Rock and Soil Mechanics

Volume 44 | Issue 3 Article 1

7-21-2023

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Rock and Soil Mechanics 2023 44(3): 663−672 ISSN 1000−7598
https: //doi.org/10.16285/j.rsm.2022.5521 http://rocksoilmech.researchcommons.org/journal

Effect of rubber–sand mixture gradation on shear characteristics of mixed soil

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Abstract: To study the shear characteristics of rubber–sand mixtures, the effects of four rubber–sand mixture gradations (one type of gap gradation, two types of continuous gradations, and one type of open gradation), three rubber contents (10%, 30%, and 60%), and three vertical stresses (30 kPa, 60 kPa, and 90 kPa) on the strength and volumetric change characteristics of rubber–sand mixtures were investigated by using a large-scale laboratory direct shear apparatus. Then, the discrete element models of pure sand and rubber–sand mixtures were established according to the same gradation and rubber content. The intrinsic mechanism of rubber–sand mixtures was explored from the perspective of particle contact state and displacement. The results show that the shear stress curve of rubber–sand mixtures is the same as that of pure sand at low rubber content, but its shear strength is lower than that of pure sand. The shear stress of rubber–sand mixtures increases with the increase in vertical stress, and the shear strength of continuous gradation SR2 is the largest among the four gradations of rubber–sand mixtures. The addition of rubber particles can effectively inhibit the dilatancy of sandy soil, among which the gap gradation SR1 has the best effect on inhibiting soil dilatancy, and the dilatancy is reduced by 37.6% compared with that of pure sand. The internal friction angle of rubber–sand mixtures decreases with the increase of rubber content, and the internal friction angle of continuous gradation SR2 is the largest under the same rubber content. Rubber particles mainly participate in the formation of weak force chain in the force chain network of rubber–sand mixtures, and the shear zone width of rubber–sand mixtures is smaller than that of pure sand.

Keywords: rubber–sand mixtures; direct shear test; gradation; force chain network; shear zone

1 Introduction

With the increase in the number of cars in cities, disposal of waste rubber tires has become a challenging issue. Conventional treatment approaches such as stacking, direct incineration, recycling and retreading will cause secondary pollution. The treatment amount is limited, and the treatment pace is slower than that of rubber tire disposal[1]. In civil engineering, the waste rubber tires are mechanically crushed and then mixed with sand to produce a new geomaterial with the advantages of light weight, large modulus, and excellent flexibility. This lightweight geomaterial has been widely used in roadbed filler, retaining walls, and other projects[2−3]. A large amount of waste tires can be consumed in one project without causing secondary pollution to the environment. Therefore, it is of significant engineering value to study the mechanical characteristics of rubber–sand mixtures.

Recently, numerous studies have been conducted on the engineering characteristics of rubber–sand mixtures. In the research of direct shear test, Li et al.[4] found that mixing rubber tire fragments into sand can effectively increase the shear strength of the mixed soil, thereby enhancing the bearing capacity of the roadbed. Ghazavi et al.[5] conducted a large-scale direct shear test on mixtures of tire fragments and sand with three aspect ratios, and proposed an optimal initial friction angle of the rubber and sand mixtures. In the research of triaxial test, Ding et al.[6] found that when the rubber content is less than 20%, the shear stiffness of the filler is sufficient for the requirement of the roadbed engineering. Meanwhile, a formula for calculating the maximum shear modulus considering the effect of equivalent intergranular void ratio and confining pressure was established. Shariatmadari et al.[7] and Li et al.[8] conducted the dynamic triaxial tests and found that the addition of rubber particles and increase of rubber particle size can enhance the anti-liquefaction capacity. Manohar et al.[9] studied the effects of different geosynthetic materials, reinforcement methods, and reinforcement layers on the shear strength of the rubber–sand mixtures using undrained triaxial test. Liu et al.[10] and Zhuang et al.[11] conducted the consolidated undrained shear tests and found that when the rubber particle size is closer to that of the sand particles, the damage to the force chain of the soil is more obvious. In the research of engineering application of the rubber–sand

Received: 14 April 2022 Accepted: 7 June 2022
This work was supported by the National Natural Science Foundation of China (52078285).
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mixtures, Liu et al.[12−13] used the GDS-RCA resonance column system to thoroughly discuss the dynamic characteristics of rubber–sand mixtures. The results showed that the addition of rubber particles increased the damping energy dissipation of the mixed soil, and the rubber–sand particle size ratio has a great impact on the dynamic shear modulus. Anvari et al.[14] found that the coarse and fine rubber particles have different effects on soil mechanical properties. Senthen et al.[15] studied the application of rubber–sand mixtures in earthquake-prone areas, and established a model to predict the cyclic characteristics of the mixtures with 10%−75% rubber content.

Since the laboratory direct shear test can only be used to perform the mechanical analysis on sand from the macroscopic perspective, the contact state between particles that affects the shear strength of the soil cannot be directly observed[16]. The micromechanical characteristics analysis of rubber–sand mixtures can be conducted using discrete element software. Gong et al.[17] conducted the triaxial test on large rubber particles and found that the addition of rubber particles can prevent the formation of shear zone. Lopera[18] and Liu et al.[19] observed the effect of rubber content on the number of strong force chain and fabric anisotropy of mixed soil from the microscale. Asadi et al.[20] conducted an one-dimensional compression test combined with the discrete element and found that the discrete element model is capable of predicting the compression behavior of the mixed soil.

Based on the discussion above, most of the existing research focused on the effects of rubber content and rubber particle size on the mechanical characteristics of rubber–sand mixtures, but seldom considered the effect of its overall gradation on the shear characteristics of soil. Therefore, this study aims to investigate the shear characteristics of four types of rubber–sand mixture gradations using a large-scale laboratory direct shear instrument and to understand the internal mechanism of rubber–sand mixtures through the discrete element method. This study will provide a theoretical basis for related engineering concerning the rubber–sand mixtures.

2 Experimental set-up and schemes

2.1 Test apparatus and material

The large-scale laboratory direct shear apparatus HM-5780.3F is used in the test, and the specific introduction to the test apparatus can be found in the literature[21]. The test materials are the rubber–sand mixtures, as shown in Fig. 1. The rubber particles are obtained by mechanically crushing waste tires, and the sand is the quartz sand. To study the effect of rubber–sand mixture gradation on the shear strength of the mixed soil, the rubber particles are passed through sieves with apertures of 0.50, 1.00, 2.00, 4.75, 6.00 and 8.00 mm to obtain the rubber particles with particle sizes of 0.50−1.00, 1.00−2.00, 2.00−4.75, 4.75−6.00 and 6.00−8.00 mm, and these rubber particles are prepared into four types of rubber samples R1, R2, R3 and R4 with different particle size ranges at a proper ratio. The particle size ranges are 0.50−2.00, 0.50−6.00, 0.50−8.00 and 6.00−8.00 mm. The particle size range of quartz sand is 6.00−8.00 mm. The rubber particles having four particle size ranges are mixed with quartz sand in volume ratio to obtain the corresponding rubber–sand mixtures, numbered S (pure quartz sand), SR1 (gap gradation), SR2 (continuous gradation), SR3 (continuous gradation) and SR4 (open gradation). The gradation curves of the particles are shown in Fig. 2, and the physical properties are listed in Table 1.

(a) Rubber particles (0.5−6 mm for example)

(b) Quartz sand

(c) Rubber–sand mixtures

Fig. 1 Test specimens

2.2 Test schemes

The rubber–sand mixtures are selected in this study. Set S as a control group, SR1 as gap gradation, SR2 and SR3 as continuous gradations, and SR4 as open gradation. Then, the effects of different vertical stresses and rubber contents are considered. According to the *Standard for geotechnical testing method* (GB/T 50123−2019)[22], the shear rate is set as 1 mm /min, and the specific test schemes are tabulated in Table 2.

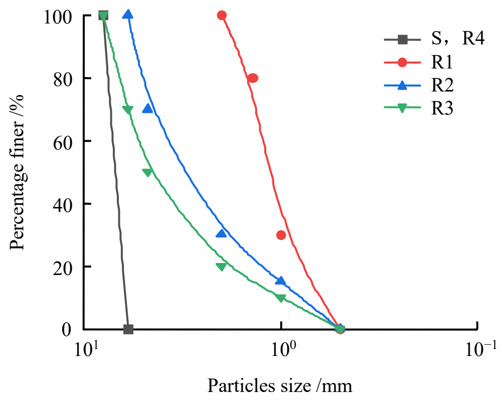


Fig. 2 Gradation curves of rubber and sand

Table 1 Physical properties of rubber and sand

NO.	Specific gravity	Effective particle size d_{10} /mm	Continuous particle size d_{30} /mm	Limited particle size d_{60} /mm	Coefficient of uniformity *Cu*	Coefficient of curvature *Cc*
S	2.6	6.20	6.60	7.2	1.16	0.98
R1	1.1	0.62	0.88	1.2	1.94	1.04
R2	1.1	0.72	1.70	3.8	5.27	1.06
R3	1.1	1.00	2.50	5.8	5.80	1.08
R4	1.1	6.20	6.60	7.2	1.16	0.98

Table 2 Test schemes

Gradation type	Rubber content χ /%	Vertical stress σ /kPa	Shear rate v /(mm • min^{-1})
S	0	30, 60, 90	1.0
SR1	10, 30, 60	30, 60, 90	1.0
SR2	10, 30, 60	30, 60, 90	1.0
SR3	10, 30, 60	30, 60, 90	1.0
SR4	10, 30, 60	30, 60, 90	1.0

3 Analysis of test results

3.1 Strength characteristics of rubber–sand mixtures

The effects of rubber–sand mixture gradation on the shear strength under three vertical stresses are the same. Due to space limitations, this study only shows the relation curve of shear stress-shear displacement of rubber–sand mixtures when the vertical stress is σ = 30 kPa. Figure 4 shows the shear stress-shear displacement relation curve of rubber–sand mixtures with different rubber contents under vertical stress of 30 kPa. Comparing Figs. 3 and 4, it can be seen that the shear strength of rubber–sand mixtures with four types of gradations is lower than that of pure sand, and the shear strength decreases more obviously with the increase of rubber content. When the rubber content reaches 10%, the trend of the shear stress curve of the rubber–sand mixtures is similar to that of pure sand. The shear stress increases with the increase in shear displacement with an obvious peak. After the peak, the shear softening phenomenon occurs[23], but the shear softening characteristics are significantly lower than those of pure sand. When the rubber content increases and reaches 30% or above, the shear stress curve of rubber–sand mixtures shows shear hardening. The reason is that at low rubber content, the stress skeleton of the mixed soil is still a "sand skeleton", i.e. the force transmission is conducted by sand particles, thus the shear properties of rubber–sand mixtures are similar to pure sand. With the increase of rubber content, the stress skeleton of mixed soil gradually changes from "sand skeleton" to "rubber skeleton", hence the shear stress curve also changes from "shear softening" to "shear hardening".

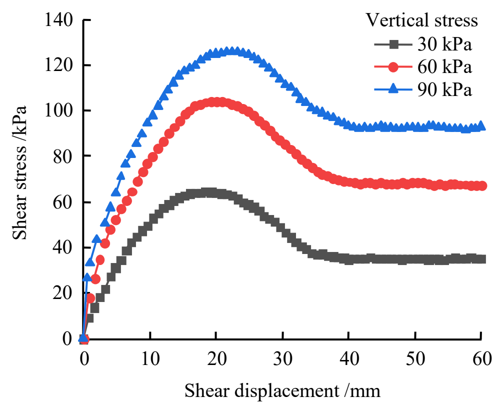


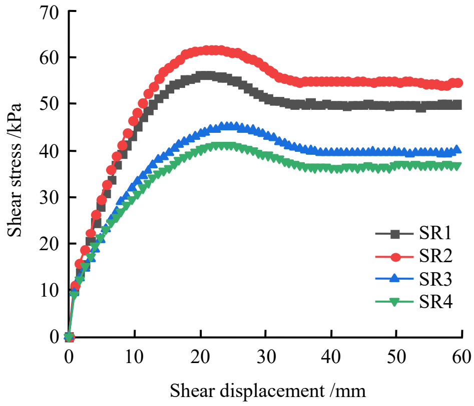
Fig. 3 Relation curves of shear stress and shear displacement of pure sand under different vertical stresses

It can be seen from Fig. 4 that when the rubber content is 10%, the shear strength is the maximum. Therefore, the rubber content is taken as 10% for rubber–sand mixture gradation, and the effect on the mixed soil's shear strength is analyzed. The ratio of shear strength of rubber–sand mixtures to that of pure sand can be defined as

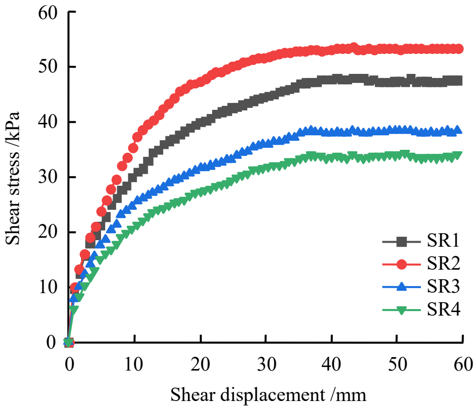
$$\chi = \frac{\tau_{SR}}{\tau_S} \tag{1}$$

where χ is the ratio of shear strength of rubber–sand mixtures to that of pure sand; τ_{SR} is the shear strength of the rubber–sand mixtures; and τ_{SR} is the shear strength of the pure sand. χ with 10% rubber content is summarized in Table 3.

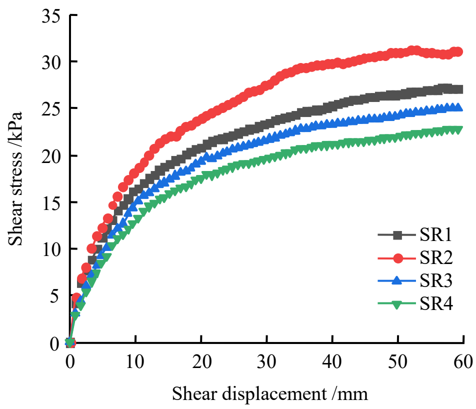
As shown in Table 3, the shear strength of SR2 is the largest among the four types of gradations of rubber–sand mixtures, and SR1 is the lowest. Compared to the shear strength of pure sand, the shear strength of SR1 decreases by 10%−20%, SR2 decreases by 2%−6%, SR3 decreases by 24%−33%, and SR4 decreases by 32%−37% within 10% rubber content.



(a) Rubber content of 10%



(b) Rubber content of 30%



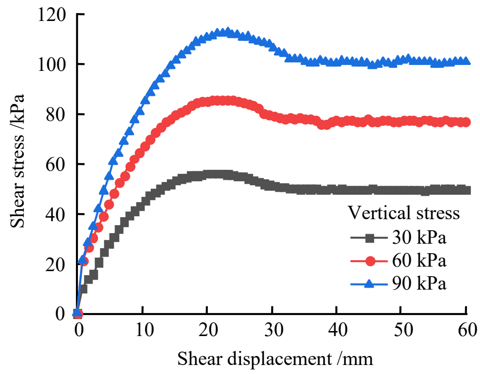
(c) Rubber content of 60%

Fig. 4 Relation curves of shear stress and shear displacement of rubber–sand mixtures under vertical stress of 30 kPa

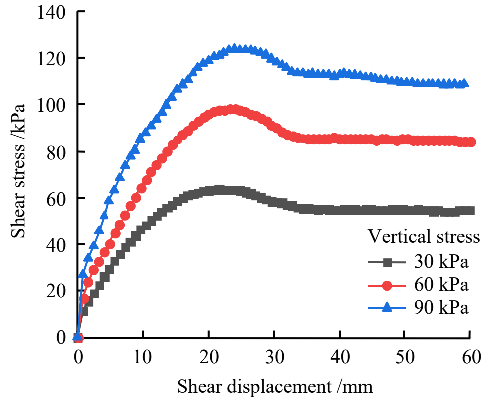
Table 3 Summary of χ at 10% rubber content

Gradation type	χ under different vertical stresses (kPa)		
	30	60	90
SR1	0.88	0.82	0.90
SR2	0.96	0.94	0.98
SR3	0.67	0.71	0.76
SR4	0.64	0.63	0.68

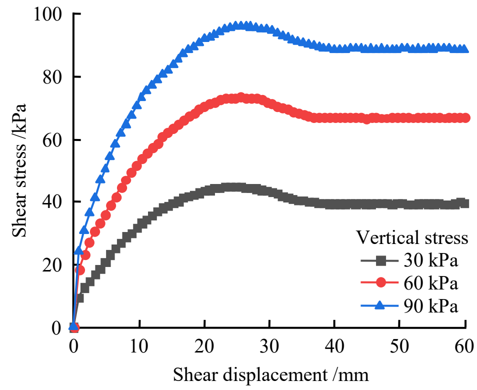
Figure 5 shows the shear stress–shear displacement relation curves of mixed soil with 10% rubber content



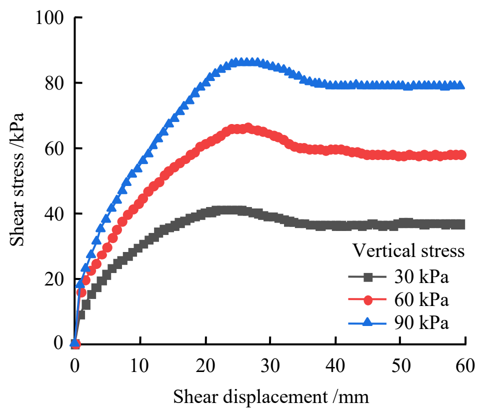
(a) SR1



(b) SR2



(c) SR3



(d) SR4

Fig. 5 Relation curves of shear stress and shear displacement of rubber–sand mixtures with 10% rubber content

under different vertical stresses. It can be seen from the figure that under the same gradation, the maximum shear stress increases with the increase of vertical stress, and the shear displacement required to reach the shear peak value moves back with the increase of vertical stress. The reason is that as the vertical stress increases, the occlusion between the particles becomes closer, and the adjustment of the position between the particles becomes more difficult. With the increase of the limited particle size of the mixed rubber particles, the displacement of the particles rolling to a stable state also becomes larger[24]. Therefore, the shear displacement required to reach the peak shear stress increases. As shown in Figs. 5(a)−5(d), under the same vertical stress, the shear displacement of the rubber–sand mixtures with different gradations reaching the peak shear stress increases with the increase in limited particle size in the incorporated rubber particles, i.e. SR4>SR3>SR2>SR1. The reason is that large rubber particles can adjust the position through the volumetric changes.

3.2 Volumetric changes of rubber–sand mixtures

Figure 6 shows the vertical displacement−shear displacement relation curves of the pure sand of the control group under different vertical stresses. Fig. 7 shows the relation curves between vertical displacement and shear displacement of rubber–sand mixtures under vertical stress of 30 kPa. By comparing Figs. 6 and 7, it can be seen that the addition of rubber particles can effectively inhibit the dilatancy of mixed soil. When the rubber content is 10%, the mixed soil body first exhibits shear shrinkage and then rapidly expands. With the increase of rubber particle size, the shear deformation of mixed soil also increases. The reason is that at the early stage of shearing, most of the small-size rubber particles added are dispersed in the pores of sand particles, which has little effect on the compressed soil. With the increase in rubber particle size, more and more rubber particles are involved in soil compression and deformation, which exhibit that the shear shrinkage of soil increases, and the overall volumetric change trend is consistent with pure sand. When the rubber content increases to 60%, the volumetric change of the rubber–sand mixtures presents shear shrinkage state.

The final volumetric change of four types of rubber–sand mixtures under three vertical stresses is presented in Fig. 8. It can be seen from the figure that, when the vertical stress is greater, the shear shrinkage is lower with smaller rubber content and greater with larger rubber content. The final dilatancy of SR1, SR2, SR3 and SR4

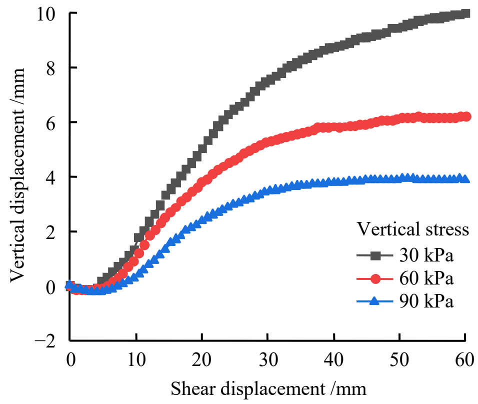
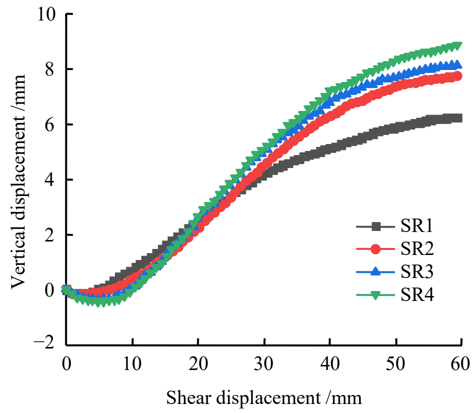
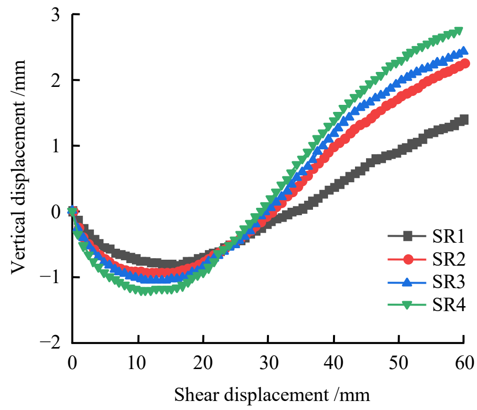


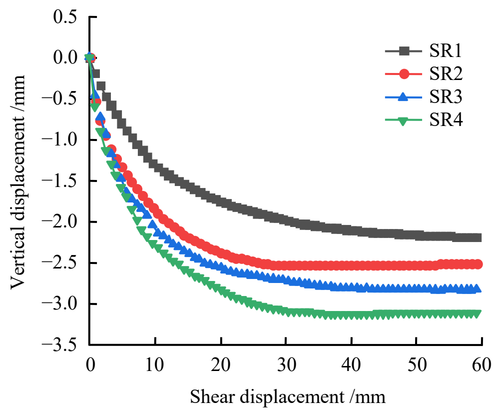
Fig. 6 Relation curves of vertical displacement and shear displacement of pure sand under different vertical stresses



(a) Rubber content of 10%

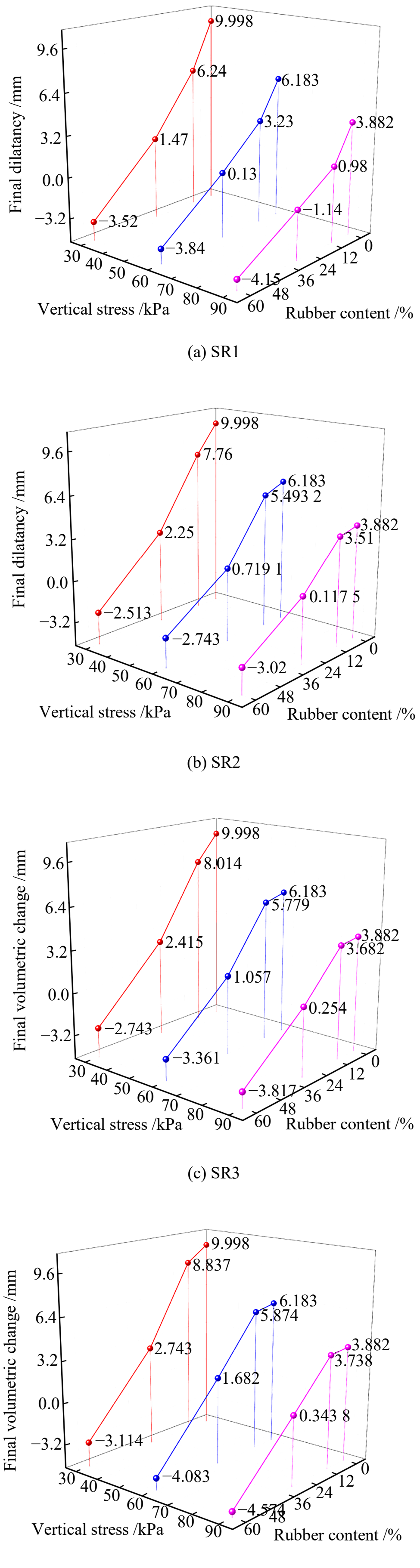


(b) Rubber content of 30%



(c) Rubber content of 60%

Fig. 7 Relation curves of vertical displacement and shear displacement of rubber–sand mixtures under vertical stress of 30 kPa



(a) SR1

(b) SR2

(c) SR3

(d) SR4

Fig. 8 Final volumetric changes of rubber–sand mixtures

is 6.24, 7.76, 8.01 and 8.83 mm with the same vertical stress of 30 kPa. Compared with the pure sand, the dilatancy decreases by 37.6%, 22.4%, 19.9% and 11.7%, indicating that the rubber particles with small particle size can effectively inhibit the soil dilatation.

3.3 Shear strength parameters of rubber–sand mixtures

According to the test results in Section 3.1, the peak shear stress curves of four types of rubber–sand mixture gradations and the corresponding three rubber contents under different vertical stresses can be calculated, in which R^2 is the correlation coefficient of the curve, and its values are close to 1. It shows that there is a good linear relationship between the shear strength of rubber–sand mixtures and the vertical stress, which is described by the following formula using the Mohr-Coulomb criterion:

$$\tau = c + \sigma \tan \varphi \qquad (2)$$

where τ is the shear stress; c is the pseudo-cohesion; σ is the vertical stress; and φ is the internal friction angle, as shown in Fig. 9.

It can be seen from Fig. 9 that the internal friction angles of four types of gradations of the rubber–sand mixtures all decrease with the increase of rubber content. Although the sliding friction between rubber particles is greater than that of pure sand, the addition of rubber particles destroys the occlusion between pure sand particles. The dominant factor determining the shear strength of mixed soil is the occlusion between particles. Therefore, the shear strength of the rubber–sand mixtures decreases with the increase in rubber content.

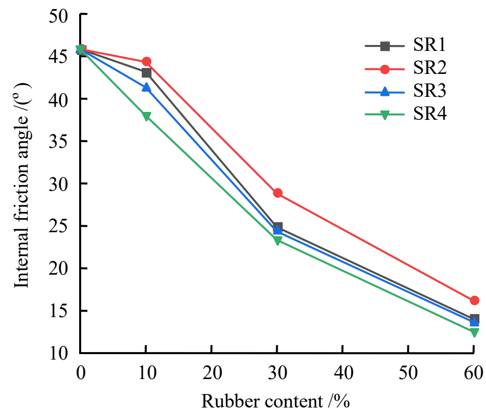


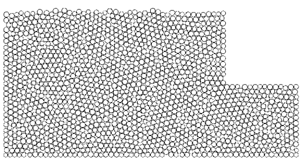
Fig. 9 Summary of internal friction angles

4 Numerical simulation

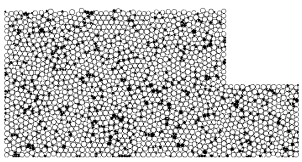
4.1 Model establishment

To better understand the mechanical behaviors of rubber–sand mixtures during shearing, the control group of pure sand S and rubber–sand mixtures SR2 in the laboratory test are selected for the analysis from the microscopic perspective. Numerical model is established using PFC^{2D} according to the size of the direct shear box test and the gradation of the rubber–sand mixtures. Meanwhile, to improve the calculation accuracy and efficiency[25], the rubber particles smaller than 1 mm are ignored. The particles are generated using radius expansion method and grouped using the group function. White stands for the sand particles and black represents the rubber particles. The pure sand model contains a total of 2 576 particles and the rubber–sand mixture model with the rubber content of 10% contains a total of 3 184 particles. The numerical model of the specimen is shown in Fig. 10, and Fig. 10(c) is a partial enlargement of the SR2 model in Fig. 10(b).

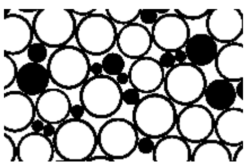
The stiffness of the wall is much greater than that of the particles, thus the wall can be regarded as a rigid body, and the linear contact model is used for both sand particles and rubber particles[26]. According to the actual condition, a constant normal load of 30 kPa is applied to the specimen using the clump, and the wall force is controlled by adjusting the shear rate of the wall to restore the shear process. Finally, the normal stiffness k_n, stiffness ratio k_n/k_s, and friction coefficient are constantly adjusted to obtain a stress–strain curve consistent with the laboratory test. The calibration of the meso-mechanical parameters of the model after the trial calculation is shown in Table 4, and the comparison of the final numerical results with the test results is shown in Fig. 11. The peak shear strength and variation trend of the shear stress–shear displacement curve obtained from the numerical simulation are basically consistent with the experimental results, which verifies the reliability of the numerical simulation.



(a) Pure sand model



(b) Rubber–sand mixtures SR2 model

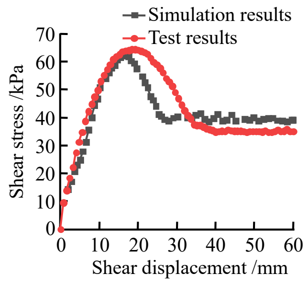


(c) Partial enlargement of rubber–sand mixtures SR2 model

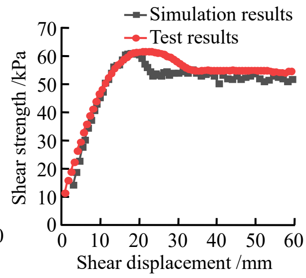
Fig. 10 Numerical models of sample

Table 4 Calibration of meso-mechanical parameters of rubber–sand mixtures

Material	Density /(kg • m^{-3})	Friction coefficient	Contact stiffness /(N • m^{-1})		Initial porosity
			Normal	Tangential	
Rubber particles	1 100	1.0	8.0×10^{3}	4.0×10^{3}	0.15
Sand particles	2 500	0.5	6.0×10^{6}	3.0×10^{6}	0.15
Wall	—	0.0	2.0×10^{10}	1.0×10^{10}	—



(a) Pure sand S

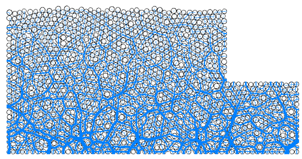


(b) Rubber–sand mixtures SR2

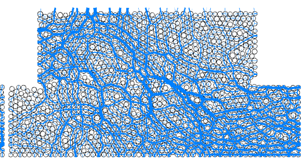
Fig. 11 Fitting curves of pure sand and rubber–sand mixtures obtained from numerical simulation and laboratory test

4.2 Interparticle contact state

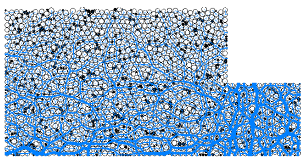
The force chain network, which is generated by the internal contact of the particle system, is a force channel that can transfer loads. The study of the stresses in the soil skeleton during shearing by observing the changes in the force chain network can provide a better description of the macroscopic mechanical behavior of the soil. The variations of the force chain network inside the specimen are shown in Fig. 12.



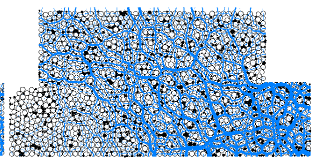
(a) Pure sand S before shearing



(b) Pure sand S after shear failure



(c) Rubber–sand mixtures SR2 before shearing



(d) Rubber–sand mixtures SR2 after shear failure

Fig. 12 Variations of force chain network in specimen

As shown in Fig. 12, the pure sand and rubber–sand mixtures are subjected to gravity only before shearing, and the force chain in the specimen is gradually enhanced from top to bottom and is uniformly distributed in the horizontal direction. After shear failure, the strong force chain is concentrated in the upper left and lower right corners, and the angle between the strong force chain and the horizontal direction of the specimen is about 45°. The force chain in the lower left and upper right corners is very weak, which is also consistent with the actual stress condition. As observed in Fig. 12(c) and 12(d), the strong force chain in the rubber–sand mixtures is still mainly composed of sand particles, and some of the rubber particles are in contact with the sand particles to form a weak force chain, which complements the force chain network and enhances the shear strength of the specimen. The dispersed fine rubber particles are outside the force chain network and are not affected by force.

Different types of particle contacts have different effects on the force mechanism of the specimen. Figure 13 shows the respective percentages of the three contact types (sand–sand, sand–rubber, and rubber–rubber contacts) included in the strong force chain network in SR2. As the shearing progresses, although the strong chain network is still mainly composed of sand–sand contact, its percentage significantly decreases, the percentage of sand–rubber contact increases slightly, and the percentage of rubber–rubber contact remains unchanged. It can be seen from Figs. 12 and 13 that the addition of rubber–sand mixtures aims to prevent the bending of the strong force chain composed of sand particles and to limit the slippage of the sand particles.

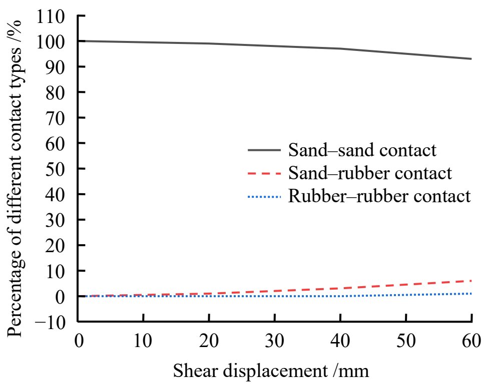
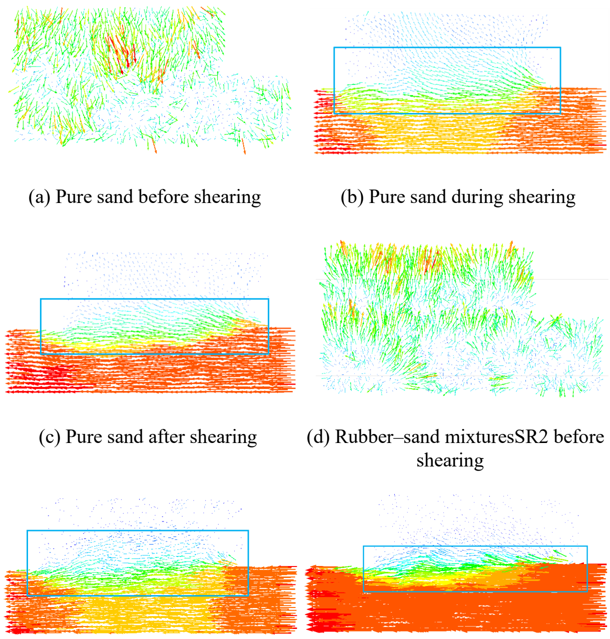


Fig. 13 Percentages of three contact types of strong force chain network in SR2

4.3 Variations of displacement field

The state of the motion of the particles inside the sample can be clearly seen from the displacement field. Figure 14 shows the variations of the displacement field during the shearing process of the sample at 30 kPa. Before shearing, the displacement field of the particles is disordered, and some particles tend to move downward under the gravity, and the other part of the particles tend to move upward due to the extrusion of the particles moving downward. The particles in the lower shear box move to the left, and the particles in the upper shear box roughly move upward as shearing progresses. Then, the initial shear zone is formed, and the rectangle in Fig. 14 is the shear zone. After shear failure, the rotation and deformation of particles intensify and concentrate near the shear band. It can be seen from Fig. 14(b) to 14(c) and 14(e) to 14(f) that with the increase of the shear displacement, the width of the shear zone is gradually concentrated and reduced. Particles in the upper shear box far away from the shear zone are almost stationary and are seldom exposed to shear stress, and the final shear zone of rubber–sand mixtures SR2 is smaller than that of pure sand.



(a) Pure sand before shearing (b) Pure sand during shearing

(c) Pure sand after shearing (d) Rubber–sand mixturesSR2 before shearing

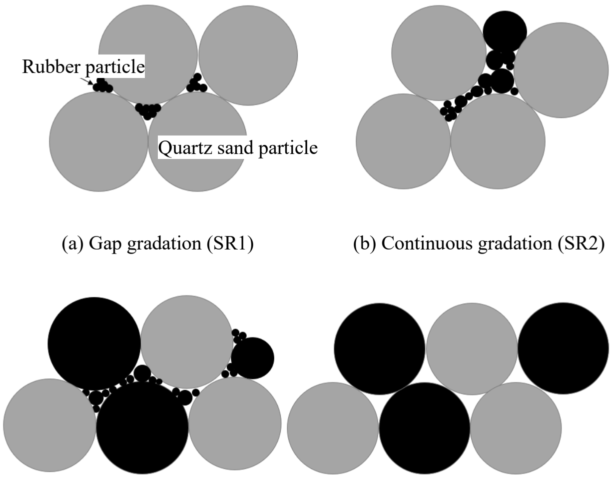
(e) Rubber–sand mixtures SR2 during shearing (f) Rubber–sand mixtures SR2 after shearing

Fig. 14 Variations of displacement field in the sample during shearing

4.4 Force analysis of rubber–sand mixtures

There are three contact modes in the rubber–sand mixtures, i.e. sand–sand contact, sand–rubber contact, and rubber–rubber contact. The addition of rubber particles changes the original particle contact mode inside the sand. Figure 15 shows the interparticle contact of four types of rubber–sand mixture gradations with 10% rubber content in this study. The particle contact in Fig. 15(b) is well represented in Fig. 10(c).

In Fig. 15, the rubber particles of the gap gradation SR1 are smaller than the sand particles with low rubber content, and a large part of the mixed rubber particles fills the pores between the sand particles, which increases the compactness of the mixed soil. The stressed skeleton



(a) Gap gradation (SR1) (b) Continuous gradation (SR2)

(c) Continuous gradation (SR3) (d) Open gradation (SR4)

Fig. 15 Particle contact diagrams of rubber–sand mixtures with different gradations

of the mixed soil is "sand skeleton", and the force chain is sand–sand contact. However, in fact, there will be a small number of rubber fines attached to the surface of quartz sand, which will destroy a small part of the "sand–sand" contact and act as "lubricant". Thus, the shear strength of SR1 will be slightly lower than that of pure sand. SR2 are the continuous-gradation rubber–sand mixtures composed of rubber and sand particles. A part of the rubber particles is filled in the pores of the sand particles as in SR1. The other part of the rubber particles directly bear the stress of the mixed soil due to their size exceeding the pore size of the sand particles and replacement of the "sand–sand" contact in the force chain with the "sand–rubber" contact[27]. In the "sand–rubber" contact, due to the appropriate gradation of the rubber, the "rubber–rubber" contact still exists. The interlocking of the rubber particles is good, and the friction resistance between the rubber particles is more excellent than that of pure sand, which increases the mixing force. Therefore, although part of the "sand–sand" contact is destroyed, a slight decrease in shear strength is observed macroscopically. When the rubber particles further increase, the damage to the "sand–sand" contact of the rubber particles continues to increase, and the increased sliding friction of the rubber particles is much smaller than the decrease in the shear strength caused by the damage of sand particle occlusion. SR4 are the open-gradation rubber–sand mixtures, the "sand–sand" contact is replaced with the "sand–rubber" contact, and the damage to the shear strength of the sand reaches a peak due to the addition of the rubber.

5 Conclusions

In this study, the shear characteristics of pure sand and four types of rubber–sand mixture gradations are studied using large-scale laboratory direct shear tests, and the PFC numerical model is established to analyze the mechanism of rubber–sand mixtures from the microscopic perspective. The following conclusions are drawn:

(1) The addition of rubber particles reduces the shear strength of the sand. As the blend ratio increases, the shear strength decreases more obviously. Compared with pure sand, the shear strengths of SR1, SR2, SR3 and SR4 are reduced by 10%−18%, 2%−6%, 24%−33%, and 32%−37%. Among the four types of rubber–sand mixture gradations, the shear strength of SR2 is the maximum. As the particle size of the rubber particles increases, the shear displacement required for the rubber–sand mixtures to reach the peak shear stress is also greater.

(2) The dilatancy of SR1 is 37.6% lower than that of pure sand, i.e. the addition of rubber particles can effectively inhibit the dilatancy of sand, and the small rubber particles have a significant inhibitory effect on the dilatancy of sand.

(3) The internal friction angle of rubber–sand mixtures is smaller than that of pure sand, and it decreases with the increase in rubber content. The internal friction angle of SR2 is the largest at the same rubber content.

(4) The rubber particles are mainly related to the formation of the weak force chain network of the mixed soil. The analysis of the displacement field shows that with the increase in shear displacement, the width of the shear zone of the sample gradually concentrates and decreases, and the addition of rubber particles reduces the width of the shear zone.

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