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Article

Study on compaction characteristics and discrete element simulation for rubber particle-loess mixed soil

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Abstract: The rapid surge in traffic volume in China has resulted in a substantial accumulation of waste tires. By harnessing the lightweight and deformable characteristics of tire rubber particles, they are combined with soil to form rubber particle-loess mixed soil, which is progressively being embraced in civil engineering as a pivotal approach towards attaining green and sustainable development. In this study, waste tire rubber particles were integrated into loess to generate rubber particle-loess mixed soil, and compaction tests were conducted to investigate its compaction characteristics. Furthermore, PFC^{3D} (Particle Flow Code 3D) was utilized for simulating the bearing ratio test of rubber particle-loess mixed soil, thereby validating the feasibility of numerical simulation for calculating CBR (California bearing ratio) values and exploring the relationship between micromechanical characteristics and macroscopic characteristics of such mixtures. The findings indicate that the maximum dry density of rubber particle-loess mixed soil significantly decreases with an increasing content of rubber particles. The utilization of PFC^{3D} discrete element software proves efficacious in examining the bearing capacity of this mixture. Notably, when 20 mesh rubber particles constitute 20% by volume, the CBR value reaches its pinnacle and exhibits optimal bearing capacity. From a micromechanical perspective, the variation in internal porosity of rubber particle-loess mixed soil is positively associated with changes in macroscopic optimal water content, and negatively associated with changes in macroscopic CBR value. incorporating rubber particles enhances resistance against external forces while diminishing deformation within loess. This study provides a guidance for the efficient utilization of waste tires and the improvement of loess's characteristics.

Keywords: rubber particles; loess; compaction characteristics; discrete element method; micromechanics

1. Introduction

In recent years, with the continuous increase in traffic volume, a significant amount of waste tires have been generated. Improper disposal of these waste tires can lead to various environmental pollution issues. Utilizing waste tires as building materials can effectively mitigate environmental pollution and reduce construction costs [1]. Extensive research has been conducted both domestically and internationally on the application of waste tire rubber particles in engineering construction. As early as the 1990s, Edil and Bosscher [2] and Bosscher et al. [3] confirmed through laboratory tests that soil mixed with rubber particles exhibited favorable economic feasibility for engineering applications. Subsequently, numerous scholars have investigated the geotechnical characteristics of soil-rubber particle mixtures and discovered their advantageous characteristics such as low density, high deformability, excellent damping capacity, superior wear resistance, strong permeability, shock absorption ability etc., making them exceptional materials suitable for civil engineering purposes [4,5]. Anvari et al. [6] employed direct shear testing to examine the influence of rubber incorporation on native physical strength transfer mechanisms. Xin et al. [7] studied shear strength by conducting shear tests on rubber particle mixed soil samples while Kong et al. [8] examined unconfined compressive strength through unconfined compressive strength tests on similar samples. Deng et al. [9] explored the shear characteristics of sand-rubber particle mixtures using direct shear tests and triaxial compression tests. Neaz Sheikh et al. [10] conducted triaxial testing to investigate the influence of incorporating tire chips into mixtures containing waste tire rubber particles on their shear strength. Liu et al. [11] employed resonance column testing and cyclic triaxial testing to analyze variations in dynamic modulus and damping ratios across a wide range of shear strains in sand. Zou et al. [12] incorporated waste tire rubber particles into plain expansive soil to enhance its characteristics, and examined the physical characteristics, expansion and shrinkage behavior, as well as strength characteristics of the improved soil. Zhou et al. [13] investigated the compaction and dynamic deformation behavior of silt mixed with rubber particles through compaction tests and dynamic triaxial tests. Hu et al. [14] studied the impact of rubber powder on the dynamic characteristics of remolded loess by conducting Triaxial shear tests on samples consisting of rubber powder mixed with loess soil.

Although some researches have been conducted on rubber particle mixed soil in China, there is still limited study on the bearing capacity of rubber particle-loess mixed soil as subgrade filler. In western regions of China, a significant amount of loess is distributed and extensively used for subgrade filling during highway construction, however, its bearing capacity often fails to meet engineering requirements [15]. Therefore, the method of adding rubber particles into loess is adopted to improve the bearing capacity of loess. California Bearing Ratio (CBR) is a rating proposed by the state of California and serves as an index for evaluating the bearing capacity of subgrade soil and pavement materials [16], and it is widely applicable to evaluate the bearing capacity of rubber particle-loess mixed soil.

This paper first determined the maximum dry density and optimum moisture content of rubber particle-loess mixture through compaction test, and studied the influence of rubber particles on the compaction characteristics of the mixture. Then, the bearing ratio test of rubber particle-loess mixture was simulated using the PFC^{3D} discrete element software to verify the feasibility of using discrete element method to study rubber particle-loess mixture. Finally, the macroscopic and microscopic mechanical characteristics of rubber particle-loess mixture were analyzed using the discrete element model.

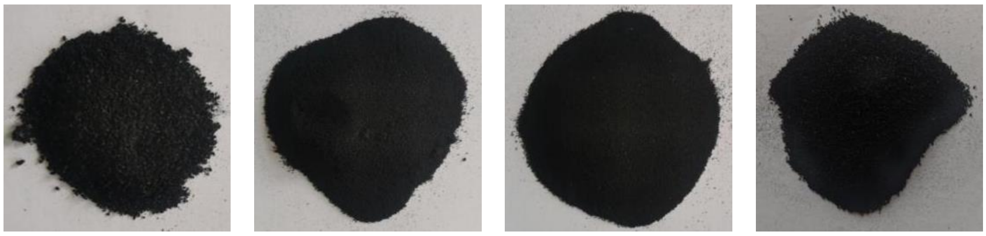
2. Materials and methods

2.1. Test material

The black rubber particles utilized in this experiment were obtained from mechanical crushing processes applied to waste tire debris, and collected from Shijiazhuang City, Hebei Province. **Figure 1** illustrates some representative examples of these particles.

The loess used in this study was collected from Hohhot City, Inner Mongolia.

The particle size distribution was assessed using the sieving method, the corresponding result is presented in **Figure 2**. The moisture content was determined through the drying method, and the liquid limit and plastic limit were determined through the combined test of liquid and plastic limits, while the maximum dry density and optimal water content were established via compaction testing. The corresponding results are presented in **Table 1**.



(a) **(b)** **(c)** **(d)**

Figure 1. Rubber particles. **(a)** 5 mesh; **(b)** 20 mesh; **(c)** 60 mesh; **(d)** 100 mesh.

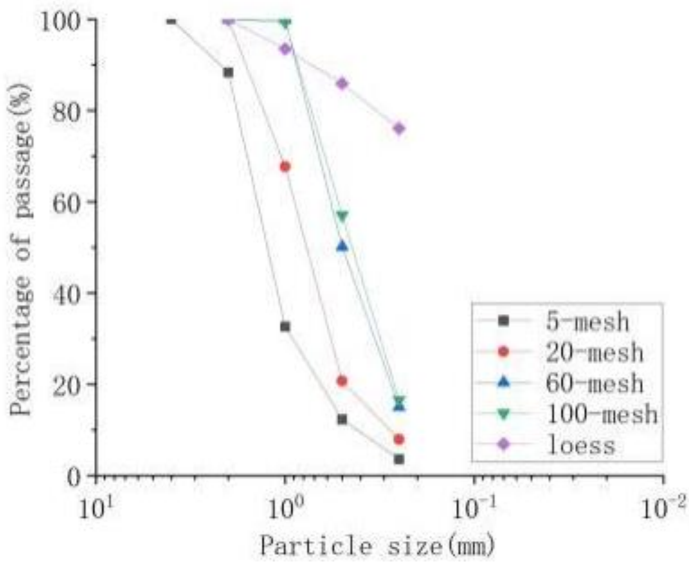


Figure 2. Particle grading curve.

Table 1. Basic mechanical parameters of experimental loess.

Moisture content (%)	Liquid limit (%)	Plastic limit (%)	Optimum moisture content (%)	Maximum dry density (g/cm^3)
15.5	24.7	15.5	12.2	1.91

2.2. Test methods

In order to investigate the influence of mesh size and rubber particle content on the maximum dry density, optimum water content, and bearing capacity of a mixed soil composed of rubber particles and loess, compaction tests and bearing ratio tests were conducted. The test equipment is presented in **Table 2**, while a portion of the test process and specimens are illustrated in **Figure 3**. The specific test scheme is presented in **Table 3**.

Table 2. Test equipment.

Name	Manufacture	Model	Size
Manual lightweight compactor	Nanjing soil instrument Factory Co., LTD	JDS-3	The inner diameter of the compaction canister is 102 mm, the height is 116 mm, and the weight of the compaction hammer is 2.5 kg
CBR tester	Nanjing soil instrument Factory Co., LTD	CBR-1	The inner diameter of the test specimen canister is 152 mm, the height is 166 mm.

(a) Loess sample. **(b)** soaked soil sample. **(c)** Compaction test. **(d)** CBR test.

Figure 3. Part test process and specimen.

Table 3. Test conditions.

Rubber mesh/mesh	Rubber particle content C/%
5	0, 10, 20, 30, 50
20	0, 10, 20, 30, 50
60	0, 10, 20, 30, 50
100	0, 10, 20, 30, 50

Note: Rubber particle content C = V_R/V_L, where: V_R is the volume of rubber particles; V_L is the volume of loess.

2.2.1. Compaction test

According to Standard for Geotechnical Test Methods [17], the compaction test was conducted to investigate the compaction characteristics of a rubber particle-loess mixed soil. The testing procedure involved mixing rubber particles of different mesh sizes with dried and sieved plain loess in specified proportions, ensuring thorough mixing. A target moisture content was set for the mixture. Five samples were prepared for each group of mixed soil, with varying moisture contents differing by 2% increments. These samples were then covered with plastic wrap and left undisturbed for 24 h to allow complete water absorption by the soil samples. After compacting the soaked soil sample, approximately 30 g of material from the central part was extracted to measure its actual moisture content and calculate the dry density.

2.2.2. Load ratio test

The CBR value was utilized in this study to assess the bearing capacity of rubber-loess mixed soil, which characterizes the material's vertical stiffness and shear resistance. The experimental procedure involved mixing rubber particles with different mesh numbers into dried and sieved plain loess according to **Table 3**, ensuring even distribution. Subsequently, the mixed soil was combined with water corresponding to the optimal moisture content determined from compaction tests, thoroughly stirred, covered with plastic wrap, and left undisturbed for 24 h. After undergoing heavy compaction testing followed by a soaking period of four days and nights for expansion purposes, the CBR value was measured through penetration testing after allowing a ten-minute rest period.

In accordance with the defined concept of CBR value, it is determined by expressing the ratio between the load needed to achieve specific penetration depths (2.5 mm and 5 mm) and that required in standard gravel, represented as a percentage relative to the resultant CBR value. The calculation of CBR is as follows [18]:

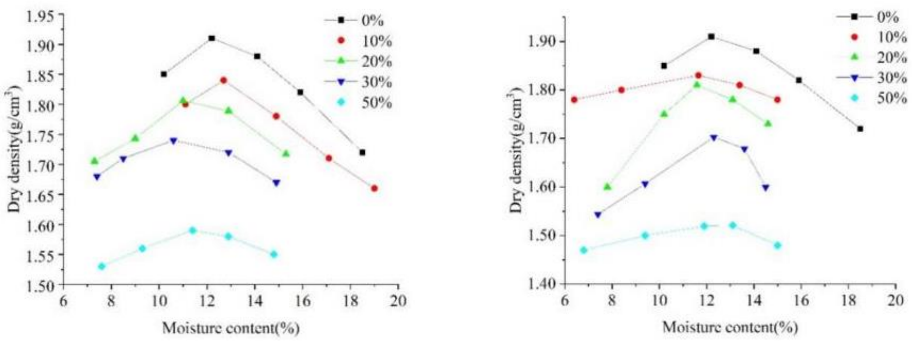
$$CBR = \frac{P}{Ps} \times 100 \tag{1}$$

where: *CBR*—California load bearing ratio; *P*—Load at a penetration volume of 2.5 mm or 5 mm; *Ps*—Standard load 7000 kPa for penetrating 2.5 mm of standard gravel or 10500 kPa for penetrating 5 mm of standard gravel.

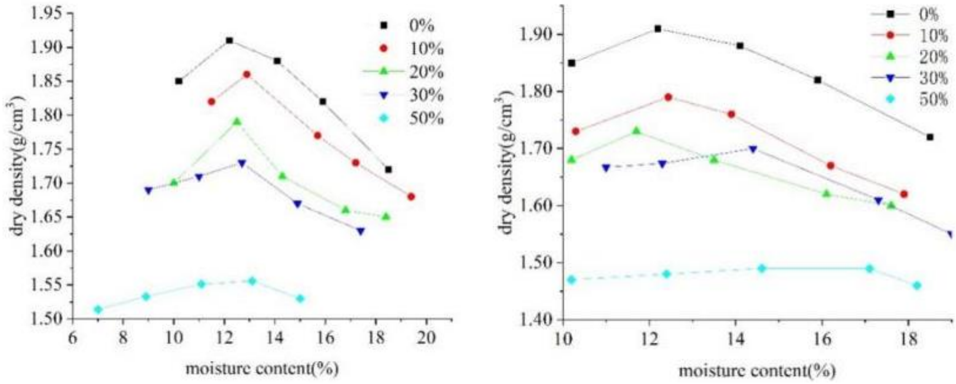
3. Results and discussion

The compaction curve of rubber particle-loess mixed soil is depicted in **Figure 4**, illustrating the significant modification of compaction characteristics induced by the inclusion of rubber particles [13]. When the moisture content falls below the optimal level, an increase in water content leads to a gradual rise in dry density, indicating progressive enhancement in compaction efficiency. However, due to the "rubber soil" effect, when the moisture content falls above the optimal level, further increment in moisture content results in a gradual decline in dry density, thereby diminishing the compaction efficiency [13].

The maximum dry density of the rubber particle-loess mixed soil exhibited a significant decrease with an increase in rubber particle content, displaying a linear trend as depicted in **Figure 5**. Compared to plain loess, the maximum dry density of the rubber particle-loess mixed soil decreased with higher rubber particle content. It can be attributed to the lower density of rubber particles compared to plain loess, resulting in an inevitable decline in overall soil density with increased rubber particle content. Furthermore, because the mesh number of rubber particles has little effect on its density, when considering equal amounts of rubber particles, variations in mesh size had minimal impact on the maximum dry density values of the rubber particle-loess mixture.



(a) 5-mesh. **(b)** 20-mesh.



(c) 60-mesh. **(d)** 100-mesh.

Figure 4. Compaction curve of rubber particle-loess mixed soil (different rubber mesh).

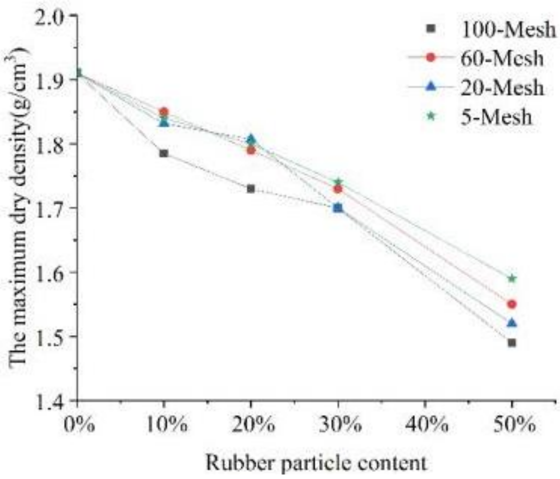


Figure 5. Maximum dry density.

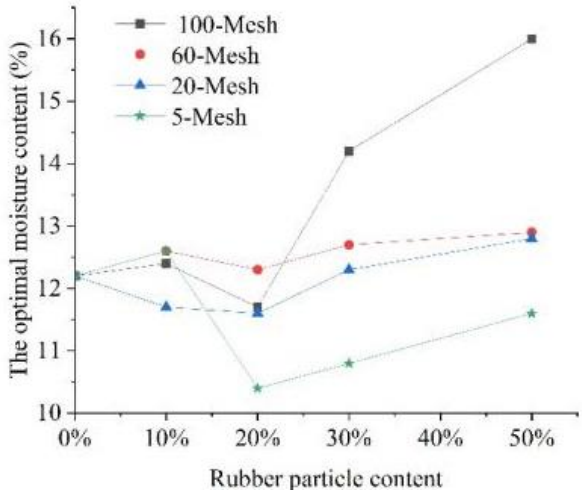


Figure 6. Optimum moisture content.

The optimal moisture content of the rubber particle-loess mixed soil exhibits an initial decrease followed by a gradual increase with increasing rubber particle content, as depicted in **Figure 6**. For different mesh sizes of rubber particles, the lowest optimal moisture content for the mixture is observed at a 20% rubber particle content. Moreover, when the content exceeds 10%, the optimal moisture content for 5-mesh rubber particle-loess mixed soil is comparatively lower than that of other mesh mixtures. This can be attributed to the larger size and smaller specific surface area of rubber particles, leading to a progressive reduction in total contact area among particles within the mixed soil. Consequently, less water is required to enhance lubrication between particles, thereby facilitating their movement and compression.

4. Discrete element numerical simulation

DEM (Discrete element method) is a numerical simulation technique that models the interaction forces between individual particles. By treating particles as fundamental units, this method simulates their interaction forces to elucidate both the macroscopic mechanical behavior and microscopic characteristics of particle systems.

Commonly utilized contact models in DEM are spring-particle models, spring-spring models, and contact force models, which characterize the interactions involving contact forces, frictional forces, and elastic forces among particles.

4.1. Model building

The test area for the bearing ratio test, constructed using particle flow software PFC^{3D}, consists of one cylindrical boundary wall and two upper and lower boundary walls [19]. To ensure accurate data simulation, it is essential that the intersection position of the boundary wall be at a specific distance from the sample, as depicted in **Figure 7**. Within the test area, a three-dimensional cylindrical soil granular structure is generated. The initial dimensions of the soil sample are 120 mm in height and 152 mm in diameter. Due to involving a large number of particles (tens of thousands), creating an accurate calculation model becomes challenging. To reduce computational complexity, we employ a radius expansion method for particle generation. Additionally, continuous circulation is utilized to minimize particle overlap and prevent excessive contact imbalance caused by overlapping particles during generation [20].

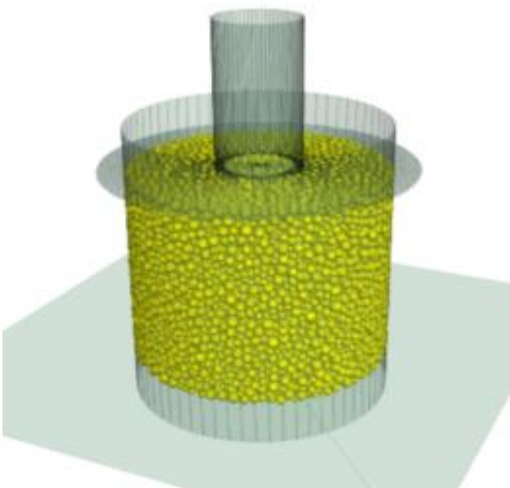


Figure 7. Particle flow simulation diagram.

4.2. Contact constitutive model

In PFC software, interactions occur both among particles and between particles and walls, which are based on the concept of 'contact' [21]. The contact types encompass particle-particle and particle-wall interactions, while the contact model primarily consists of sliding, rigid, and bonding models.

The choice of contact models plays a crucial role in determining the mechanical characteristics of materials. Taking into account the inherent physical attributes of the investigated materials, there exists an interlocking phenomenon among loess particles and between loess and rubber particles, leading to primarily localized contacts. Consequently, we adopt a linear contact bonding model to describe particle-particle interactions and employ a linear contact model for particle-wall interactions.

4.3. Model loading

To simulate the CBR test using PFC^{3D}, a model is established and an injection rod with dimensions of 50mm in diameter and 100mm in length is generated within the compaction barrel to apply loading on the sample. Additionally, to replicate the effect of a 5 kg load block on the specimen's top surface, a force equivalent to its gravitational action is applied [22]. The calibration of microscopic material parameters in PFC software typically involves iterative adjustments [23]. After conducting multiple trial calculations and necessary modifications, **Table 4** presents the selected mesoscopic parameters for this model.

Table 4. Microscopic parameters.

Materials	density (g/cm^3)	Friction coefficient	Normal contact stiffness (N/m)	Tangential contact stiffness (N/m)
Loess particle	1.91	0.4	3×10^5	3×10^5
Rubber particle	0.95	1.0	1×10^5	1×10^5
wall			1.5×10^8	1×10^8

4.4. Feasibility study

The CBR values obtained from the PFC^{3D} simulation were compared with those acquired through the load ratio test (Equation (1)) to validate the accuracy of the numerical simulation, and the comparative results are presented in **Table 5**.

The results presented in **Table 5** demonstrate that the discrepancy between the CBR values obtained from PFC^{3D} numerical simulation and laboratory testing is less than 6%. Notably, the error associated with the CBR value of plain loess is merely 0.55%. Hence, it can be inferred that employing PFC^{3D} for investigating the load-bearing capacity of rubber particle-loess mixed soil is a viable approach.

Table 5. Comparison table of CBR values of rubber granules and loess mixed soil.

name	Rubber particle size	Rubber particle content (%)				
		0	10	20	30	50
Experimental value *x* (%)	5-mesh	4.97	5.90	7.55	4.58	3.07
	20-mesh	4.97	7.13	7.56	6.70	3.23
	60-mesh	4.97	5.18	5.40	4.35	4.22

Table 5. (*Continued*).

name	Rubber particle size	Rubber particle content (%)				
		0	10	20	30	50
Simulated value y (%)	100-mesh	4.97	4.62	5.31	3.66	2.44
	5-mesh	4.94	6.07	7.77	4.50	3.09
	20-mesh	4.94	6.94	7.74	6.51	3.34
	60-mesh	4.94	5.34	5.26	4.56	4.07
	100-mesh	4.94	4.86	5.63	3.80	2.51
error (%)	5-mesh	0.55	2.91	2.93	1.75	0.51
	20-mesh	0.55	2.62	2.42	2.77	3.49
	60-mesh	0.55	3.14	2.65	4.76	3.52
	100-mesh	0.55	5.13	6.00	3.83	3.04

Note: error = $|(y - x)/x|$

4.5. Analysis of numerical simulation results

4.5.1. CBR value analysis

The relationship between the CBR value of rubber particle-loess mixed soil and the mesh number and content of rubber particles is depicted in **Figure 8**. As illustrated, there is an initial increase followed by a subsequent decrease in the CBR value with an increasing content of rubber particles. When the rubber particle content reaches 20%, the CBR value peaks due to the increased contact area between rubber particles and soil, leading to improved bearing capacity of the mixed soil. However, excessive rubber particle content results in a reduction of occluding effect with soil, as some of the contact shifts from soil-rubber to rubber-rubber interaction. This diminishes bearing capacity. The larger mesh number of rubber particles corresponds to smaller particle size and greater compression difficulty. Consequently, 20-mesh rubber particle-loess mixed soil exhibits the highest CBR value while 100-mesh counterpart shows the lowest at equivalent rubber particle content.

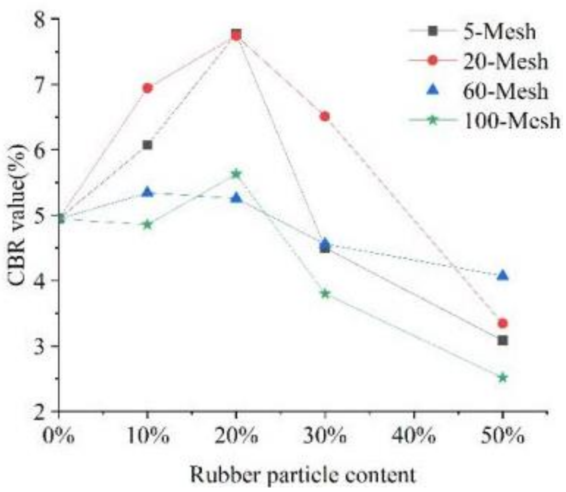


Figure 8. CBR value diagram.

4.5.2. Porosity analysis

Porosity is a fundamental parameter that characterizes the internal density and particle distribution of a sample. Additionally, it plays a crucial role in influencing the shear strength and deformation behavior of soil. **Figure 9** illustrates the correlation between porosity in rubber particle-loess mixed soil and both mesh number and rubber particle content.

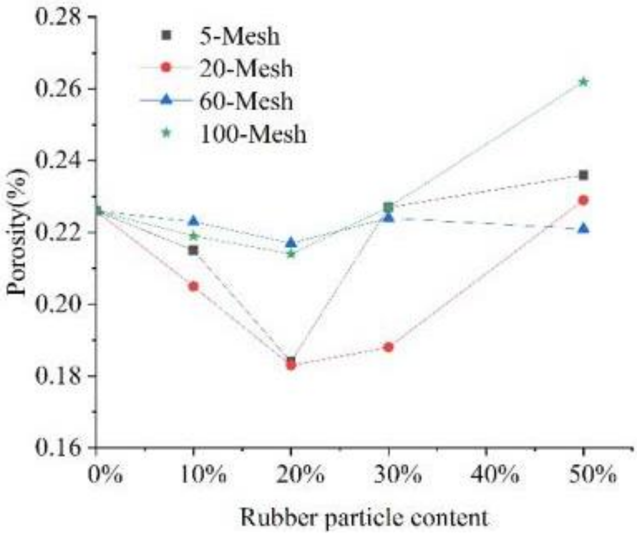


Figure 9. Porosity.

Figure 9 illustrates that an increase in the rubber particle content leads to a deterioration in the contact between rubber particles and soil, resulting in an initial decrease followed by an increase in the porosity of the mixed soil. For a constant rubber particle content, the 20-mesh rubber particle-loess mixed soil exhibits the smallest porosity, while the 100-mesh rubber particle-loess mixed soil shows the largest porosity. This phenomenon can be attributed to the smaller mesh number of rubber particles, which corresponds to a reduced specific surface area and consequently lower porosity.

The changing trend of porosity and optimal water content in rubber particle-loess mixed soil can be observed from **Figures 9** and **6**. This indicates that the incorporation of rubber particles alters the contact state between particles, leading to changes in internal pore characteristics, including the optimal water content.

According to **Figures 8** and **9**, the porosity of the rubber particle-loess mixture exhibits an inverse relationship with changes in rubber particle content, as observed in **Figure 9**. Additionally, a similar trend is observed for the CBR value, as shown in **Figure 8**. Specifically, when the rubber particle mesh size is 20 mesh and its content is at 20%, the porosity of the mixed soil reaches its minimum while achieving maximum CBR value. Consequently, this combination results in optimal bearing capacity.

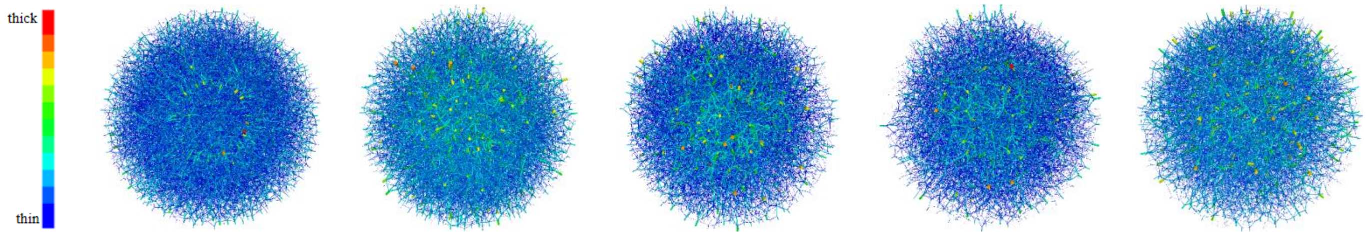
4.5.3. Analysis of inter particle state

Based on the aforementioned analysis, it is evident that the 20-mesh rubber particle-loess mixed soil exhibits superior bearing capacity, thus subsequent analysis will employ this particular mixture.

The force chain represents the mechanical manifestation of contact forces between particles when a specimen is subjected to external forces. **Figure10** illustrates the variation in contact forces among soil particles in a sample of 20-mesh rubber particle-loess mixed soil under different rubber particle content during numerical simulations of load-bearing ratio tests. In this figure, thicker chains denote stronger connections, while thinner chains represent weaker connections.

The presence of a weak intergranular force chain can be observed in **Figure 10** when the loess is in its plain state, with only a limited number of strong chains surrounding the penetration rod at the center of the sample. However, upon incorporating rubber particles, an increase in the number of strong chains becomes evident, resulting in a more uniform distribution of both strong and weak chains throughout the sample. This indicates that the inclusion of rubber particles modifies particle-particle contact by filling up interfacial gaps, thereby enhancing resistance to external forces and forming stable strong chains. Consequently, this improvement leads to an enhanced macro-bearing capacity of the sample.

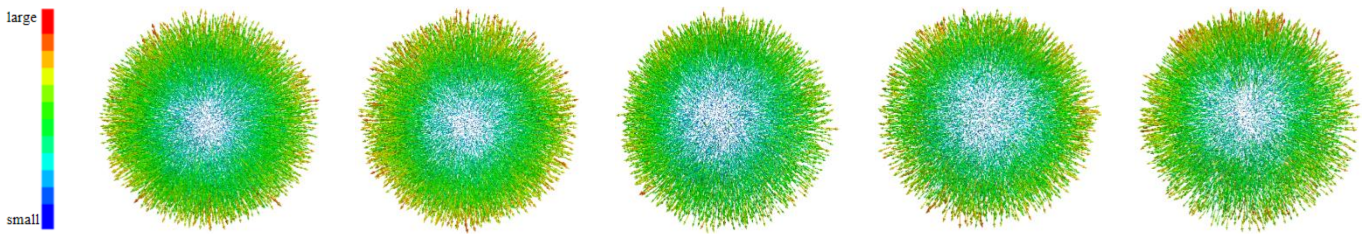
The analysis of **Figure 10** reveals that the distribution of strong and weak force chains among particles is most uniform when the content of rubber particles reaches 20%. Furthermore, in conjunction with **Figure 8**, it can be inferred that this specific composition yields optimal bearing capacity for the sample.



(a) 0%. **(b)** 10%. **(c)** 20%. **(d)** 30%. **(e)** 50%.

Figure 10. Contact force chain diagram of rubber particle-loess mixed soil (different rubber content).

The deformation of the sample is primarily attributed to the displacement and repositioning of particles within the soil matrix under applied forces. **Figure 11** presents a numerical simulation depicting bearing ratio tests conducted on loess soil samples that were reinforced with 20-mesh rubber meshes at different dosages, thereby illustrating both magnitude and depth of internal particle displacements through color-coded arrows in this figure.



(a) 0%. **(b)** 10%. **(c)** 20%. **(d)** 30%. **(e)** 50%.

Figure 11. Displacement diagram of rubber particles and loess mixed soil (different rubber content).

The addition of rubber particles effectively enhances the cooperative force between loess and rubber particles, thereby expanding the range of particles with minimal displacement in the middle of the specimen, as illustrated in **Figure 11**. This observation indicates that the incorporation of rubber particles restricts particle displacement and mitigates specimen deformation when compared to plain loess.

5. Conclusion

In this study, the compaction and CBR tests were conducted to investigate the compaction and load-bearing characteristics of rubber particle-loess mixed soil with varying rubber particle mesh sizes and content. Additionally, PFC^{3D} was utilized to simulate CBR tests and examine the correlation between the microscopic characteristics and macroscopic characteristics of the mixed soil. The key findings are as follows:

(1) The inclusion of rubber particles significantly influenced the compaction behavior of loess. Due to the lightweight characteristics of rubber particles, the maximum dry density of the mixed soil composed of rubber particles and loess exhibited a linear decrease as the content of rubber particles increased. However, the mesh size of rubber particles had negligible impact on the maximum dry density of the mixed soil. With an increase in rubber particle content, there was an initial decrease followed by a gradual increase in the optimum moisture content of the mixed soil.

(2) The PFC^{3D} discrete element software was utilized to simulate the bearing ratio test of rubber particle-loess mixed soil. In comparison with the laboratory test's CBR value, the numerical simulation exhibited an error rate below 6%, thereby validating the applicability of employing the discrete element method for analyzing the bearing capacity performance of rubber particle-loess mixed soil.

(3) The CBR value of rubber particle-loess mixed soil exhibits an initial increase followed by a subsequent decrease as the content of rubber particles increases. Notably, when the rubber particle content reaches 20-mesh and 20%, the CBR value of rubber particle-loess mixed soil attains its maximum, indicating optimal carrying capacity.

(4) The porosity of rubber particle-loess mixed soil initially decreases and subsequently increases with increasing rubber particle content. The variation in internal porosity of the rubber particle and loess mixed soil is positively correlated with changes in macroscopic optimal water content, while it is negatively correlated with changes in macroscopic CBR value.

(5) Compared to plain loess, rubber particle-loess mixed soil exhibits a higher abundance of robust chains, with an even distribution of both strong and weak chains. Additionally, the range of particles experiencing minimal displacement within the sample's central region is increased. These findings indicate that the incorporation of rubber particles alters particle-particle contact conditions, effectively constraining particle rolling and sliding, enhancing resistance against external forces, and reducing deformation.

(6) As the micromechanical characteristics of rubber particle-loess mixed soil have not been measured, further refinement of the discrete element analysis model is necessary. In the future, we will intensify our research on dynamics and micromechanics, conduct further investigation into the engineering characteristics of rubber particle-loess mixed soil as a subgrade filler, and explore as well as promote its application scope.

Author contributions: Conceptualization, WK and JB; methodology, WK; software, JB; validation, WK, JB, HL and QL; formal analysis, WK; investigation, JB; resources, HL; data curation, QL; writing—original draft preparation, WK; writing—review and editing, WK; visualization, WK; supervision, WK; project administration, JB; funding acquisition, JB. All authors have read and agreed to the published version of the manuscript.

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Conflict of interest: The authors declare no conflict of interest.

References

1. Gu Y, Liu J. Experimental study on compressibility of lightweight granulated rubber-sand mixtures (Chinese). Henan Science. 2022; 40(9): 1427-1433.
2. Edil T, Bosscher P. Engineering Properties of Tire Chips and Soil Mixtures. Geotechnical Testing Journal. 1994; 17(4): 453-464. doi: 10.1520/gtj10306j
3. Bosscher PJ, Thncer BE, Senro K. Design of high-way embankments using tire chips. Journal of Geotechnical and Geoenvironmental Engineering. 1997; 123(4): 295-304. doi: 10.1061/(ASCE)1090-0241(1997)123:4(295)
4. Calabrese A, Losanno D, Spizzuoco M, et al. Recycled Rubber Fiber Reinforced Bearings (RR-FRBs) as base isolators for residential buildings in developing countries: The demonstration building of Pasir Badak, Indonesia. Engineering Structures. 2019; 192: 126-144. doi: 10.1016/j.engstruct.2019.04.076
5. Rao SM, Joshua RE, Rekapalli M. Batch-scale remediation of toluene contaminated groundwater using PRB system with tyre crumb rubber and sand mixture. Journal of Water Process Engineering. 2020; 35: 101198. doi: 10.1016/j.jwpe.2020.101198
6. Anvari SM, Shooshpasha I, Kutanaei SS. Effect of granulated rubber on shear strength of fine-grained sand. Journal of Rock Mechanics and Geotechnical Engineering. 2017; 9(5): 936-944. doi: 10.1016/j.jrmge.2017.03.008
7. Xin L, Liu H, Shen Y, He J. Consolidated undrained triaxial compression tests on lightweight soil mixed with rubber chips of scrap tires (Chinese). Chinese Journal of Geotechnical Engineering. 2010; 32(3): 428-433.
8. Kong D, Jia T, Wang X, et al. Test on unconfined compressive strength of lightweight soil mixed with rubber chips of scrap tires (Chinese). Journal of Central South University (Science and Technology). 2016; 47(1): 225-231.
9. Deng A, Feng J. Effect of scrap tire bead addition on shear behavior of sand (Chinese). Journal of PLA University of Science and Technology (Nature Science Edition). 2009; 10(5): 483-487.
10. Neaz Sheikh M, Mashiri MS, Vinod JS, et al. Shear and compressibility behavior of sand-tire crumb mixtures. Journal of Materials in Civil Engineering. 2013; 25(10): 1366–1374.
11. Liu Q, Zhuang H, Wu Q, et al. Dynamic shear modulus and damping ratio of rubber-sand mixtures in different range of shearing strain amplitudes (Chinese). Journal of Vibration Engineering. 2021; 34(4): 712-720.
12. Zou W, Xie P, Ma Q, et al. Experiment on characteristics of expansive soil modified with waste tire rubber particles (Chinese). Journal of Sichuan University (Nature Science Edition). 2011; 43(3): 44-48.
13. Zhou E, Zhang J, Cui L, et al. Compaction and dynamic deformation properties of rubber-Silt lightweight mixed soil (Chinese). Journal of Building Materials. 2021; 24(6): 1242-1247.
14. Hu Z, Liu Z, Zhang Z, et al. Tset on influence of rubber powder on dynamic mechanic properties of manipulated loess (Chinese). Journal of Chang'an University (Nature Science Edition). 2013; 33(4): 62-67.
15. Chen B, Zhu F, Han Q. Study on the intrinsic mechanism and influencing factors of CBR test (Chinese). Traffic Standardization. 2001; 29(1): 28-30.
16. Li P, Xu J, Wen X, Yu L. CBR experiment study of loess subgrade meliorated with lime (Chinese). Journal of Gansu Sciences. 2008; 20(4): 74-77.
17. Ministry of Housing and Urban-Rural Development, People's Republic of China. GB/T 50123-2019. Standard for Geotechnical Test Methods. Ministry of Housing and Urban-Rural Development; 2019.
18. ASTM International. ASTM(D1883-14), Standard Test Method for California Bearing Ratio (CBR) of Laboratory

Compacted Soils. ASTM International, West Conshohocken; 2014.

19. Fu X, Hou D, Li Q, et al. Characteristics between macro-meso parameters and calibration method of soft creep particle flow (Chinese). Soil Eng.and Foundation. 2023; 37(3): 501-505.
20. Xu J, Cao B, Yu Y, Luo Y. Sensitivity analysis of meso-parameters in loess triaxial test based on PFC^{3D} (Chinese). Journal of Engineering Geology. 2021; 29(5): 1342-1353.
21. Liu F, Wu M. Micromechanics simulation of direct shear test of rubber-sand mixture with discrete element method (Chinese). Journal of Hefei University of Technology. 2017; 40(7): 944-951.
22. Peng A, Li L, Zhang Z. Study on the meso-mechanical behavior of California bearing ratio of graded gravel with discrete element method (Chinese). Journal of Railway Science and Engineering. 2019; 16(10): 2467-2474.
23. Hou J, Xu D, Zhang C. Meso mechanism analysis of geogrid reinforced foundations under strip footing (Chinese). Journal of Shanghai University (Natural Science Edition). 2023; 29(6): 1030-1041.