Research on mechanical performance of crushed stones by large-scale triaxial shear tests

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Abstract: Crushed stones were used as furrowed subgrade in recent project. Triaxial shear tests were carried out on selected crushed stone with the gradation of 20 mm to 40 mm. The dry densities of specimens were controlled to be 1.450 g/cm³, 1.600 g/cm³ and 1.721 g/cm³, respectively. Test results show that the constitutive relationship conforms to hyperbola, which can be simulated by Duncan-Chang model. At lower stress level, the crushed stones show slight dilatancy, while at the higher stress level, the crushed stones show shear shrinkage. The shear strength is nonlinear with an interlocking force between aggregates. A linear relation is proposed to describe the variation of angel of internal friction.

1. Introduction
Crushed stone is a loose granular material, which is generally made by manually crushing rocks. It has a certain gradation, high particle strength without cohesion. Its strength mainly depends on the friction and interlocking between particles. The most important factor affecting the strength of graded crushed stone is the gradation. In order to achieve the maximum compactness, continuous gradation is generally adopted. For the calculation method of continuous gradation, Fuller put forward the ideal gradation according to experiments in the early years [1]. According to the theoretical analysis and experiments of Thepot, it is believed that \( n = 0.3 \) to 0.5 has good compactness [2]. The calculation methods of continuous gradation in various countries have evolved from the Thepot formula. Cao et al. studied the influence of compaction equipment on the optimal porosity of crushed stone [3]. Ma et al. studied the shear resistance of graded crushed stone and found that graded crushed stone with a maximum particle size of not less than 31.5 mm and an index \( n \) value below 0.5 have good shear resistance [4]. Dong studied the relationship between the strength of graded crushed stone and the changes of moisture content and compactness [5]. Zhu et al. studied the strength characteristics and stress-strain curve characteristics of crushed stones through large-scale triaxial shear tests and large-scale uniaxial compression tests, and found that the stress-strain curve is hyperbolic, the volume change curve is parabolic, and the compression modulus changes in power function with axial stress [6]. Although the strength of crushed stone soil conforms to the Mohr Coulomb strength criterion, it is found in the triaxial test on large rockfill that the strength curve has a tendency of bending under lower stress and presents nonlinear characteristics [7]. Pan studied the influence of different gradation and sample preparation methods on the strength of crushed stone, and found that vibration compaction is closer to the site construction method [8]. In the process of vibration compaction, the particles are
filled into void in close contact, which increases the internal friction resistance and the bearing capacity. Due to the crushing of aggregates, the compaction has changed the original good gradation to different degrees. Wang et al. found that increasing the elastic modulus of graded crushed stones is more effective than increasing the thickness of asphalt pavement to reduce pavement compression [9]. The thickness of the crushed-stone cushion has certain influence on the settlement. Under the same other conditions, the thicker the crushed-stone cushion, the greater the settlement.

A typical application of crushed stone in the construction of harbor engineering is as subgrade with furrows under the concrete tunnel sections of the Hongkong-Zhuhai-Macao Bridge. We have done a series of model tests and researches on this. An important research is to understand the deformation characteristics or constitutive relation of crushed stones. In this paper, through large-scale triaxial tests, the compression and strength of crushed stone materials with different compactness are analysed. These tests include particle analysis, relative density test and triaxial compression test, which are all carried out in accordance with Geotechnical Test Regulations (SL237-1999) issued by the Chinese Ministry of Water Resources.

2. Properties of crushed stone

Particle analysis test was carried out on crushed stones. The sample was screened by sieving method with a set of round-hole sieves with the size of 60 mm, 40 mm, 20 mm, 10 mm and mm, respectively. It is showed that the particle size of the sample was concentrated in the particle group of 20 mm to 40 mm. Hence there is no need to draw the gradation curve.

According to relevant engineering experience, the surface vibration method is close to the actual working conditions of the construction. The relative density was tested with a large-scale relative density tester by surface vibration. The inner diameter of the sample tube is 300 mm, the height is 340 mm, and the maximum allowable particle diameter is 60 mm. The vibrator can compact the sample with a top force of 85.8 kg (equivalent to 14 kPa) with a vibration frequency of 50 Hz. The sample is divided equally into two parts and filled by two layers, each layer vibrates for 8 min.

The minimum dry density is determined by pouring method. Calculate the minimum and maximum dry density of the sample according to the total mass of stones and their volume.

A set of relative density tests includes two parallel tests. Take the average value as the maximum and minimum dry density of each material. Under the test conditions, the minimum dry density of the crushed stone bed material is 1.358 g/cm³ and the maximum dry density is 1.721 g/cm³, as listed in Table 1.

| Crushed stone | Dry density (g/cm³) |
|---------------|---------------------|
|               | Max.                | Min.                |
| Test 1        | 1.723               | 1.350               |
| Test 2        | 1.718               | 1.367               |
| Average       | 1.721               | 1.358               |

Three relative densities, \( D_r=0.3 \), \( D_r=0.72 \) and \( D_r=1.0 \), were selected for subsequent triaxial tests, with dry densities of 1.450 g/cm³, 1.600 g/cm³ and 1.721 g/cm³, respectively.

3. Large scale triaxial test

The SJ-70 large-scale high-pressure triaxial apparatus is adopted as shown in Figure 1. It has a maximum axial output of 250 t and a maximum confining pressure of 7 MPa. Saturated consolidated drained shear test (CD) were conducted on the specimens has a diameter of 300 mm and a height of 700 mm.

The specimen is prepared in five layers. A vibrator was used to compact to the designated density by controlling the vibrating time. The static pressure of the vibrator is 14 kPa under bottom plate with a vibration frequency of 40 Hz. The specimen was saturated by air pumping and then filling water. The confining pressures are 0.4 MPa, 0.6 MPa, 0.8 MPa while the shear strain rate is controlled to 1.0 mm/min.
4. Test results

For a purpose of simplicity, only the test result of density of 1.721 g/cm$^3$ was presented. Figure 2 shows the stress-strain relationship obtained in triaxial compression test (CD). It is strain-hardened without obvious stress peaks. Judging from the characteristics of volumetric variation, no obvious dilatancy phenomenon is found, and shear shrinkage occurs under higher stress. It is found that Duncan-Chang model is suitable for stress-strain analysis. Table 2 shows Duncan-Chang model parameters of the crushed stone.

![a) Triaxial test apparatus](image1)
![b) Test specimen](image2)

Figure 1 Triaxial compression apparatus and a prepared specimen

![a) deviator stress versus axial strain](image3)
![b) volumetric strain versus axial strain](image4)

Figure 2 Curve of triaxial compression

| Dry density(g/cm$^3$) | $R_f$ | $K$ | $n$ | $K_b$ | $m$ |
|----------------------|-------|-----|-----|-------|-----|
| 1.721                | 0.766 | 500 | 0.318 | 175   | 0.079 |
| 1.600                | 0.697 | 395 | 0.253 | 140   | 0.063 |
| 1.450                | 0.731 | 315 | 0.313 | 100   | 0.014 |

Table 2 Duncan-Chang model parameters of crushed stone

Figures 3 shows the strength envelopes for three stress levels. It can be seen that in a relatively large stress range, the proportional relationship not constant between shear strength and normal stress is. The strength decreases with an increase of confining stress while it shows a downward inclination. Therefore, a non-linear parameter is proposed for each Mohr circle passing through the origin corresponding to the confining stress $\sigma_3$. The nonlinear strength index is proposed in Table 3 and may be described by the following expression:
\[ \phi' = \phi_0 - \Delta\phi_0 \log(\sigma_3 / P_a) \]

where \( \phi' \) — angle of internal friction (°); \( \phi_0 \) — reference angle of internal friction at one atmosphere pressure (°); \( \Delta\phi_0 \) — angle of internal friction, varied with confining pressure (°); \( \sigma_3 \) — confining stress in test or minimum principal stress (MPa); \( P_a \) — standard atmosphere pressure (0.1 MPa).

![Figure 3 Strength envelope and Mohr circles under triaxial compression for (1.721 g/cm³)](image)

Table 3 Strength parameters for crushed stone under triaxial consolidated drained compression

| Dry density (g/cm³) | Non-linear strength index | Linear strength index |
|--------------------|---------------------------|-----------------------|
|                    | \( \phi_i \) (°) | \( \Delta\phi_i \) (°) | Interlocking force (kPa) | Angel of internal friction (°) |
|--------------------|---------------------------|-----------------------|
| 1.721              | 47.5                      | 9.3                   | 100                     | 36.2                     |
| 1.600              | 43.6                      | 7.9                   | 90                      | 33.8                     |
| 1.450              | 38.8                      | 4.2                   | 40                      | 32.6                     |

5. Conclusions
The triaxial shear tests were carried out on the crushed stone with the gradation of 20 mm to 40 mm. The minimum and maximum dry densities of the selected crushed stones are 1.450 g/cm³ and 1.721 g/cm³. The dry densities of specimens were controlled to be 1.450 g/cm³, 1.600 g/cm³ and 1.721 g/cm³, respectively. Triaxial compression tests show that the constitutive relationship conforms to hyperbola, which can be simulated by Duncan-Chang model. The shear strength is nonlinear with an interlocking force between aggregates. At lower stress level, the crushed stones show slight dilatancy, while at the higher stress level, the crushed stones show shear shrinkage.

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