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EXPERIMENTAL INVESTIGATIONS

A SIMPLE METHOD TO PREDICT TENSILE STRENGTH OF GRAVELLY SOIL USING SHEAR STRENGTH INDEXES

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The tensile strength of gravelly soil plays a decisive role in the formation or initiation of longitudinal cracks or hydraulic fracturing in the core of earth and rockfill dams. For this study, a series of uniaxial tensile tests and consolidated drained triaxial shear tests was carried out to study the relationships between the tensile strength and shear strength indexes of gravelly soils with gravel contents ranging from 0% to 50%. The test results indicate that the tensile strength decreases linearly with increasing gravel content when the soil is at its maximum dry density and optimum water content. An equation for estimating tensile strength of gravelly soil without tensile strength testing is proposed. The relevant test results can provide guidance for anti-crack designs for earth-core rockfill dams.

Introduction

In the field of geotechnical engineering, there are relatively few published studies on the tensile properties of soil. In most cases, the structural stability calculations do not consider the tensile strength of the soil [1]. However, completed structures commonly show obvious tensile cracks on their surfaces before serious damage develops [2-3].

In recent years, some tall earth-core rockfill dams in China [4, 5] have developed serious longitudinal cracks at the top of the core. These problems emphasize the importance of studying the tensile strength of gravelly soil to understand crack formation and crack initiation in dam cores. The relationship between tensile strength and dry density as well as the relationship between tensile strength and water content in gravelly soil were investigated [6, 7]. However, the influence of gravel content on the tensile strength is still not clear. A special device [8] was constructed to perform uniaxial tensile tests to determine the tensile strength of gravelly soil. The end effect and membrane restraint effect inherent in standard triaxial tensile tests [9] results in inaccurate test data. Consequently, establishing the relationship between the shear strength index and tensile strength is a simple approach.

For this study, a series of uniaxial tensile tests and consolidated drained (CD) triaxial shear tests was carried out to study the relationship between tensile strength and the shear strength indexes (cohesion c and friction angle φ) of gravelly soil with gravel contents ranging from 0% to 50%. Based on the results of the tests, the influence of gravel content on the tensile strength was determined and a quantitative expression to predict tensile strength based on shear strength is put forward.

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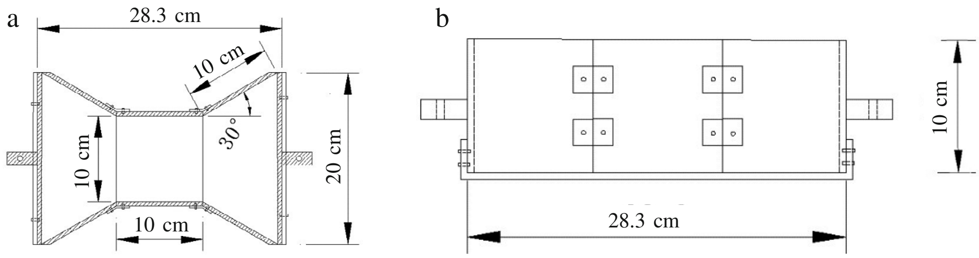

Fig. 1. Schematic diagram of tensile device: a) Overhead view; b) side view.

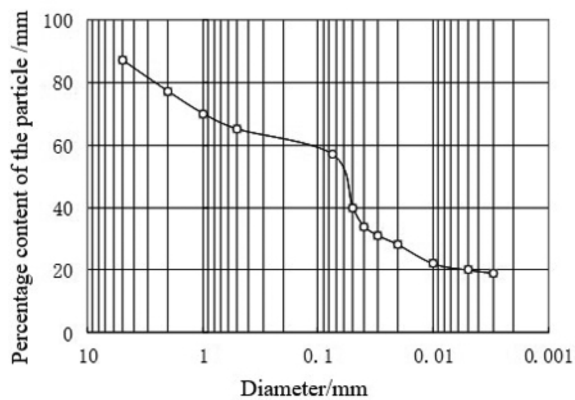

Fig. 2. Gradation curve of the clay.

TABLE 1

Parameters	Gravel content					
	0%	10%	20%	30%	40%	50%
Optimum water content, %	17.5	16.4	14.8	13.3	11.5	10.1
Maximum dry density, g/cm^3	1.73	1.82	1.88	1.98	2.01	2.05
c, kPa	92.5	83.3	61.4	54.4	35.1	30.9
φ, °	19.3	21.2	27.4	27.9	36.3	37.9

Test Device and Testing Procedures

The new type of dumbbell-shape uniaxial tensile device constructed for and used in this study is shown in Fig. 1. The device separates the loading section from the tensile testing section. The tensile testing section is 10 × 10 cm in size and the angle between the loading surface and the tensile surface is set to 30°. The device integrates sampling and testing and does not require any accessories or other equipment. Consolidated drained triaxial tests were carried out under 0.2, 0.4, and 0.8 MPa confining pressure according to ASTM Standard D7181-11 [10].

The gravelly soil tested came from the core and rockfill material of the Changheba earth-core rockfill dam, Sichuan Province, China. The clay was sieved from the core material, the gradation curve is shown in Fig. 2. After artificial crushing from rockfill material, the gravel was obtained. The maximum particle size was 20 mm (one-fifth the length of the tensile section of testing device), and the minimum particle size was 2 mm.

The compaction tests on the gravelly soil containing 0%-50% very fine to coarse gravel were conducted to determine the maximum dry density (MDD) and the optimum water content (OWC) (Table 1).

The control variate method was used to study the influence of dry density, water content, and gravel content on the tensile strength of the gravelly soil and to formulate the test schemes listed in Table 2.

TABLE 2

Gravel content	Parameters	
	Dry density, g/cm^3	Water content, %
0%	1.73 1.73, 1.63, 1.53	17.5, 15.5, 19.5 17.5
10%	1.82 1.82, 1.72, 1.62	16.4, 14.4, 18.4 16.4
20%	1.88 1.88, 1.78, 1.68	14.8, 12.8, 16.8 14.8
30%	1.98 1.88, 1.78, 1.68	13.3, 11.3, 15.3 13.3
40%	2.01 2.01, 1.91, 1.81	11.5, 9.5, 13.5 11.5
50%	2.05 2.05, 1.95, 1.85	10.1, 8.1, 12.1 10.1

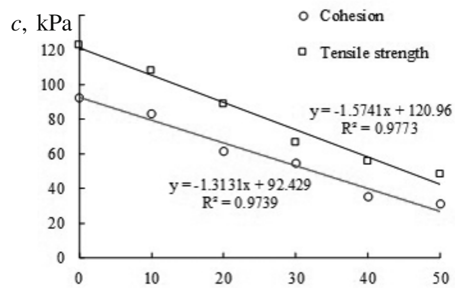

Fig. 3. Relation curves of tensile strength and cohesion versus gravel content.

Results and Analysis

Figure 2 shows the tensile strength of gravelly soil versus gravel content. It can be seen that when the gravel content increases from 0% to 50%, the tensile strength decreases from 122.6 to 49.8 kPa. The linear relationship can be expressed as

$$\sigma_t = (-1.5741\lambda)\times 100 + 120.96, \quad (1)$$

where λ is gravel content (%). Because the core of an earth and rockfill dam must not only be stiff but must also be impervious to water, the gravel content of the core is commonly controlled to be about 35% [11]. The OWC and MDD must also be strictly controlled. According to Eq. (1), when the gravel content is 35%, the tensile strength of the gravelly soil is about 65.9 kPa. The tensile strength of the gravelly soil used in the tests will decrease to zero when the gravel content increases to about 80%. However, when the gravel percentage is greater than some value, most of the cohesion in the soil will be gone. Any tensile strength remaining in a soil composed of this high proportion of gravel will be provided by biting forces between the coarse-grained soil grains. Preparing a representative sample of gravelly soil with a high gravel content is difficult, and it is also difficult to measure the tensile strength of this type of soil with the testing device.

Recent research [12-13] on gravelly soil indicates that the shear strength indexes c and φ vary with the gravel content. To study the relationship between the tensile strength and shear strength indexes, CD triaxial shear tests were carried out at 200, 400, and 800 kPa confining pressure. The Mohr's circle for each specimen was drawn on the normal stress-shear stress (σ–τ) plane to obtain c and φ. Table 1 lists c and φ for samples with different gravel contents. The samples were kept at their respective MDD's and OWC's during the tests. Generally, it can be seen that the sample's cohesive force decreases significantly, but the internal friction angle increases slightly as the gravel content increases.

Figure 3 shows curves for tensile strength and cohesion plotted against the gravelly soil's gravel content. There is a good linear relationship between cohesion and gravel content. As the gravel content increases, the cohesion and tensile strength both decrease. In fact, as mentioned above, as the gravel content increases, the proportion of soil particles on the fracture surface decreases and the proportion of gravel increases. Thus, the macroscopic tensile stress changes from completely capillary tension between soil particles to the tension between soil particles and soil-gravel. Because the tension between soil/gravel particles is relatively low, the tensile stress decreases and the macroscopic cohesion also decreases. There is an interrelationship between tensile strength and cohesion.

From Fig. 3, the relationship between tensile strength and cohesion can be expressed as

$$\sigma_t = 1.2c + 10.2. \tag{2}$$

Equation (2) can be used to estimate the tensile strength of gravelly soil from the cohesion, and cohesion is easy to measure using triaxial shear tests.

Conclusions

For this study, a series of uniaxial tensile tests and consolidated drained (CD) triaxial shear tests was carried out to study the relationship between the tensile strength and shear strength indexes (c and φ) of gravelly soil containing 0% to 50% gravel.

The test results show that the tensile strength decreases linearly with increasing gravel content when the samples is at its maximum dry density (MDD) and optimum water content (OWC). The tensile strengths for the specimens tested ranged from 122.6 to 49.8 kPa. The tests also show that tensile strength correlates linearly with cohesion. An equation for estimating the tensile strength of gravelly soil from its measured cohesion is proposed.

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