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Experimental study on the tensile strength of gravelly soil with different gravel content

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Abstract. In recent years, the crack accidents of earth and rockfill dams occur frequently. It is urgent to study the tensile strength and tensile failure mechanism of the gravelly soil in the core for the anti-crack design of the actual high earth core rockfill dam. Based on the self-developed uniaxial tensile test device, a series of uniaxial tensile test was carried out on gravelly soil with different gravel content. The compaction test shows a good linear relationship between the optimum water content and gravel content, and the relation curve of optimum water content versus maximum dry density can be fitting by two times polynomial. For the gravelly soil under its optimum water content and maximum dry density, as the gravel content increased from 0% to 50%, the tensile strength of specimens decreased from 122.6 kPa to 49.8 kPa linearly. The peak tensile strain and ultimate tensile strain all decrease with the increase of the gravel content. From the analysis of fracture energy, it is proved that the tensile capacity of gravelly soil decreases slightly with the increasing gravel content. In the case that the sample under the maximum dry density and the water content higher than the optimum water content, the comprehensive tensile capacity of the sample is the strongest. The relevant test results can provide support for the anti-crack design of the high earth core rockfill dam.

Keywords: gravelly soil; gravel content; uniaxial tensile test; tensile strength; tensile strain; fracture energy

1. Introduction

High earth and rockfill dams are widely distributed in China especially in poor geological conditions because of their excellent ability to coordinate deformation. Generally, a certain proportion of gravel is often incorporated into the clay as the core materials to reduce the difference between the modulus of the core and the dam shell (Zhou *et al.* 2016). Thus, the arch effect can be reduced. With the increase of gravel content, the ability of the gravelly soil to resist shear deformation increases significantly (Zhang *et al.* 2015). However, whether the crack resistance of the gravelly soil can still meet the anti-crack design requirements of the dam is worth further study. In recent years, tension cracks frequently happen on the core of earth core rockfill dams under excessive tension stress. For example, cracks appeared on the core of Xiaolangdi (154 m), Pubugou (186 m) and Nuozhadu (261.5 m) earth core rockfill dam at the operational stage. On the other hand, some tensile failure criterions (Zhu *et al.* 2015, Wang *et al.* 2016, Liu *et al.* 2017) which demand tensile test to determine tensile strength were proposed to predict hydraulic fracturing in the core of the dam. Consequently, it is necessary to study the tensile behavior of gravelly soil.

At present, tensile behavior of rock materials have been deep investigated by many researchers (Komurlu *et al.* 2016, Komurlu *et al.* 2017, Tutmez *et al.* 2017), and the test results are meaningful to the research of soils. Previously, researchers (Tang and Graham 2000, Shinde *et al.* 2012, Tej *et al.* 2012) have conducted a large number of uniaxial and triaxial tensile tests on clay, and obtained quantitative relations between tensile strength and properties (eg. dry density, matrix suction). The influences of water content and dry density on the tensile strength and softening behavior of compacted cohesive soils were analyzed by Zhang *et al.* (2014). By using epoxy resin as binder, uniaxial tensile tests of clay with different moisture content were carried out by Heibrock *et al.* (2005). Besides, some researchers have conducted a series of tensile tests toward some special soils. Sun *et al.* (2005) pointed out that the tensile strength of original loess is about in the range of 10.5 kPa to 46.5 kPa. Lv *et al.* (2013) proved that the tensile strength of the shrinking soil reached its maximum at a saturation of about 66%. The tensile strength of statically-compacted sand bentonite and cement-enhanced sand bentonite mixtures was measured in varying curing time periods using the “double punch” test by Anoosheh and Huriye (2016). Lu *et al.* (2014) analyzed the tensile strength

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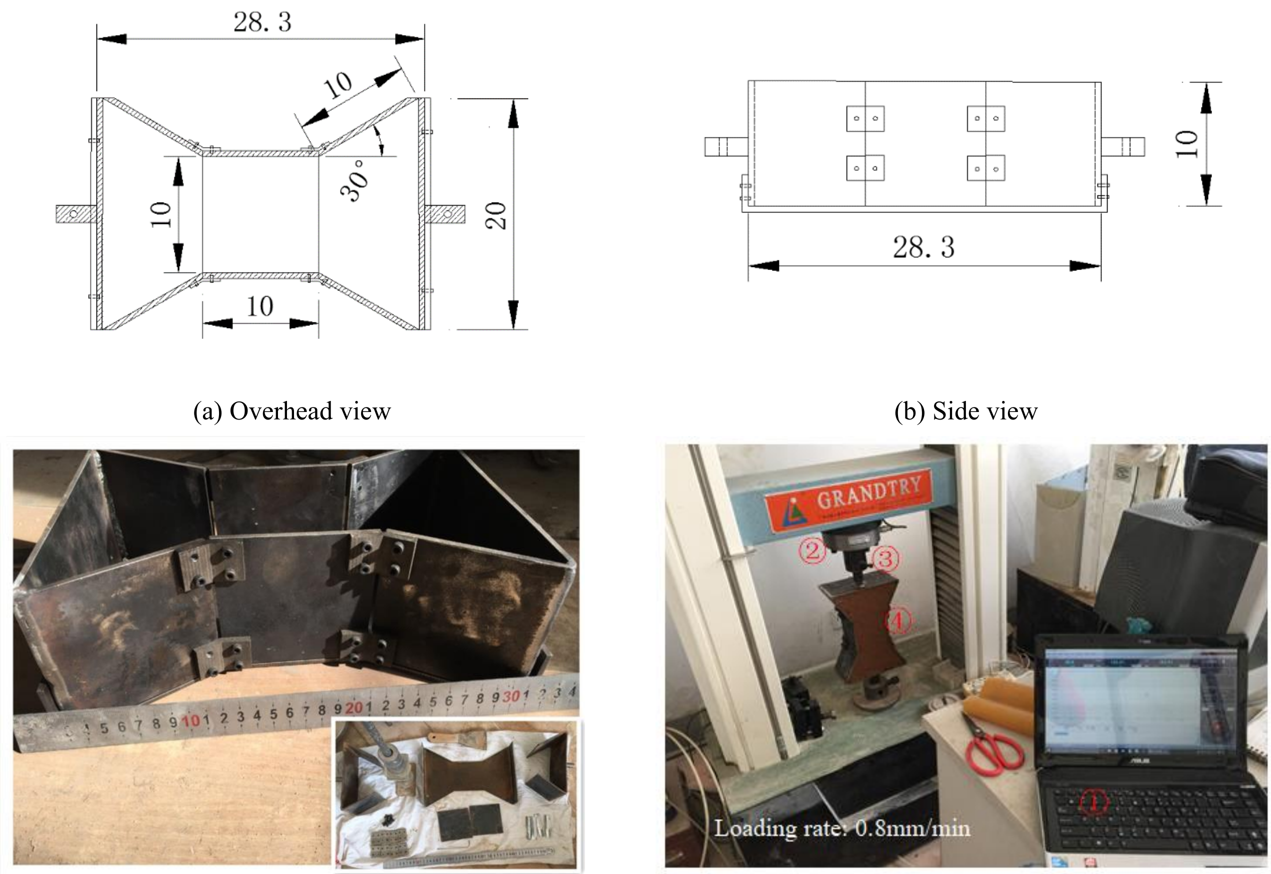


(a) Overhead view (b) Side view

(c) Overview of the tensile device (d) Testing progress

Fig. 1 Schematic diagram of tensile device and testing progress(unit: cm) Note: (1): tensile device, (2): loading equipment, (3): Coupled Stress and Displacement Sensor, (4): Software system

and fracture mechanism of dispersed soils systematically. In order to avoid the end effects and the effect of self-weight, the length-diameter ratio of the sample is considered to be 2.5, and the loading rate should be less than 0.08 mm/min. Divya *et al.* (2013) studied the tensile behavior of reinforced soil by using self developed device, and then used the image measuring technology to study the micromechanical characteristics of reinforced soil. Tang *et al.* (2016) developed a dumbbell shape tensile mould, and performed tensile tests on artificially reinforced clays with different water content and dry densities. Zhu *et al.* (2007) studied the variation of tensile strength on gravelly soil with different compaction energy, saturation and water content.

In general, there are few studies on the tensile properties of gravelly soil, and the variation of tensile strength with different gravel content on gravelly soil needs to be further investigated. In this paper, based on the self-developed uniaxial tensile test device, a series of uniaxial tensile test was carried out on gravelly soil with different gravel content. The relations of tensile strength versus gravel content, water content and dry density are discussed. In addition, the fracture energy and tensile strain of gravelly soil are also investigated. The relevant test results can provide support for the anti-crack design of the high earth and rockfill dam.

2. Soils and test schemes

2.1 Test device

For gravelly soils, if the epoxy resin is used to bond the sample with the loading plate, the sample will be fractured in the bonding zone. Thus, certain errors of the tensile strength and strain measured from the test will exist. In this paper, a new type of uniaxial tensile device was used considering the disadvantages of the previous tensile devices. The device separates the specimen into loading section and tensile section as can be seen in Fig. 1. The new device integrates sample preparation and testing into one and does not require other complicated equipment.

The test was carried out on a universal testing machine. In order to reduce the influence of the loading rate on the test results, the loading rate was controlled to be 0.8 mm/min (Lu *et al.* 2014). After the test, the upper half of the sample was pulled off along with the upper half of the device, and was moved to the electronic scale. The self-weight of the sample was measured and recorded. The self-weight of the upper part of the sample was subtracted from the measured force-displacement data and converted into tensile stress. Then, the tensile stress-displacement curve of each test scheme can be obtained.

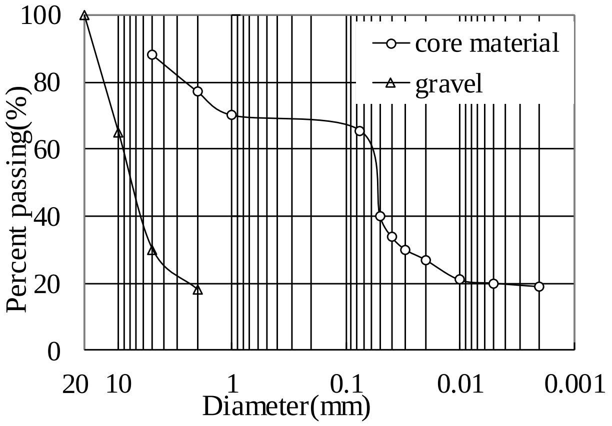


Fig. 2 Gradation curve of the core material (ASTM D2488)

Table 1 Basic parameters of the core material

Gs	ω_L (%)	ω_P (%)	I_p	ω (%)	k (cm·sec^{-1})
2.74	30.4	20.5	10	22.2	2.0×10^{-6}

2.2 Test Procedure

The test procedure consisted of four steps:

1. Specimen preparation: Soil and water of calculated weights were mixed and sealed in a plastic bag for 24 h to homogenize the water by giving the required dry density, and water content. Then the soil was compacted layer by layer (with a total of three equal layers) into the tensile device using a specialized compacting instrument. Each layer was compacted to the designed height to reach the required dry density. The surface of each layer was roughened to make the specimen integrity.
2. Specimen installation: The sample together with the tensile device is moved to the universal testing machine, and the two ends of the device are fixed on the testing machine with pins. Remove the hexagonal bolts on the middle of the device, then slowly remove the bottom plate and square iron plates on the side of the device. The sample after installation is shown in Fig. 1(d).
3. Examination of the data acquisition system: The readings from the force and displacement transducers were examined and the initial values were recorded.
4. Tensile test: A proper displacement rate was set (0.8 mm/min), and the complete tensile stress-displacement curve was recorded.

2.3 Material characterization

The clay used in this paper is from the mixture of a dam core. Particle analysis was performed on the mixture using sieve analysis method and densitometer method. The gradation curve of the core material and gravel is shown in Fig. 2 according to ASTM D2488.

Based on the geotechnical testing rules (ASTM D2487), the basic parameters of the clay are shown in Table 1.

The gravel used in the test is from an earth and rockfill dam and the parent rock is granite. After manual crushing and screening, the gradation needed for the test are obtained. As the central dimension of the device used in the

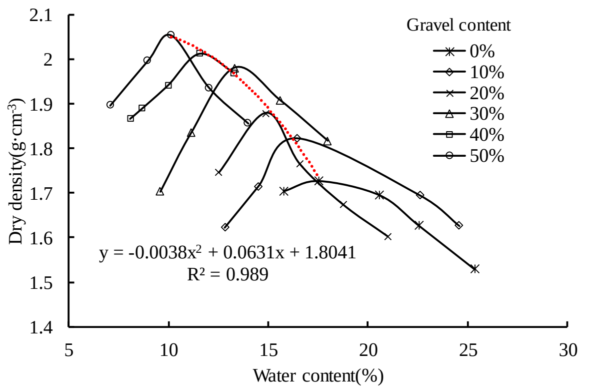


Fig. 3 Relation curve of dry density versus water content for various gravel content

Table 2 ω_{op} and ρ_{dmax} of the gravelly soils with gravel content varies from 0-50%

Gravel content(%)	0%	10%	20%	30%	40%	50%
ω_{op} (%)	17.5	16.4	14.8	13.3	11.5	10.1
ρ_{dmax} (g/cm^3)	1.73	1.82	1.88	1.98	2.01	2.05

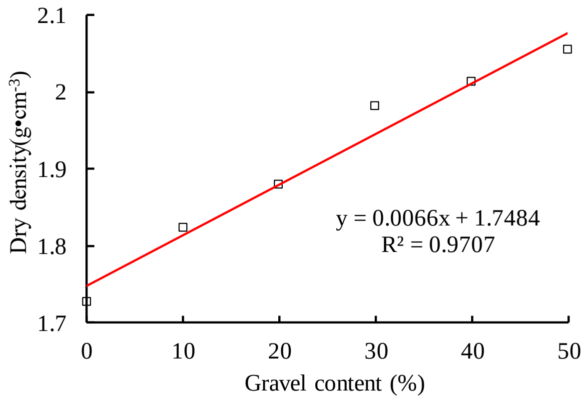


Fig. 4 Relation curve of dry density versus water content for various gravel content

Table 3 Tensile test schemes of gravelly soil

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

paper is 10 cm*10 cm, the maximum particle size of the gravel is controlled to be 20 mm (1/5 of the longest side of the sample) according to the rules of geotechnical testing (ASTM D4767-02). The minimum particle size of the gravel is 2 mm.

2.4 Test schemes

First, compaction tests were conducted on gravelly soils with different gravel content to obtain maximum dry density(ρ_{dmax}) and optimum water content(ω_{op}). Fig. 3 shows the relation curve of dry density versus water content of gravelly soil during the increase of gravel content from 0% to 50%. The inflection point of each curve is obvious, and the horizontal and vertical coordinates of the peak point on the curve represent ρ_{dmax} and ω_{op} of gravelly soils respectively. It can be seen that with the increase of gravel content, the ρ_{dmax} of gravelly soil increases gradually, while the ω_{op} decreases.

Table 2 shows the ω_{op} and ρ_{dmax} of the gravelly soils with different gravel content. The preparation of the following samples is based on the ω_{op} and ρ_{dmax} in Table 2.

Fig. 4 shows the relationship between dry density and gravel content of gravelly soil. It can be seen that the maximum dry density increases almost linearly with the increasing gravel content. As the gravel content increasing, the particle area of the clay-gravel mixture in unit volume of soil will decreases. The unit volume weight of gravel is larger than clay, consequently, the dry density of gravelly soil will increases. The relation equation can be given by

$$\rho_{d\,max} = 0.0066\lambda + 1.7484 \tag{1}$$

For the actual dam engineering, the ρ_{dmax} and ω_{op} are two construction parameters of the core that should be strictly controlled during construction period. Therefore, this two parameters cannot be always steady under different construction quality or changing climate especially in frigid region. So, this paper mainly studies the influence of dry density, water content and the gravel content on the tensile strength of gravelly soil. Variable-controlling approach is used to draw up the test schemes as shown in Table 3.

3. Analysis of the test results

3.1 Test results due to variable water content

In the construction process of dam engineering, the water content of core material may changes due to evaporation of water under direct-sun exposure or rainfall. On the other hand, during operation stage of the dam, the water content may also changes due to water level rises of falls and reservoir water level fluctuation. As a consequent, it is necessary to study the tensile behavior of gravelly soil with variable water content.

Fig. 5 shows the relationship between tensile stress and tensile displacement of gravelly soils with different water content at different gravel content and maximum dry density. It can be seen that as the water content increases, the tensile strength of each scheme decreases significantly. On the contrary, the tensile displacement increases with the water content. All the samples are under unsaturated state. Previous studies on unsaturated soils have shown that the matric suction decreases with the increasing water content (Tang and Graham 2000). As the water content increases, the capillary tube in the soil is gradually filled with the gravity water. The surface tension between the soil particles due to the capillary force gradually weakens, the matric suction decreases. Consequently, the macroscopic cohesion between the soil particles decreases, resulting in reduced tensile strength of soil samples.

On the other hand, when the water content is relatively low, the initial tangent modulus of the stress-displacement curve is large, and the nonlinear behavior is not obvious. On the contrary, when the water content increases, the initial tangent modulus decreases, and the nonlinear behavior of the curve is significant. During the tensile failure process, softening behavior is obvious. With the increasing gravel content, the softening behavior become more significant.

To further study the relationship between water content and tensile strength of gravelly soils with different gravel content, Fig. 6 shows the relation curve of the tensile strength versus water content with the gravel content changes from 0% to 50%. It can be seen that the tensile strength of the specimens with different gravel content decreases with the increasing water content. Obviously, an approximate nonlinear relationship can be obtained from Fig. 6.

As illustrated in Fig. 6, the relationship between the tensile strength and the optimum water content of gravelly soil under various gravel content can be obtained as

$$\sigma_t = 0.7885\omega_{op}^{\;2} - 11.476\omega_{op} + 83.1 \tag{2}$$

3.2 Test results due to variable dry density

By keeping the water content of the sample (optimal moisture content) constant, tensile strength of each scheme can be obtained under different dry densities. As shown in Fig. 7, the tensile strength of gravelly soil with different gravel content under each maximum dry density is the largest.

As the dry density decreased, the tensile strength of the sample decreased significantly. Approximately, the average tensile strength decreased by 1/2. For gravelly soils under low dry density, the key factor controlling tensile strength is the cohesion between soil particles. As the pores between particles are gradually squeezed and compacted, the increasing tendency of cohesive force decreases. The molecular force between soil particles becomes to domain tensile strength. With the further increasing of dry density, the radius of the soil pores become smaller. The air entry value of the SWCC depends on the void ratio of the soil. Then, the air entry value became larger, and the SWCC shifted rightward. The changes of S_r and volume had opposing effects on the change of suction (Zhou and Ng 2014, Tang et. al 2017). Consequently, the curvature of the meniscus and the matrix suction become greater, resulting in the greater tensile strength. In addition, for all test schemes, the ultimate and total tensile displacement decrease as the decreasing dry density.

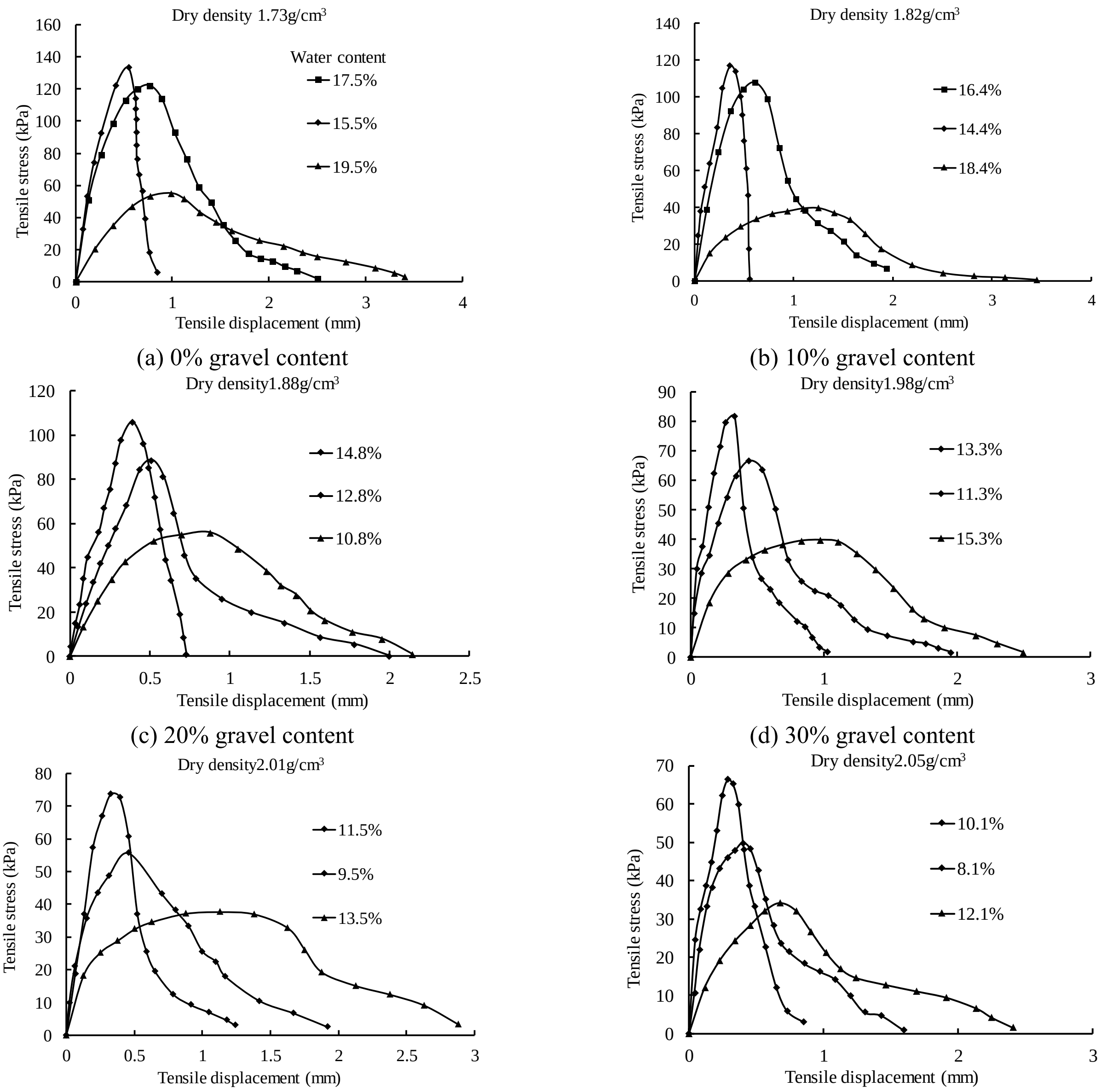


Fig. 5 Relation curves of tensile stress versus tensile displacement of the gravelly soil with different water content under various gravel content

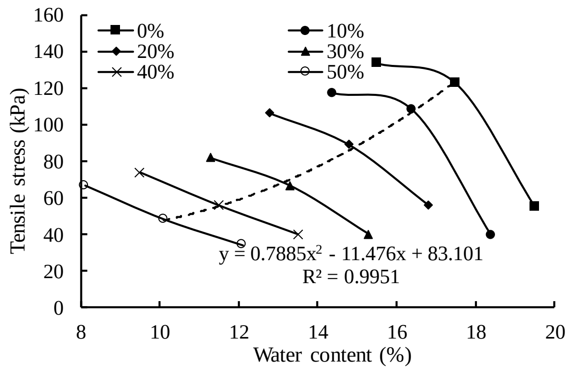


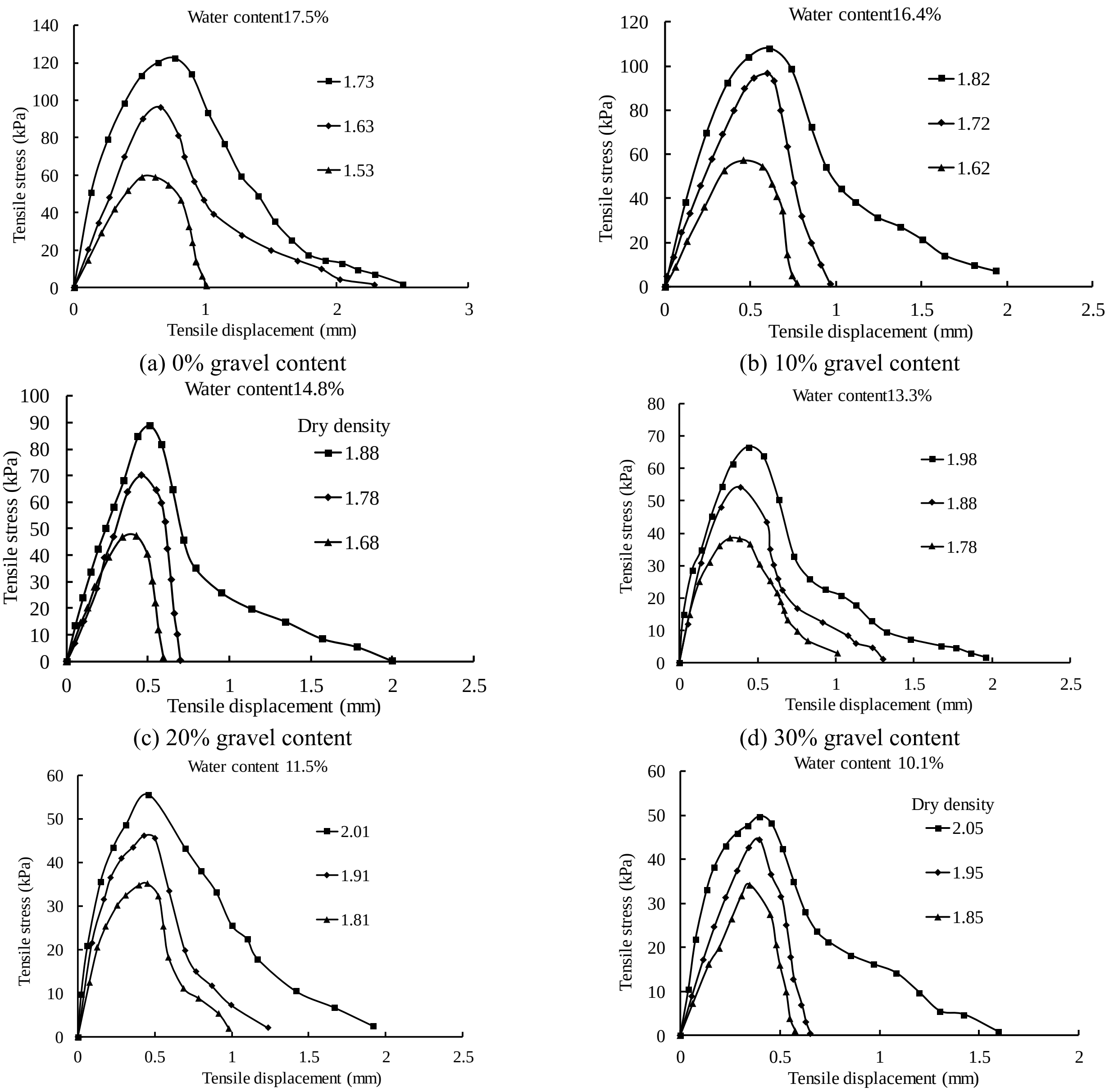
Fig. 6 Relation curves of tensile strength versus water content under different gravel content

To further study the relationship between dry density and tensile strength under different gravel content, Fig. 8 shows the relation curve between dry densities and tensile strength for each gravel content. As the dry density decreases, the tensile strength decreases under each gravel content. The larger the gravel content, the lower the clay content of the sample, and the smaller the reduction of tensile strength is. A good linear relationship between the tensile strength and the maximum dry density of the gravelly soil can be expressed as

$$\sigma_t = -239.91\rho_{d\max} + 536.68 \tag{3}$$

3.3 Analysis of the effect of gravel content on the tensile strength

Fig. 9 shows the tensile strength of gravelly soil with different gravel content. It can be seen that when the gravel content increases from 0% to 50%, the tensile strength



(a) 0% gravel content

(b) 10% gravel content

(c) 20% gravel content

(d) 30% gravel content

(e) 40% gravel content

(f) 50% gravel content

Fig. 7 Relation curves of tensile stress and displacement of the gravelly soil with different maximum dry density under different gravel content and optimum water content

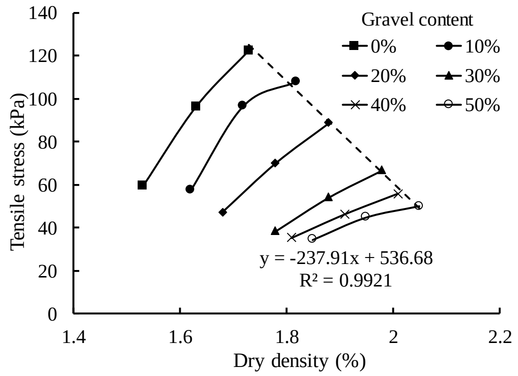


Fig. 8 Relation curves of tensile strength and dry density under different gravel content

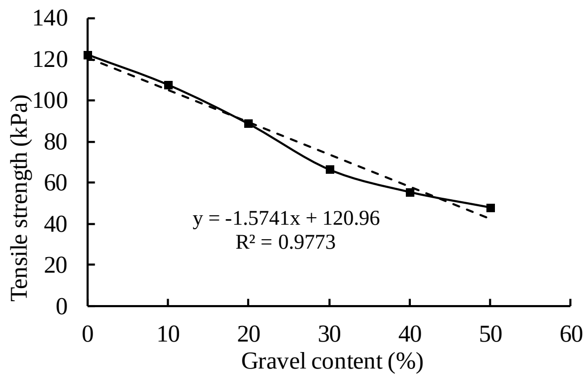


Fig. 9 Relation curve of tensile strength and gravel content

decreases from 122.6 kPa to 49.8 kPa. The linear relationship can be expressed as

$$\sigma_t = -1.5741\lambda + 120.96 \qquad (4)$$

where λ is gravel content. Considering that the core of the actual earth and rockfill dam must not only need enough stiffness but also satisfy impervious requirements, the gravel content of the core is usually controlled to be about 35%. Moreover, the optimum water content and maximum dry density are strictly controlled as the construction parameters. According to the formula (4), when the gravel content is 35%, the tensile strength of the gravelly soil is about 65.9 kPa.

According to Formula 4, the tensile strength of the gravelly soil used in this paper will be close to 0 when the gravel content increased to about 80%. In fact, after the gravel is increased to a certain value, some of the cohesive particles will be emptied by gravel. In this condition, tensile strength will be provided by biting force between the coarse-grained soils except the matrix suction. Certainly, sample preparation is difficult for gravelly soil with high gravel content and its tensile strength is more difficult to measure through the test.

3.4 Analysis of fracture energy

Fracture energy refers to the energy required for crack propagation per unit area of specimen under tensile loading which equals to the area contained under tensile stress-strain curve. In the field of numerical simulation, fracture energy is used to determine whether the longitudinal crack or hydraulic fracture will propagate in the core of the earth core rockfill dam (Ji et. al 2018, Chin et. al 2017 and Su et. al 2017).

Fig. 10 shows the relationship between gravel content and fracture energy. The fracture energy is calculated from the optimum water content and the maximum dry density condition of the gravelly soil under each gravel content. It can be seen that with the increase of gravel content, fracture energy decreases obviously. However, when gravel content is in the range of 40%-25%, the reduction of fracture energy is not significant. Subsequently, after gravel content is increased to 40%, the decrease in fracture energy begins to increase again. When gravel content reaches 50%, fracture energy of the sample is only 3.5 N/m, indicating that the energy required for cracking is extremely low.

For gravelly soil, due to the increase of gravel content, the interaction surface of clay and gravel on the cracking surface is expanding, and the corresponding interaction between the clay particles is decreasing. Consequently, the matrix suction is decreasing, the total fracture energy required for tensile failure is decreasing, and the tensile stress and strain becomes to reduce macroscopically.

The tensile strength of gravelly soil used in this paper with 0% gravel content is 122.5 kPa when water content is 17.5%, and the corresponding fracture energy can reach a maximum of 14.3 N/m. However, with the increasing gravel content, the fracture energy reaches its maximum value when water content is 2% more than that under the optimum water content. In other words, gravelly soil is not able to reach its maximum resistance to cracking deformation strictly under the optimum water content, but is slightly larger than the optimum water content. This shows

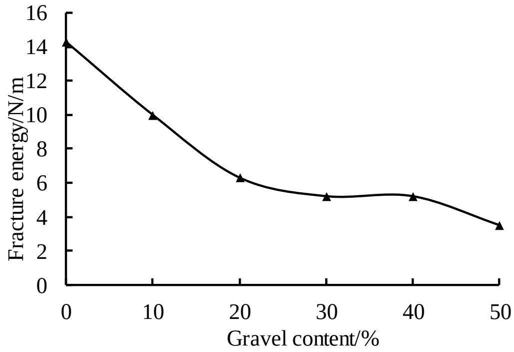


Fig. 10 Relation curve of gravel content and fracture energy

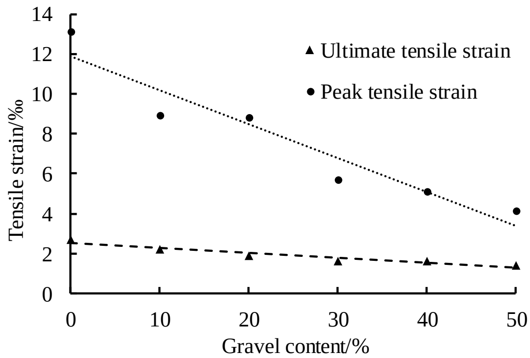


Fig. 11 Relation curve of gravel content and tensile strain

that controlling the water content of the core material slightly higher than the optimum water content in the actual dam construction is conducive to resisting uneven deformation and reducing the possibility of crack occurrence.

On the other hand, gravelly soil with various gravel content reached the maximum value of the fracture energy with the maximum dry density, which means that gravelly soil has stronger resistance to cracking deformation under the larger compaction degree. Strictly controlling compaction standard is an effective measure to increase the cracking resistance of impervious material in actual dam construction.

Fig. 11 shows the relation curve of gravel content versus tensile strain. It can be seen that with the increase of gravel content, the ultimate tensile strain and the peak tensile strain all show a decreasing trend and satisfy a linear relationship. In general, an increase of gravel content will reduce the resistance to plastic deformation of gravelly soil.

4. Conclusions

In this paper, based on the self-developed uniaxial tensile device, a series of uniaxial tensile tests were performed using gravelly soils with different gravel content. The variation of tensile strength, fracture energy and tensile strain versus gravel content, water content and dry density are analyzed. The main conclusions are as follows:

(1) Within the range of test parameters of gravelly soils used in the test, tensile strength decreases with the increase

of water content and increases with the increase of dry density. When the gravel content is 30%, the increase of water content makes the tensile strength decrease from 81.8kPa to 39.8kPa. In addition, the decrease of dry density causes the tensile strength decrease from 66.6kPa to 38.5kPa.

(2) Tensile strength decreases linearly with the increase of gravel content for gravelly soils with different gravel content under the optimum water content and maximum dry density. The peak tensile strain together with ultimate tensile strain decreases with the increase of gravel content.

(3) Through the analysis of fracture energy, it is proved that the tensile capacity of gravelly soil is the strongest when the water content is slightly higher than the optimum water content. Furthermore, tensile capacity of gravelly soil decreases with the increasing gravel content.

(4) It is suggested that strictly controlling compaction standard is an effective measure to increase the tensile capacity of gravelly soil in actual dam construction.

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