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Research Article

Experimental Study on the Shear Strength of Cement-Sand-Gravel Material

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An experimental study on the shear strength development of cement-sand-gravel (CSG) material was carried out using triaxial compression tests. The effects of the cementing agent content, aggregate content, and gradation on the shear strength of CSG material were analyzed. The shear strength remarkably increased with increasing cementing agent content and aggregate content for a given confining pressure. The increase in shear strength with increasing cementing agent content far exceeded that with increasing aggregate content. However, the stress-strain curves and shear strength changed only slightly when the aggregate gradation for CSG material was adjusted. Based on the test data, a strength criterion for CSG material is proposed as a function of the cementing agent content, aggregate content, and shear strength of the aggregate gradation.

1. Introduction

Like roller-compacted concrete (RCC), cement-sand-gravel (CSG) material consists of water, aggregate (rockfill material, sandy gravel material, etc.), and cementing agents such as Portland cement and fly ash. As compared to RCC, the advantages of CSG material include a lower requirement of cementing agent content, its compatibility with local aggregate, and less stringent temperature control requirements. CSG materials with varying cementing agent contents, aggregate contents, and gradations have been utilized in various infrastructure applications, such as embankments, soil treatments, reinforcement for small rural hydropower structures, and, most commonly, in dam construction [1].

A strength requirement is a basic premise in engineering applications of geotechnical materials; thus, examination of the strength characteristics of geotechnical materials is extremely important. Since the 1990s, scholars have been researching cemented sand. Some researchers [2, 3] have obtained results on the strength characteristics of CSG materials from a series of compressive strength tests. The results of previous research indicate that the compressive strength of CSG material increases with increased cementing agent content, the optimal water-cement ratio is 1.2, and the strength is maximized when the fines content lies within the range of 25–30%. Kongsukprasert et al. [4] studied the effects of several factors, including the water content, cementing agent content, dry density, and curing period, on the shear strength of CSG material using triaxial compression tests conducted at a confining pressure of 19.8 kPa. Although extensive, the effects of the confining pressure on the shear strength of CSG material were not considered in these previous studies. Wu et al. [5] analyzed the effects of curing age on the shear strength of CSG material via triaxial testing and subsequently used the test data to establish a shear strength criterion as a function of the curing age and confining pressure. Sun et al. [6] conducted triaxial tests on CSG materials with cementing agent content of less than 60 kg/m^3; additionally, static and dynamic triaxial tests on CSG materials with cementing agent content exceeding 60 kg/m^3 were conducted by Fu et al. [7]. These studies mainly focused on the effects of the cementing agent content

Table 1: Aggregate gradation for Material II.

Name	Smaller than 1 mm	1–5 mm	5–10 mm	10–20 mm	20–40 mm
No. 2 gradation	17%	12%	22%	15.5%	33.5%
No. 3 gradation	16.25%	8.75%	21.25%	28.75%	25%

on the shear strength of CSG material under different confining pressures. Amini and Hamidi [8] analyzed the effects of the cementing agent content on the cohesion c and internal friction angle φ in the Mohr–Coulomb criterion under drained and undrained conditions using triaxial compression testing. However, a shear strength criterion based on the cementing agent content and confining pressure was not proposed in these studies. Li et al. [9] conducted triaxial compression tests on artificial cemented sand, which is a type of material similar to CSG material, and proposed several novel strength criteria based on the experimental results for varying cementing agent content. Because the size of the aggregate in CSG material is significantly different from that in cemented sand, it is unclear whether a strength criterion developed for artificial cemented sand can be directly applied to CSG material. Clough et al. [10] and Wang [11] analyzed the effects of the aggregate content on the shear strength of CSG material for different confining pressures, but did not propose an aggregate content-based strength criterion. A review of the literature shows that research regarding the effects of aggregate gradation on the shear strength of CSG material is insufficient. For CSG dams, because the geological conditions and requirements of each dam project differ, the cementing agent content, aggregate content, and gradation of CSG material also vary for different dams.

In this study, triaxial compression tests were conducted to assess the effects of the cementing agent content, aggregate content, and gradation on the shear strength of CSG material. Additionally, a new strength criterion for CSG material is proposed based on the results. The purpose of the proposed strength criterion is to provide a basis for the construction of a reasonable constitutive model suitable for various types of CSG materials and to meet the engineering requirements for various infrastructure applications, including CSG dam construction.

2. Materials and Methods

2.1. Raw Materials. Two types of CSG materials, hereinafter referred to as Material I and Material II, were examined by means of drained triaxial shear tests.

2.1.1. Material I

Cement: 32.5 grade ordinary silicate cement from the Anhui Digang Hailuo Cement Co., Ltd.

Crushed stone: particle sizes less than 5 mm (3%), 5–10 mm (20%), 10–20 mm (35%), and 20–40 mm (42%), sourced from a Nanjing suburb [5].

Sand: particle size of approximately 0–4.75 mm, medium-coarse sand crushed from limestone.

Water: tap water.

Table 2: Test programs on Material I to investigate effects of cementing agent content and aggregate content.

Sequence number	Cementing agent content (kg/m^3)	Aggregate content (kg/m^3)	Aggregate gradation
1	20	2130	No. 1
2	40	2130	No. 1
3	60	2110	No. 1
4	60	2130	No. 1
5	80	2090	No. 1
6	80	2110	No. 1
7	80	2130	No. 1
8	100	2130	No. 1

The ratio of sand to crushed stone is 1 : 4, which was the same as that used in the experimental study by Sun et al. [5]. In this paper, the aggregate gradation for Material I is termed No. 1.

2.1.2. Material II

Cement: 42.5 grade ordinary silicate cement from the Anhui Digang Hailuo Cement Co., Ltd.

Fly ash: Type I fly ash from the Nanjing market.

Sand and gravel: One aggregate gradation (No. 2) and a second gradation (No. 3), which are listed in Table 1.

Water: tap water.

2.2. Mix Proportions of CSG Material and Test programs. For Material I, the water-cement ratio was 1.0 [12], and the cementing agent contents were 20 kg/m^3, 40 kg/m^3, 60 kg/m^3, 80 kg/m^3, and 100 kg/m^3; the aggregate contents, including the crushed stone and sand contents, were 2090 kg/m^3, 2110 kg/m^3, and 2130 kg/m^3. Samples of Material I, which vary in cementing agent content and aggregate content, were subjected to drained triaxial shear tests under various confining pressures (300 kPa, 600 kPa, 900 kPa, and 1200 kPa). To confirm the adequacy of the strength of CSG material in this paper, a mixture of Material I, with a cementing agent content of 60 kg/m^3 and an aggregate content of 2110 kg/m^3, was used in samples subjected to additional drained triaxial shear tests carried out under varying confining pressures. Test programs conducted on Material I, to investigate the effects of cementing agent content and aggregate content, are presented in Table 2.

For Material II, the ratio of cement to coal ash was 1 : 1, and the water-cement ratio was 1.0 [12]. One aggregate gradation (No. 2) samples of Material II were subjected to drained triaxial shear tests under various confining pressures (300 kPa, 600 kPa, 900 kPa, and 1200 kPa) and varying cementing agent content (20 kg/m^3, 80 kg/m^3, and 100 kg/m^3). In addition, to assess the effects of aggregate gradation on the strength characteristics of CSG, a second gradation (No. 3) was tested in Material II samples. They

Table 3: Test programs of Material II to investigate effects of cementing agent content and aggregate gradation.

Sequence number	Cementing agent content (kg/m^3)	Aggregate content (kg/m^3)	Aggregate gradation
1	20	2130	No. 2
2	80	2130	No. 2
3	80	2130	No. 2
4	100	2130	No. 2

(a) (b)

Figure 1: TYD-1500 triaxial tester, which should be listed as (a) large-scale dynamic triaxial tester; (b) data acquisition system.

(a) (b)

Figure 2: (a) Mixed materials; (b) samples of CSG material.

were subjected to drained triaxial shear tests under different confining pressures (300 kPa, 600 kPa, 900 kPa, and 1200 kPa). Test programs conducted on Material II, to investigate the effects of cementing agent content and aggregate gradation, are presented in Table 3.

2.3. Equipment and Test Methods Used in Drained Triaxial Shear Tests. Drained triaxial shear tests of CSG material samples were conducted using a TYD-1500 dynamic triaxial tester, as is shown in Figure 1.

The mixing materials used to produce CSG material samples for a series of large-scale triaxial tests are shown in Figure 2(a). The materials were compacted in steel molds of 30 cm in diameter and 70 cm in height (Figure 2(b)). The samples were cured in a laboratory at a temperature of $20 \pm 2^{\circ}$C for 28 days.

The triaxial tests for determination of the shear strength of the CSG materials were conducted in accordance with China Standard SL237-1999 [13]. The samples were first saturated and then subjected to one of the four levels of confining pressures (300, 600, 900, or 1200 kPa) for 10 min prior to axial loading. Axial loading at a strain rate of 2 mm/min was then applied and stopped when the axial strain reached 15%.

To improve the accuracy of the results, two samples were prepared and tested for each test group. To prevent damage to the tester due to particles falling from damaged samples, the samples were covered with rubber sleeves that were securely fastened.

3. Results and Discussion

3.1. Shear Strength versus Cementing Agent Content. The results of the drained triaxial shear tests performed on the samples of Material I and Material II are presented in Figures 3 and 4. As these figures show, when the cementing agent content is low, the $q - \varepsilon_a$ curves of CSG material comprise of three stages: an initial stress increase, a slowing

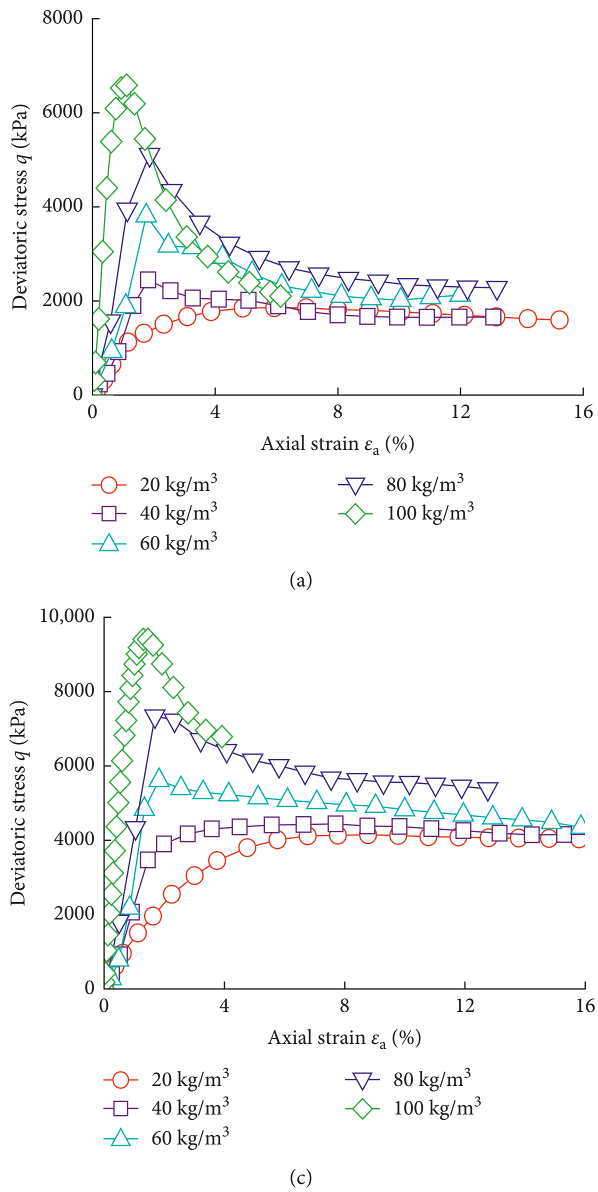


Figure 3: Stress-strain curves of Material I with regard to the effect of cementing agent content under various confining pressures: (a) 300 kPa; (b) 600 kPa; (c) 900 kPa; (d) 1200 kPa.

stress increase, and a peak stress similar to that of the rockfill material in the CSG material. The influence of the cementing agent content on the strain-softening behavior of the material is apparent. The stress-strain curves consist of five stages: an initial stress increase, a slowing stress increase, a peak stress, plastic softening, and a residual strength that approaches that of RCC material when the cementing agent content is increased to 100 kg/m^3. The maximum stress and stress at a given axial strain both significantly increase with increasing cementing agent content at each confining pressure considered in this study (300 kPa, 600 kPa, 900 kPa, and 1200 kPa). This is because cementation between the particles in the CSG material increases with the cementing agent content, thus causing the internal bearing capacity mechanism to change from friction between particles, as in rockfill material, to gradually increasing internal cohesive strength. This is consistent with the results of Li et al. [9], who reported that the cementing agent content is the main factor influencing the strength of artificial cemented sand, which is similar to CSG material.

Figure 5 illustrates the shear strength, which is the maximum stress shown in the curves in Figures 3 and 4 under varying confining pressure and cementing agent content. As Figure 5 shows, the shear strength of CSG material ranges from 1200 to 12,000 kPa and increases with increasing cementing agent content and confining pressure. The relationship between the peak strength and confining pressure is approximately linear for a given cementing agent content. This is consistent with the observations of Fu et al. [7] and other researchers [5] who have reported that increasing the cementing agent content is highly effective in enhancing the shear strength of CSG and various other

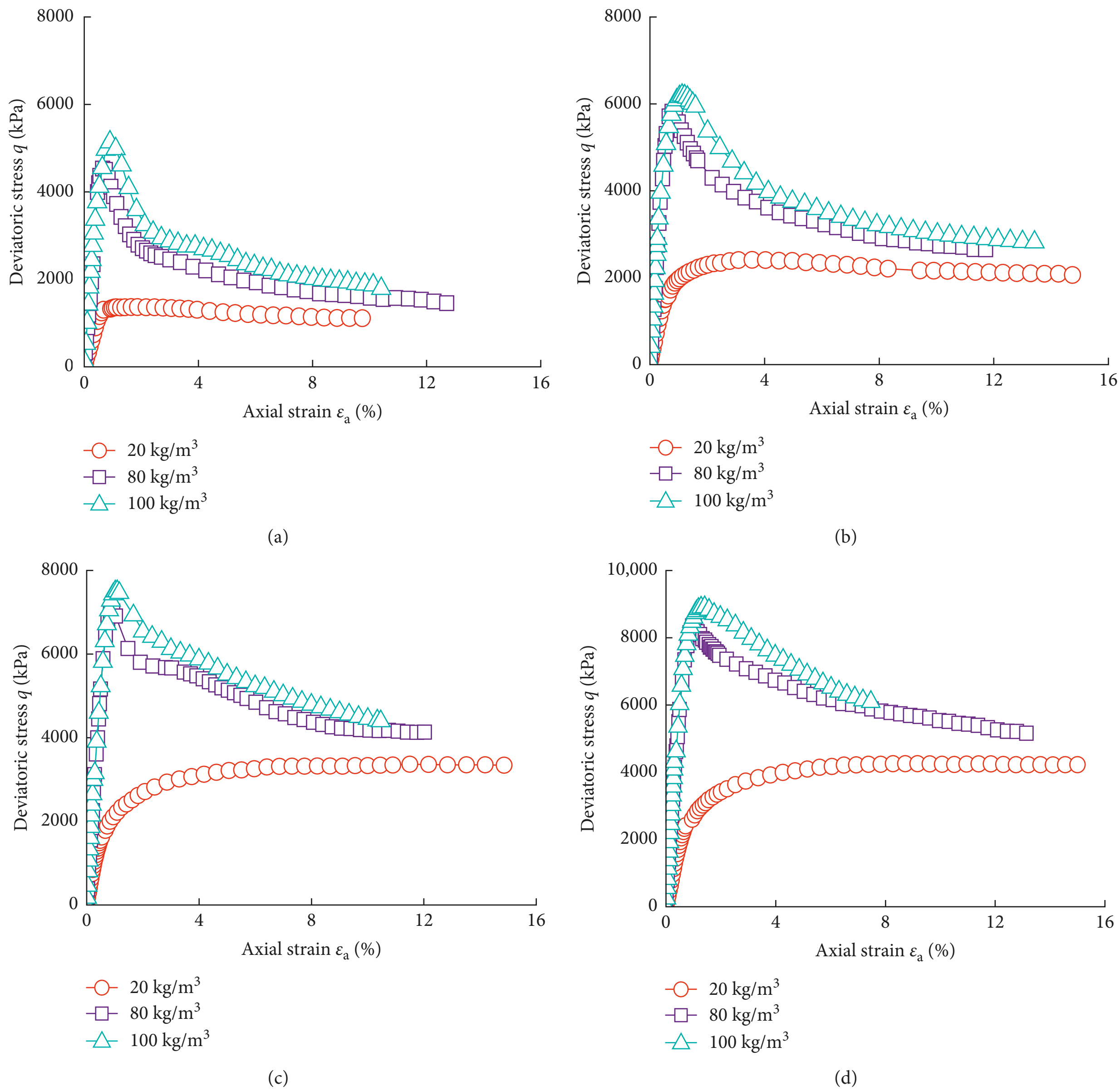


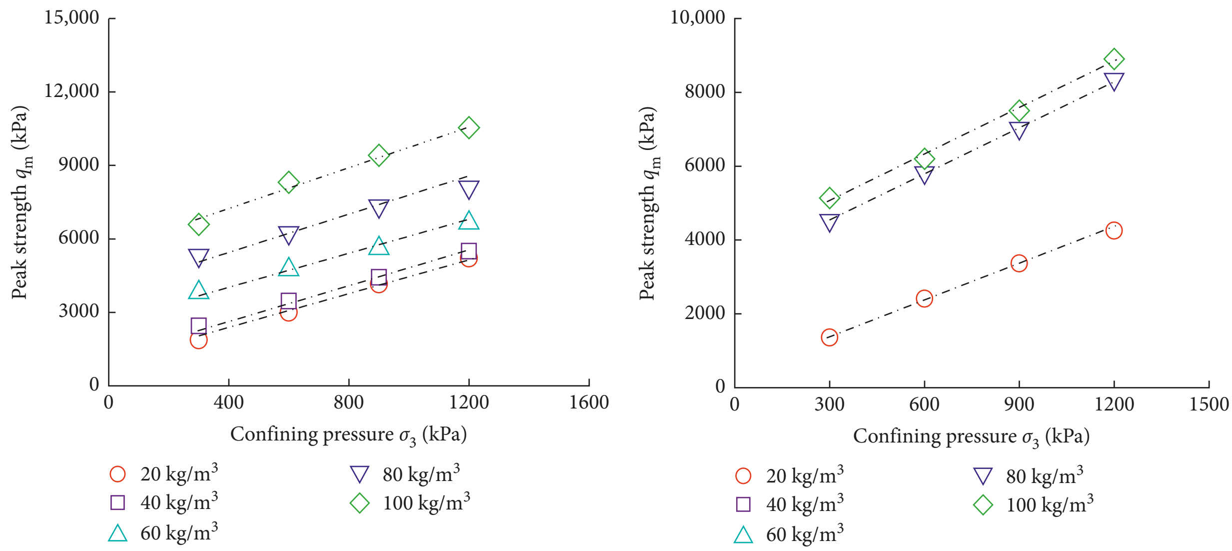
FIGURE 4: Stress-strain curve of Material II with regard to the effect of cementing agent content under various confining pressures: (a) 300 kPa; (b) 600 kPa; (c) 900 kPa; (d) 1200 kPa.

materials, such as cemented sand and polyurethane foam adhesive rockfill materials.

3.2. Shear Strength versus Aggregate Content. Figure 6 shows the stress-strain curves for CSG materials with respect to the aggregate content, obtained via drained triaxial shear testing. As Figure 6 shows, the aggregate content has little effect on the shape of the stress-strain curve, but the peak stress increases as the aggregate content increases. This is attributed to an increase in the aggregate content reinforcing the internal bearing capacity of the CSG material, which is a result of increased particle contact area.

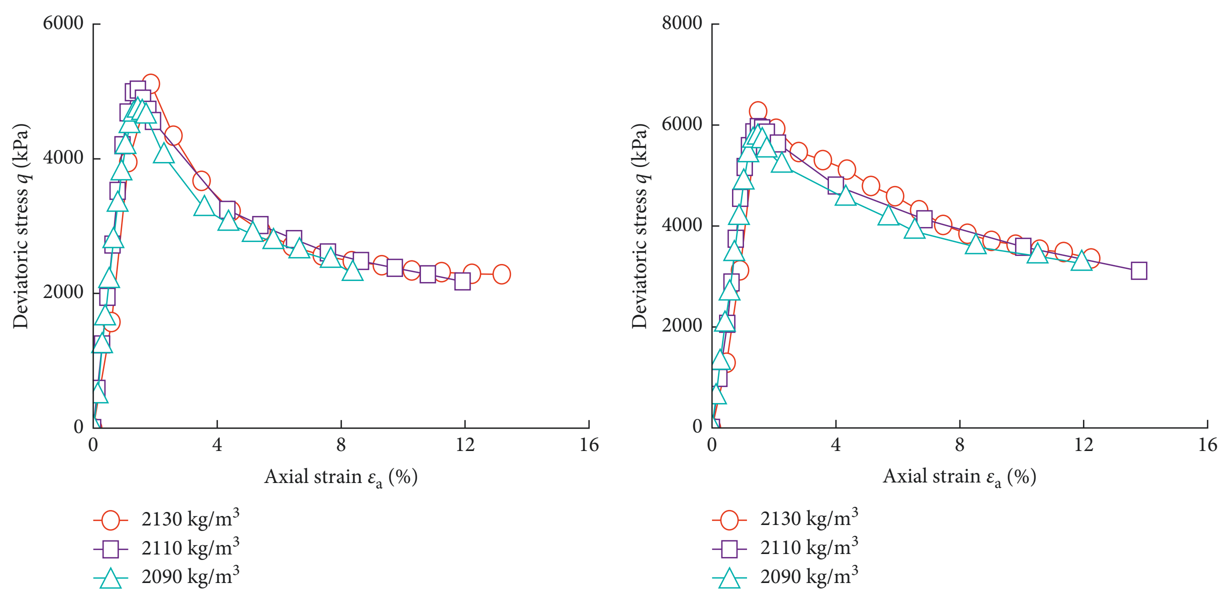
Figure 7 shows the shear strength, which is the maximum stress in the curves shown in Figure 6, for varying confining pressure and aggregate content. As these figures show, the shear strength increases with increased confining pressure and aggregate content. This is consistent with the results of Wang [11] regarding the changes in the strength characteristics of CSG material with relative density and a confining pressure below 300 kPa. In comparison with the cementing agent content, the aggregate content yields less effect on the shear strength of CSG material.

3.3. Shear Strength versus Aggregate Gradation. Figure 8 shows the stress-strain curves for CSG materials with different aggregate gradations, obtained via drained triaxial shear testing. The effects of aggregate gradation on the stress-strain behavior of CSG material are not notable for any of the confining pressures considered (300 kPa, 600 kPa, 900 kPa, and 1200 kPa). This is similar to the minimal effect of



(a) (b)

FIGURE 5: Relation curves of peak strength and confining pressure of CSG material with different cementing agent contents: (a) Material I and (b) Material II.



(a) (b)

FIGURE 6: Continued.

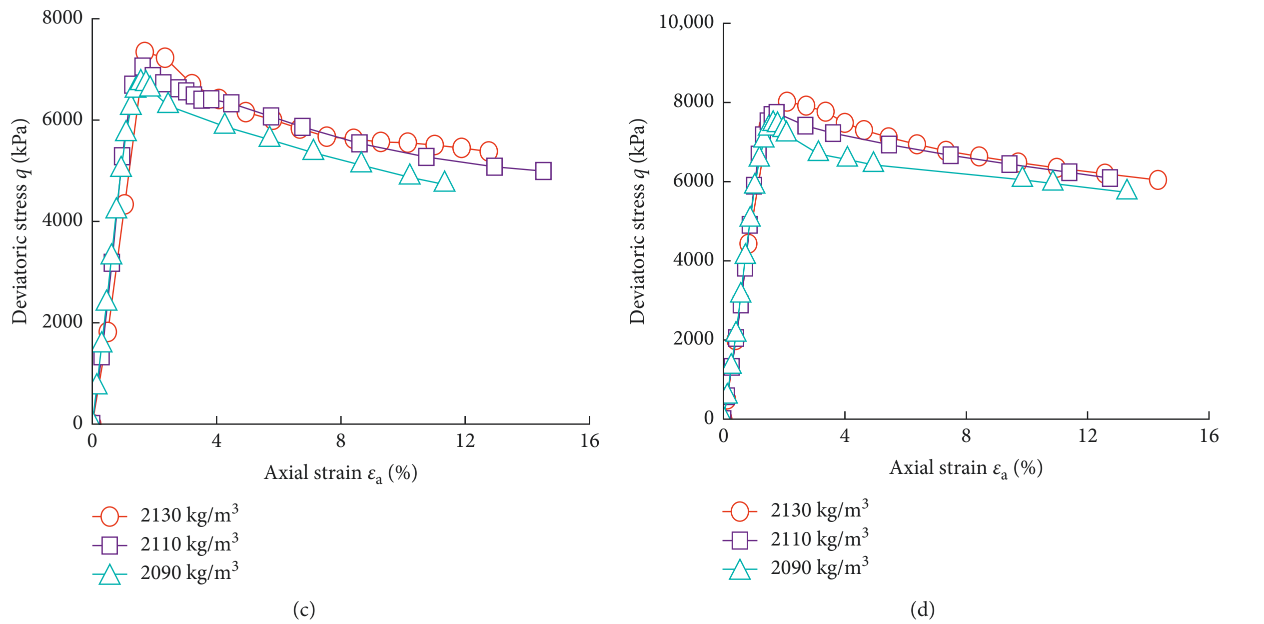


Figure 6: Stress-strain curve of CSG material considering the effect of aggregate content under various confining pressures: (a) 300 kPa; (b) 600 kPa; (c) 900 kPa; (d) 1200 kPa.

gradation on the strength of rockfill material when the aggregate content ranges from 60 to 70%.

4. Strength Criterion

The Mohr–Coulomb theory, which serves as the basis for the strength criterion for CSG material in this study, is commonly used to describe the stress-strain response of materials [5–8]. It can be expressed as follows:

$$\tau_f = c + \sigma \tan \varphi, \tag{1}$$

where c is the cohesion of the material, φ is the angle of the internal friction, τ_f is the shearing stress, and σ is the normal stress.

To describe the relationships between the peak strength and confining pressure for the varying cementing agent content and aggregate content shown in Figures 6 and 7, the Mohr–Coulomb criterion represented by the principal stress in (1) can be expressed as follows:

$$q_m = \frac{2c\cos\varphi}{1-\sin\varphi} + \frac{2\sin\varphi}{1-\sin\varphi}\sigma_3, \tag{2}$$

where q_m is the peak strength, σ_3 is the confining pressure for drained triaxial shear testing, c is the cohesion, and φ is the angle of the internal friction (shearing resistance).

Based on (2) and the shear strength test results obtained for differing cementing agent content and aggregate content, values for the cohesion c and angle of internal friction (shearing resistance) φ were extracted for this analysis, as is shown in Tables 4 and 5.

The Mohr–Coulomb theory is based on the assumption that the cohesion and angle of shearing resistance in (1) are constant. However, for CSG materials used in practical engineering applications, the cohesion and angle of shearing resistance vary according to the cementing agent content and aggregate content. This means that the original Mohr–Coulomb strength theory expression is not suitable for CSG materials with varying cementing agent content and aggregate content. Thus, a new strength criterion for the shear strength of CSG material is proposed. This criterion is a function of the cementing agent content and aggregate content.

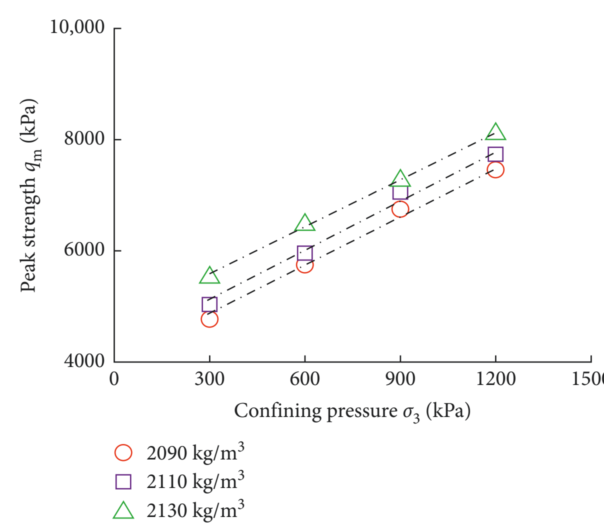


Figure 7: Relation between peak strength and confining pressure under different aggregate contents.

4.1. Cohesion c. Based on the cohesion values obtained for different cementing agent contents (listed in Table 4), the relationship between cohesion and the cementing agent content can be expressed as follows:

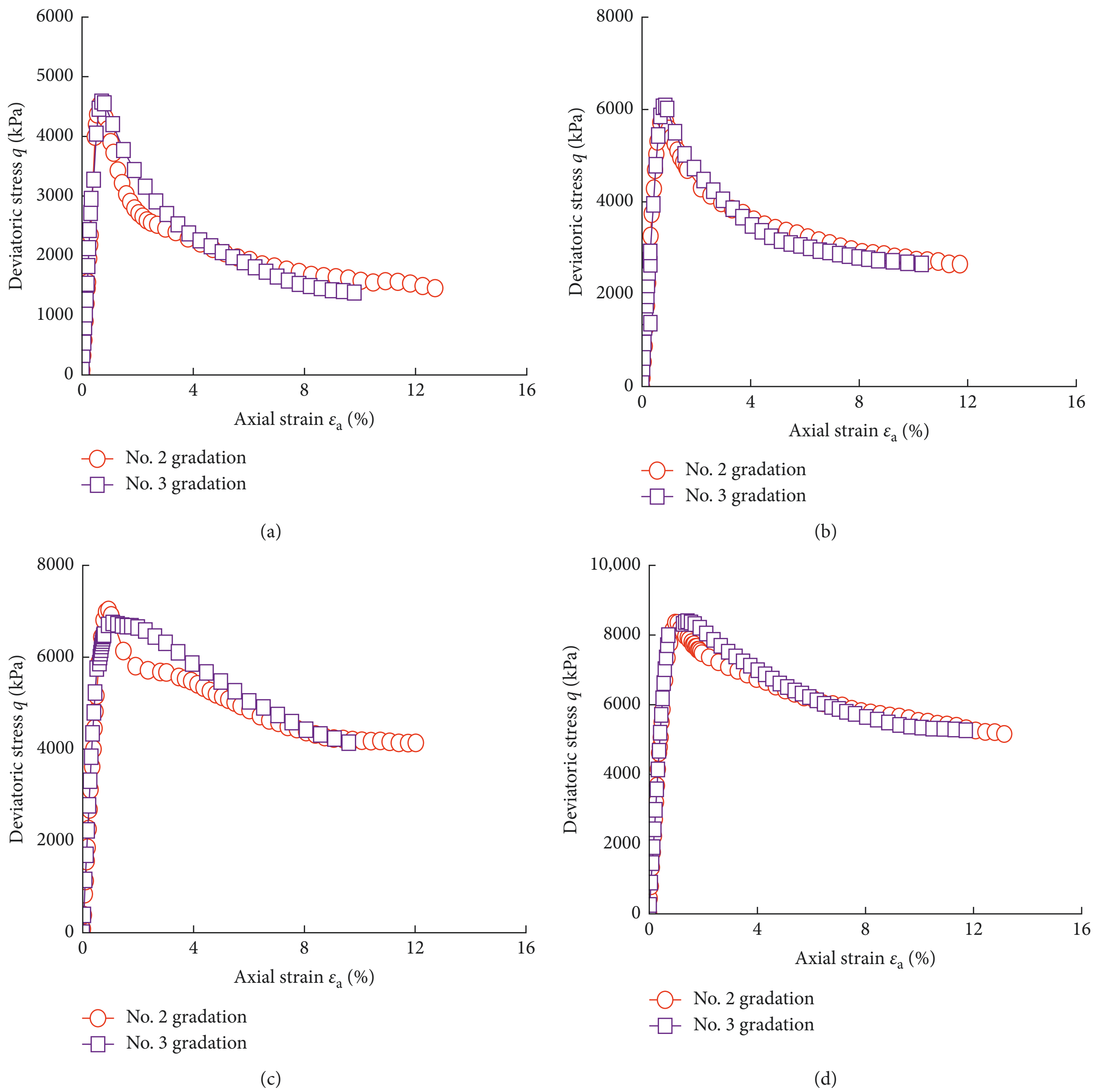


Figure 8: Stress-strain curve of CSG material with regard to the effect of aggregate gradation under various confining pressures: (a) 300 kPa; (b) 600 kPa; (c) 900 kPa; (d) 1200 kPa.

$$c = H_0 C_c, \tag{3}$$

where H_0 is the parameter related to the composition of the CSG material and C_c is the cementing agent content.

When the cementing agent content in (3) is low, the cohesion of the CSG material is near zero, which is close to the cohesion of rockfill material, as calculated by Sun et al. [5]. Figure 9 shows a comparison of the test data and results calculated using (3) for CSG material [5, 6, 8], PFA-reinforced rockfill material [14], cemented sand [9], and cemented soil [15] for different cementing agent contents. As Figure 9 shows, the calculated results for CSG material, PFA-reinforced rockfill material, and cemented sand fit the experimental results well; this confirms that (3) yields a reasonable description of the cohesion of those cemented and bonded materials as a function of the cementing agent content. However, because the soil in the cemented soil studied by Baxter et al. [15] had some viscosity and a cohesion value greater than zero, (3) is not suitable for this type of cemented soil.

Based on the cohesion values obtained for different aggregate contents (Table 5), curves of cohesion as a function of aggregate content were developed, as shown in Figure 10. These curves show that the cohesion of CSG material increases with increasing aggregate content. However, compared to the influence of the cementing agent content, the influence of the aggregate content on the cohesion of CSG is lower.

The relationship between cohesion and aggregate content can be formulated as follows:

$$c = H_g \rho_g, \tag{4}$$

where H_g is the parameter related to the type of aggregate in the CSG material and ρ_g is the aggregate content. By

Table 4: Cohesion and internal friction angle under different cementing agent contents.

Cementing agent content, C_c (kg/m^3)	Cohesion, c (kPa)	Internal friction angle (°)
20	256.1	40.3
40	405.2	38.9
60	691.9	38.0
80	1031.2	39.3
100	1280.1	41.4

Table 5: Cohesion and internal friction angle under different aggregate contents.

Aggregate contents, ρ_g (kg/m^3)	Cohesion, c (kPa)	Internal friction angle (°)
2090	934.4	38.8
2110	989.2	39.1
2130	1031	39.3

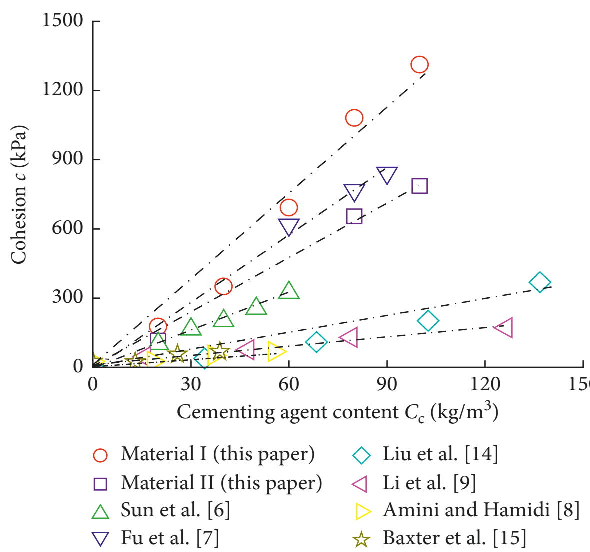


Figure 9: Relation between cohesion and cementing agent content.

combining (3 and 4), the following expression for cohesion c as a function of the cementing agent content and aggregate content can be obtained:

$$c = H_z \rho_g C_c, \tag{5}$$

where H_z is the parameter related to the composition and type of aggregate for CSG material. According to the results of the drained triaxial shear tests described above, $H_z = 0.005$.

4.2. Internal Friction Angle φ. Figure 11 illustrates the internal friction angle values obtained for CSG material [5, 6, 8], PFA-reinforced rockfill material [14], cemented sand [9], and cemented soil [15] for different cementing agent contents. As Figure 11 shows, the internal friction angle of CSG material, PFA-reinforced rockfill material, cemented sand, and cemented soil ranges from 30° to 50°, which moderately differs from the range of 25° to 65° for

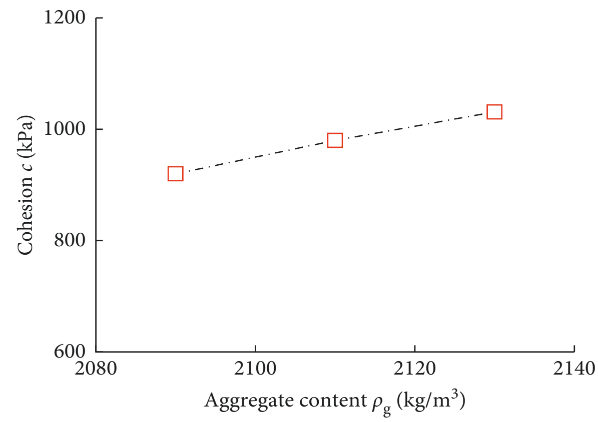


Figure 10: Relation between cohesion and aggregate content.

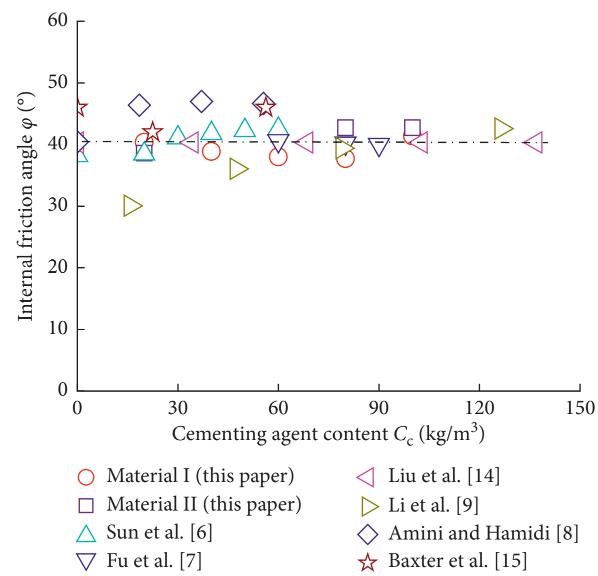


Figure 11: Relation between internal friction angle and cementing agent content.

gravel [16]. The reason for this difference is that the cementing agents in the cemented materials limit the slippage angle of the aggregate. The internal friction angle of CSG material and PFA-reinforced rockfill material for various cementing agent contents is approximately 39.5°. Similarly, the internal friction angle of CSG material is approximately 39° for various aggregate contents, as presented in Table 5. Based on these results, the internal friction angle value for CSG material is taken as 39.3° for a range of cementing agent contents and aggregate contents.

4.3. Strength Criterion according to Cementing Agent Content and Aggregate Content. Based on the results summarized above, the following expression for the shear strength of CSG material as a function of the cementing agent content and aggregate content is proposed:

$$q_m = \frac{2H_z \rho_g C_c \cos\varphi}{1-\sin\varphi} + \frac{2\sin\varphi}{1-\sin\varphi}\sigma_3, \tag{6}$$

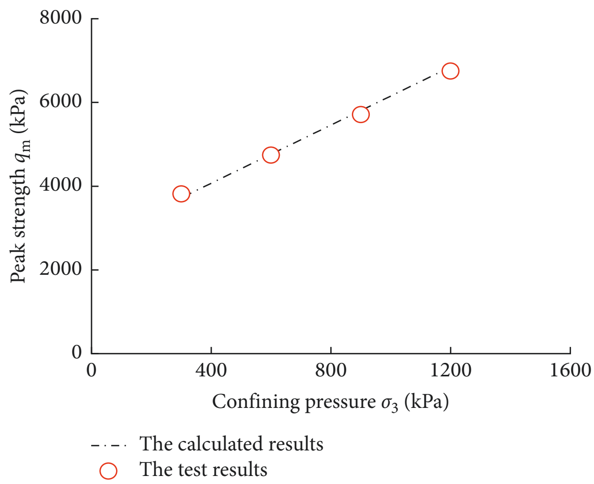


Figure 12: Comparison of the test results and calculated results.

where H_z is a parameter associated with the type and composition of the CSG material.

For a given value of c, (6) describes the peak strength of CSG material for varying aggregate content. For a given value of ρ_g, (6) describes the peak strength of CSG material for varying cementing agent content.

According to the results of triaxial testing on Material I for various cementing agent contents and (6), $H_z = 0.005$ and $\varphi = 39.3^{\circ}$. Equation (6) can also be expressed as follows:

$$q_m = 0.021\rho_g C_c + 3.47\sigma_3. \tag{7}$$

To verify (6), drained triaxial shear tests on samples with a cementing agent content of 60 kg/m^3 and aggregate content of 2110 kg/m^3 were conducted under confining pressures of 300 kPa, 600 kPa, 900 kPa, and 1200 kPa. The test results and calculated results are shown in Figure 12. The calculated results fit the experimental results well, thereby demonstrating that (6) can be used to describe the shear strength of CSG material as a function of the cementing agent content and aggregate content.

5. Conclusions

The effects of the cementing agent content, aggregate content, and gradation on the shear strength of CSG material were investigated by means of drained triaxial shear testing. The conclusions drawn from the test results can be summarized as follows.

(a) The influence of the cementing agent content on the shear strength of CSG material is much more significant than the influence of the aggregate content and gradation.

(b) The cohesion of CSG increases with increasing cementing agent content and aggregate content, whereas the internal friction angle changes only slightly. The effects of the aggregate gradation on cohesion and the internal friction angle are negligible.

(c) A strength criterion for CSG material is proposed based on an analysis of the strength characteristics of the material as a function of the cementing agent content, aggregate content, and aggregate gradation. Overall, the strength model fits the test data well of CSG material and can provide evidence for numerical calculation of CSG dam.

Data Availability

The test and calculated data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no actual or potential conflicts of interests regarding the publication of this paper.

Acknowledgments

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