianqian et al., 2011). In order to analyze the effect of permeated cement stabilized macadam on contaminants, raw water with a COD concentration of 65 mg/L was used. According to the above-mentioned 27.9%, 24%, 20%, 15%, 4.5% theoretical porosity (valid porosity were 19.7%, 15.2%, 11.3%, 7.9%, 3.1%) to prepare standard samples (diameter
150mm, height 150mm). Samples of different porosity were placed in the contaminated water sample, and appropriate water samples were taken at different intervals to determine the COD concentration in the water and analyze the changes. The test results are shown in Table 5.

### Table 5. The results of COD removal experiment

| Theoretical porosity (%) | Mass concentration of COD (mg/L) | 0h  | 3h  | 9h  | 24h | 48h | 72h | 120h |
|--------------------------|----------------------------------|-----|-----|-----|-----|-----|-----|------|
| 27.9                     |                                 | 65  | 36.05 | 33.16 | 31.68 | 29.89 | 30.02 | 30.11 |
| 24                       |                                 | 65  | 41.77 | 38.15 | 36.49 | 33.77 | 33.33 | 33.26 |
| 20                       |                                 | 65  | 49.97 | 46.31 | 44.91 | 41.15 | 41.01 | 41.02 |
| 15                       |                                 | 65  | 53.92 | 50.83 | 48.54 | 46.02 | 45.89 | 45.78 |
| 4.5                      |                                 | 65  | 59.82 | 56.66 | 54.09 | 51.23 | 50.87 | 50.54 |

According to the test results, cement stabilized macadam materials have a certain adsorption capacity for COD, and the adsorption capacity increases with the increase of porosity. When the porosity exceeds 20%, the adsorption capacity is significantly affected by the porosity. When the porosity is less than 20%, the influence of porosity is moderated. This is similar to the effective porosity, the effective porosity increases, the contact area between water and water-permeable cement stabilized macadam increases, and its adsorption capacity also increases. With the prolonged soaking time, the COD concentration in the water also gradually decreased. Especially in the early 3 hours, the COD concentration decreased especially. When the water soaking time exceeded 48 hours, the COD concentration in water basically stabilized. The COD removal rate of the permeable cement stabilized macadam with a theoretical porosity of 27.9% can reach 53.7%.

### 6. Conclusion

(1) The comprehensive application of the Bailey method and the Taibal method can be used as a design index for the design of porous cement stabilized macadam materials.

(2) The experimental results show that the effective porosity is proportional to the theoretical porosity, the effective porosity ratio is 52.7%~70.6%, the permeability coefficient is proportional to the effective porosity, and the compressive strength and splitting strength are inversely proportional to the theoretical porosity. The effect of the rate on the unconfined compressive strength is even more pronounced. For the requirements of comprehensive strength, porosity, and permeability, the theoretical porosity of the porous cement stabilized macadam is recommended to be 20%.

(3) Porous cement stabilized gravel has the ability to absorb the COD of stormwater pollutants. The larger the theoretical porosity, the stronger the adsorption capacity. The adsorption capacity is most significant in the first 3 hours. After 48 hours, the adsorption capacity is basically stable.

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