JJMIE

Volume 14, Number 1, March. 2020
ISSN 1995-6665
Pages 71 - 79

Jordan Journal of Mechanical and Industrial Engineering

Review Study of Physical and Mechanical Characteristics on Mixed Soil with Scrap Tire Rubber Particles

Jianguang Bai, Yan Zhang*, Shuzheng Wu

College of Energy and Transportation Engineering, Inner Mongolia Agricultural University, Hohhot 010018, China

Received OCT 16 2019 *Accepted JAN 8 2020*

Abstract

When the sand is mixed with rubber particles, the cohesion and the internal friction angle can be increased, whereas the dynamic shear modulus can be reduced and the damping ration and the liquefaction resistance can be increased. can be increased. The addition of rubber particles affects the skeleton structure of mixed sand, and affects its stress-strain relationship. The compressibility of mixed sand can be increased and the Poisson's ratio can be changed. When the clay is mixed with rubber particle, the shear strength can be increased. The compression coefficient of mixed clay can be reduced and compression modulus can be increased, and the removal rate of phenol can be improved. It can improve the strength, deformation and physical characteristics of mixed clay. When loess is mixed with rubber particle, its dynamic characteristics and compaction characteristics can be changed. When expansive soil is mixed with rubber particle, its swelling and shrinkage characteristics and compressive strength can be improved, and its shear strength can be changed. When fly ash soil is mixed with rubber particle, its dynamic characteristics and shear strength can be affected. In order to further ascertain the effect of rubber particles on soil, the following aspects should be further studied: comprehensive effect of rubber particle content and size on the skeleton structure and stress-strain relationship of mixed sand; mechanism of dynamic characteristics of mixed sand; rubber particle content and size meeting the needs of engineering in the aspects of strength and deformation; effect of rubber particles on physical and mechanical characteristics of silt and silty clay; effect of rubber particles on permeability of clay; effect of rubber particles on collapsibility and strength of loess; effect of rubber particles on compaction and dynamic characteristics of expansive soil; effect of rubber particles on deformation, compressive strength and compaction characteristics of fly ash soil; durability and environmental influence on strength and deformation characteristics. It provides a direction for the rational utilization of scrap tire because of its effect of rubber particles on improvement of the characteristics of soil.

In the paper, the physical and mechanical characteristics on mixed soil with rubber particles are reviewed, and the problems existing in the improvement of soil characteristics by rubber particles are analyzed and the prospects are forecasted. It is a reference for the utilization of scrap tire and the improvement of soil characteristics.

Keywords: rubber particle, mixed soil, scrap tire, strength and deformation.

1. Introduction

In recent years, with the rise of global automobile industry, the number of scrap tires is increasing day by day. The number of scrap tires in China has exceeded 300 million by 2015, and it is growing at an annual rate of 8%-10%.Tire rubber belongs to the refractory or non-fusible polymer materials, it has strong corrosion resistance and hard to degradation. Under the influence of natural force, it would not disappear for decades or even centuries. Scrap tires are hazardous industrial solid waste, which would seriously pollute the ecological environment and affect human health [1, 2]. Therefore, the rational use of scrap tires has become a hot topic to solve environmental problems and promote economic development.

The application of scrap tires in civil engineering is a good way to solve this problem. And it is also one of the development directions of circular economy [3]. Scrap tires can be used in concrete to improve the seismic performance [4], resilience [5], toughness [6, 7], ductility [8], durability [9], workability [10], and strength characteristics of concrete [11, 12]. It can also be widely used to improve soil characteristics [13, 14] as seismic backfill material for slope, retaining wall, bridge and other geological structures [15]. Mixed soil formed by mixing scrap tire rubber particles into soil does not pollute the soil [16]. It is environmentally friendly [17, 18]. Scrap tires become valuable material resources [19]. In this paper, the strength, deformation, dynamic characteristics and physical characteristics of mixed soil formed by mixing scrap tire rubber particles into the soil are studied.

* Corresponding author e-mail: zhanyanli@imau.edu.cn.

2. Rubber particle sand mixed soil

2.1. Shear strength

There are many factors affecting the shear strength of rubber particle sand mixed soil, including rubber particle content, size, size ratio of rubber particles to sand, temperature and so on. Different size ratio and rubber particle content can increase or decrease the shear strength of the mixed soil [20].

Studies by Zhang Yongfu et al. [21], with the increase of rubber particle content, the cohesion and internal friction angle of mixed soil are increased first and then decreased. The internal friction angle reaches the maximum when the rubber particle content is 10%. The cohesion reaches its maximum when the rubber particle content is 20%, as indicated in Table 1. The cohesion and internal friction angle of rubber particle sand mixed soil are affected not only by rubber particle content, but also by rubber particle size [22]. With the increase of rubber particle size, the role of rubber particles in the internal structure is weakened, and the stress transfer mainly through sand-sand [23]. Rubber particles with 6 mm size can provide the maximum shear strength at 30% rubber particles content. Compared with pure sand, the addition of rubber particles can improve the shear strength of soil.

The main reason is that the addition of rubber particles makes the contact and occlusion between particles more sufficient in rubber particle sand mixed soil. When shear occurs, rubber particles undergo continuous extrusion and deformation. It fills the entire interface voids. It enhances the ability to resist deformation of the specimen. At the same time, the sliding and rolling of particles are limited to a certain degree. Rubber particles can inhibit the buckling of bearing capacity chain. Therefore, the shear strength of rubber particle sand mixed soil can be improved [24].

Some studies showed that the addition of rubber particles would slightly reduce the internal friction angle of sand [25]. The higher content of rubber particle it has, the lower the strength is [26]. It has differences with the former [21, 22] in the form of research results. Actually, both of them have coincidence. As Table 1 [21], when the content of rubber particles is less than 30%, the internal friction angle of sand can be increased by adding rubber particles, but it is opposite when the content of rubber particles is more than 30%. The more amount of doping, the more obvious the reduction of internal friction angle. Size Ratio of Particles to Sand decides the mixture behavior of rigid sand and soft rubber particles [27]. It is also an important reason for differences in result due to the different size ratio. Therefore, the mechanical behavior of rubber particles in sand is closely related to content, particle size and size ratio. There are differences between the two research conditions, so the results are not contradictory.

Table 1. Tested values of shear strength parameters of rubber particle sand mixed soil under different proportions [21]

Proportion/%	Cohesion/kPa	Internal friction angle/(°)
0	7.5	36.02
10	14.7	42.27
20	18.9	38.34
30	18.2	34.42
40	15	31.95
50	12.4	27.4

Rubber particle content and confining pressure can influence shear characteristics of mixed soil. When the content of rubber particles is not more than 20%, it is similar to pure sand and has the characteristics of first shear shrinkage and then shear dilation. When it is above 20%, it shows monotonous shear shrinkage characteristics [21]. The higher the content of rubber particles, the more obvious the shear shrinkage. And its strain-stress curve($\varepsilon_c - p$ curve) is hyperbolic, as shown in Fig. 1 [28]. The extended Duncan-Chang Hyperbolic Model Parameter can also be used for simulation [29]. With the increase of rubber particle content, mixed soil gradually changes from sand skeleton to rubber particle skeleton which generates different contact systems [30]. The stress-strain characteristics of rubber particle sand mixed soil changes from brittle to ductile [31]. Different confining pressure and different types of contacts have different influence on deviating stress of system. When the confining pressure is 300-400 kPa, peak deviating stress decreases with the increase of rubber particle content [32]. When the confining pressure is less than 200 kPa, it is basically unchanged [33].

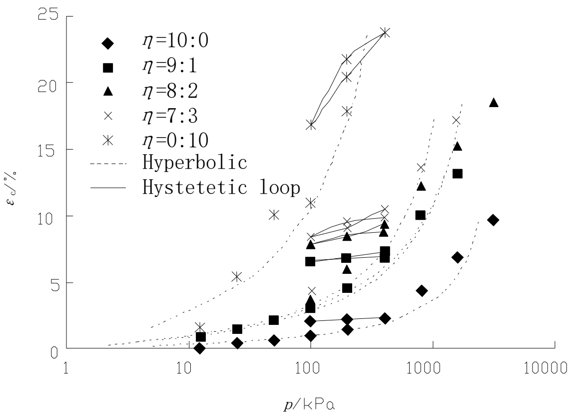
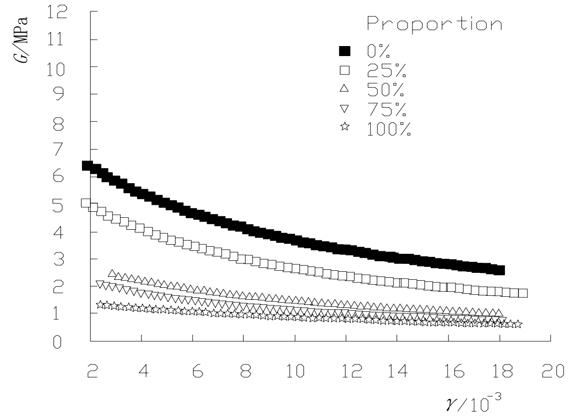


Figure 1. $\varepsilon_c - p$ curves (η is proportion) [28]

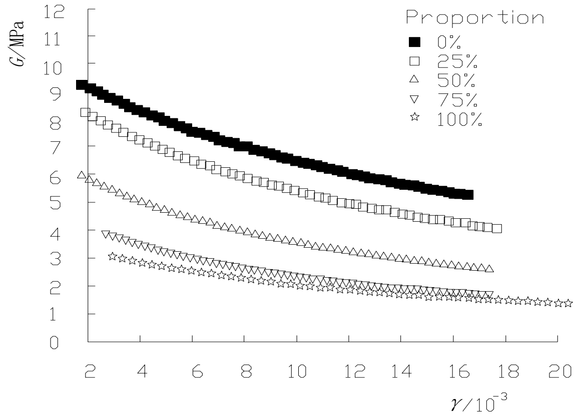
2.2. Dynamic characteristics

Rubber particle sand mixed soil can be used as light fill material for slope, pavement base and retaining wall. It may bear dynamic load. Dynamic shear modulus, damping factor and liquefaction resistance are important indexes for evaluating the dynamic characteristics of rubber particle mixed soil [34]. The size and content of rubber particles can influence dynamic shear modulus and damping ratio of mixed soil [35, 36].

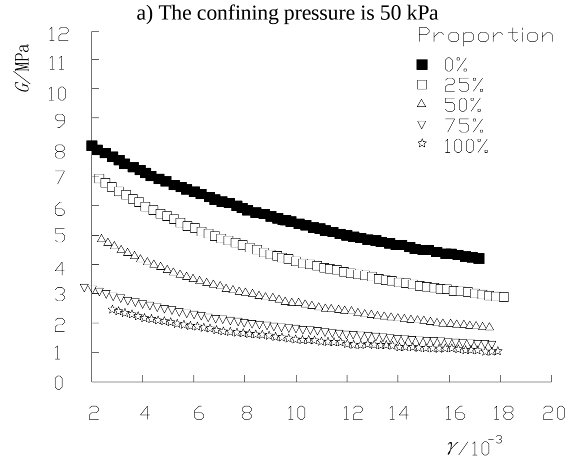
According to the curves of dynamic shear modulus and shear stress($G-\gamma$ curves),as shown in Fig. 2 [37],the dynamic shear modulus of rubber particle sand mixed soil would decrease with the increase of rubber particle content and shear-strain. The attenuation coefficient decreases with the increase of rubber content. The attenuation coefficient increases with increase of consolidation pressure. And consolidation pressure has nonlinear influence on the dynamic shear modulus-dynamic shear strain curve, the rubber particle content increases but it decreases [38]. The dynamic shear modulus can be forecasted by considering confining pressure and rubber particle content [39].



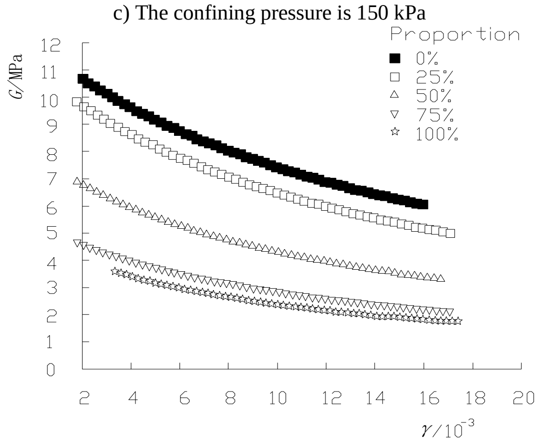
a) The confining pressure is 50 kPa



c) The confining pressure is 150 kPa

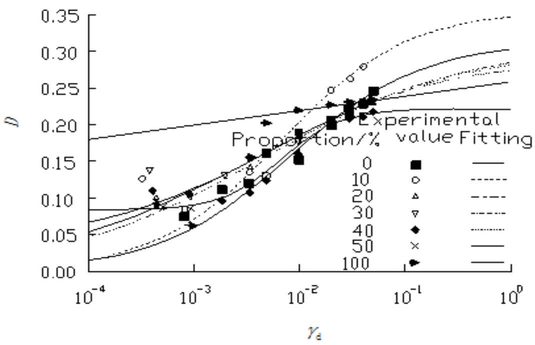


b) The confining pressure is 100 kPa

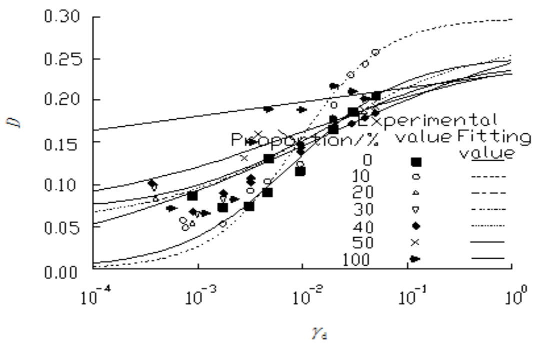


d) The confining pressure is 200 kPa

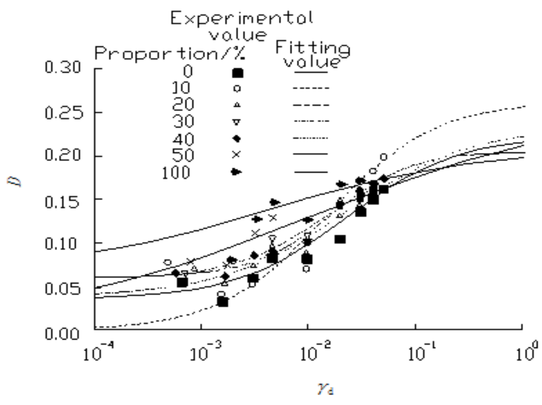
Figure 2. $G-\gamma$ curves of composite soil with rubber and sand with different contents [37]



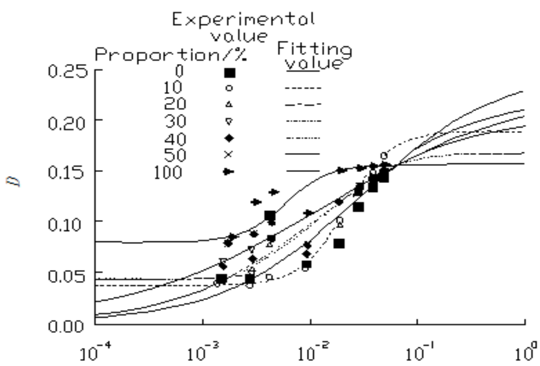
(a) p =50 kPa



(b) p =100 kPa



(c) p =200 kPa



(d) p =300 kPa

Figure 3. $D-\gamma_d$ curves of composite soil with rubber and sand with different contents(p is confining pressure) [41]

The damping ratio of rubber particle sand mixed soil is not only related to rubber particle content, but also related to shear strain size, confining pressure and average effective stress. At small strain, the damping ratio of rubber particle sand mixed soil increases with the increase of rubber particle content [40]. According to the curves of damping ratio and shear stress($D-\gamma_d$ curves),as shown in Fig. 3 [41]at large strain (10^{-2}-10^{-1}), the damping ratio of 10% rubber particle content is greater than that of pure sand and mixed soil of other rubber particle content . The greater the confining pressure is, the higher the damping ratio of rubber sand is [42]. The ratio is a power function of the average effective stress [43].

The sand mixed by rubber particles performs well in dynamic characteristic. No matter how big the particle size is, the more the content of rubber particles is, the more obvious the anti-liquefaction performance of sand is improved [44].

Because of the improvement on dynamic shear modulus, damping ratio and liquefaction resistance of rubber particle sand mixed soil, it can be used as base cushion for seismic isolation. The acceleration reduction coefficient is 0.212-0.592 and the displacement coefficient is 1.01-1.39 for rubber particle is added to sand for seismic isolation [45]. And the dynamic characteristics of the superstructure are improved and the isolation effect is obvious.

With the content of rubber particles increasing, the maximum acceleration of mixed soil cushion decreases. When the volume fraction of rubber particles is 45%, the maximum acceleration is the best [46]. When the volume fraction of rubber particles is 10%, mixed soil can isolate low-rise buildings [47]. For tall buildings, isolation cushion can reduce basal shear by 40% [48]. Therefore, when rubber particle sand mixed soil worked as isolation cushion, the maximum acceleration and building size must be considered to determine the optimum content of rubber particle.

2.3. Deformation

Rubber particles have a positive effect on deformation in mixed soil [49]. Rubber particle content is the decisive factor to control the deformation of rubber particle sand mixed soil. With the increase of the content of rubber particles, the residual strain of mixed soil increased, oedometric modulus decreases, compression increases. Mixed soil behaves natures similar to rubber particles [50]. The pure sand and rubber-sand with 10% rubber content, its e-log(p) curves has linear regression characteristic. Rubber-sand with 20%-25% rubber content and pure rubber particles, its e-log(p) curves has approximate linear characteristics. And its linear fitting slop increases with the rubber particle content increasing. When rubber particle content is less than 30%, it is medium compression material; When rubber particle content is 40% and 50% or 100%, it is high compression material [51]. The rubber particle size also influences the deformation of the mixed soil, and the rubber particle size of 4-9 mm has the greatest influence on reducing the settlement of fine sand [52].

The Poisson's Ratio of rubber particle sand mixed soil mainly is effected by relative compactness and rubber particle content. Poisson's Ratio increases with the relative compactness increasing. However, with the increase of rubber particle content, the effect of relative compactness on Poisson's ratio decreases [53]. The initial Poisson's Ratio curve of mixed soil varies in V-shape with rubber content, decrease first and increase second. And the critical rubber content ranges from 35% to 40%.The Poisson's Ratio tend to 0.5 in failure stage. Rubber particles and sand in mixed soil form different force skeleton which causes this change [54]. Poisson's Ratio under triaxial stress can be calculated by formula (1) [55].

$$\mu=\frac{1}{2}\cdot\frac{(\sigma_z+2\sigma_x)\varepsilon_z-\sigma_z\varepsilon_y}{(\sigma_z+2\sigma_x)\varepsilon_z-\sigma_x\varepsilon_y} \tag{1}$$

In the formula: μ is Poisson's Ratio; σ_x is confining pressure; σ_z is axial pressure; ε_y is radial strain in direction y ; ε_z is axial strain.

The size, content, and size ratio of rubber particle determine the type of force skeleton and stress ratio of rubber particles to rubber particle sand mixed soil. Strain and confining pressure influence the action behavior of mixed soil. The interaction of them make rubber particle sand mixed soil shows different natures in strength and deformation.

3. Rubber particle clay mixed soil

3.1. Strength characteristics

The shear strength of rubber particle clay mixed soil is affected by the content and size of rubber particles. It tends to increase first and then decrease with the increase of rubber particle content. When rubber particle content is 40%, the shear strength is maximum. And its strength is 20-40% higher than that of clay. When rubber particle content is less than 20%, increasing the size of rubber particles can significantly improve the shear strength of mixed soil. The internal friction angle decreases first and then increases with the increase of rubber particle content. As shown in Fig. 4(a) [56]. And the trend of cohesion is the same as that of shear strength, which increases first and then decreases, as shown in Fig. 4(b) [56]. After the shear displacement reaches 3-5 mm, the shear strength remains basically unchanged [57]. The samples exhibit the characteristics of first shear shrinkage and then dilation.

Rubber particles can also be mixed with clay and a certain amount of cement to form light mixed soil. Cement content, rubber particle content and water content has remarkable influence on strength and engineering characteristics of mixed soil. The increase of cement content can obviously strengthen the material unconfined compressive strength and Shear strength. When the cement content is small (10%), rubber particle content has little effect on the unconfined compressive strength of mixed soil; When the cement content is small (13%, 15%), unconfined compressive strength decreases obviously as the rubber particle content increases [58]. With the increase of the content of rubber particle, the cohesion of mixed soil increases, and its internal friction angle reduces [59]. The stress-strain relationship of mixed soil transits from strain softening to strain hardening [60]. Rubber particles change the brittle failure behavior of cemented clay and reduce the expansive force of clay [61]. The workability and fluidity of mixed soil become better as water content increases. But after forming, its strength reduces.

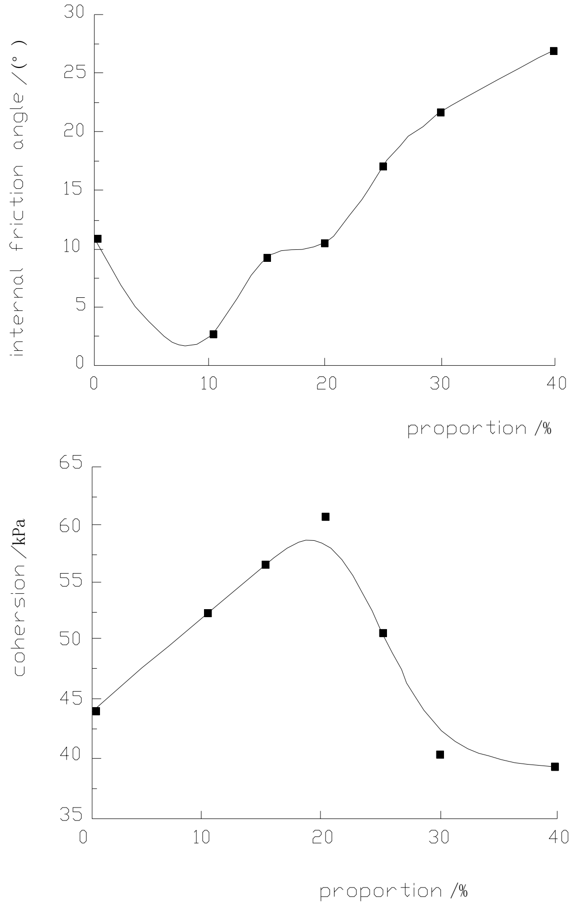


Figure 4. Effect of scrap tire particles on (a) internal fraction angle and (b) cohesion for soft dredger fill [56]

3.2. Deformation

The compressibility of rubber particle clay mixed soil is between clay and pure rubber particles. It shows low compressibility at low dosage and high compressibility at high dosage. With the increase of rubber particle content, the void ratio and compressibility coefficient decrease first and then increase, and compression modulus increases first and then decreases. When the content is 30%, the void ratio and compressibility coefficient are minimum, and compression modulus is maximum. Moreover, the consolidation rate of cohesive soil can be increased by 400% with the addition of rubber particles [62]. The main reason is that rubber particles fill the voids between clay particles to reduce the void volume and compressibility of soil. With the increase of rubber particle content, the soil skeleton is gradually transformed into rubber particle skeleton, which leads to the increase of void ratio. The formation mechanism is similar to that of rubber particle sand. However, this change occurs only when the size of rubber particles and clay is relatively small. If the size of rubber particles and clay is big, the skeleton structure of mixed soil can change. Besides, the compressibility of mixed soils should consider the influence of the compressibility of rubber particles themselves.

Effect of rubber particles on optimum water content of rubber particle clay mixed soil is mainly influenced by rebound effect and specific surface area of rubber particles in compaction process. When the rubber particle size is 30 mesh and 12 mesh, with the increase of rubber particle content, optimum water content of rubber particles-kaolin increases, optimum water content of rubber particles-red clay decreases, and the maximum dry density of mixed soil decreases. The effect of rubber particle size on the optimum water content and maximum dry density of mixed soil is not significant [63]. Different types of clay minerals, such as kaolin, montmorillonite and illite, have different water absorption ability because of their own structure and composition. However, after adding rubber particles, there are differences in interaction mode and interaction strength between soil and rubber particles which leads to different trends of optimum water content.

3.3 Physics

The removal rate of phenol from clay can be improved by adding rubber particles into clay. The adsorption effect of rubber particles is better than that of clay. The removal rate of phenol decreases with the increase of concentration of phenol. The adsorption of phenol by rubber particles, bentonite and kaolin conforms to Langmuir and Freundlich adsorption—isotherm, and it has good linear correlation [64]. However, the influence of rubber particle size and its size ratio to clay was not considered.

Clay generally has small void and bad water permeability, which leads to many engineering geology problems. When rubber particle size and size ratio between rubber particles and soil are big, the addition of rubber particles can cause the changes of pore size and connectivity of soil. Therefore, the permeability of soil is affected by rubber particle, and the specific change law needs to be further studied.

4. Rubber particle special soil mixed soil

4.1. Loess

Dynamic characteristics are improved after adding rubber particles into loess. The change law is affected by rubber particle content and dynamic shear strain. The max dynamic elastic modulus and dynamic shear modulus of mixed soil decrease significantly with the increase of rubber particle content. The maximum damping ratio increases with the increase of rubber particle content. When dynamic shear strain ranges from 0-0.002, the content of rubber particles has little effect on dynamic shear modulus ratio; When dynamic shear strain is bigger than 0.002, the dynamic shear modulus ratio increases with the increase of the rubber particle content. When dynamic shear strain ranges from 0-0.01, damping ratio varies greatly. When dynamic shear strain is bigger than 0.01, damping ratio tends to be stable [65]. In the study of dynamic elastic modulus, dynamic shear modulus and damping ratio, the influence of confining pressure and rubber particle size on them needs to be considered.

The compactibility of rubber particle loess mixed soil has closely relation with rubber particle content. When rubber particle content is less than 20%, compactibility characteristics of mixed soil are similar to loess; when rubber particle content is higher than 40%, compactibility characteristics of mixed soil are similar to non-cohesive soil. There is a power function relationship between the maximum dry density and the optimum water content of mixed soils with different rubber particle content, as shown formulas (2) and (4). There is a functional relationship between rubber particle content and the optimum water content of mixed soil under different compaction energy, as shown formulas (3) and (5). Under light and heavy compaction energy conditions, the optimum content of compaction of mixed soil is 30% and 40% respectively.

The recommended values of compaction index for mixed soils with different rubber particle content are shown in Table 2 [66].

Rubber particles can be mixed with baryta powder and added to loess. The internal friction angle of mixed soil increases with the increase of Barites and rubber particle content and it increases almost linearly with the increase of rubber particles content. However, the cohesion decreases with the increase of Barytes and rubber particle content [67]. Effect on shear strength of mixed soil caused by rubber particles and barytes powder also is determined by comprehensive effect of internal friction angle and cohesion. At the same time, the influence of rubber particles and baryte particles size needs b to be considered.

Table 2. Compaction parameters of mixtures [66]

Light compaction			Heavy compaction		
Proportio (%)	Optimum water content (%)	Maximum dry density (g/cm³)	Proportion (%)	Optimum water content (%)	Maximum dry density (g/cm³)
20	14.5	1.48	20	12.0	1.58
30	14.0	1.43	30	11.7	1.47

Note: Formula (2)-Formula (5) can be used to calculate other content.

Light compaction:

$$\rho_{\mathrm{d\,max}} = 6.57 - 1.10 w_{\mathrm{opt}} + 0.057 w_{\mathrm{opt}}^2 \quad (2)$$

$$w_{\mathrm{opt}} = 12.66 - 0.016x - 5.71x^2 \times 10^{-4} \quad (3)$$

Heavy compaction:

$$\rho_{\mathrm{d\,max}} = -14.40 + 2.06 w_{\mathrm{opt}} - 0.067 w_{\mathrm{opt}}^2 \quad (4)$$

$$w_{\mathrm{opt}} = 17.66 - 0.185x + 1.93x^2 \times 10^{-4} \quad (5)$$

In the formula: $\rho_{\mathrm{d\,max}}$ is the maximum dry density; w_{opt} is the optimum water content; x is rubber particle content.

4.2. Expansive soil

Expansive soil has typical characteristics of swelling in water absorption and shrinkage in water loss. It always causes unfavorable engineering geological problems such as settlement of ground and slope collapse. Therefore, engineering geological characteristics of expansive soil generally needs to be improved to meet engineering requirements.

Property improvement of expansive soil can be achieved by mixing coal gangue, lime and chemical solution. By adding a certain amount of coal gangue, the compression strength [68], shear strength [69] and CBR value [70] of expansive soil can be improved. Besides, coal gangue can control the attenuation of internal friction angle and cohesion of pure expansive soil caused by dry-wet cycling [71]. By adding a certain amount of coal gangue and lime in expansive soil, it can improve its compaction characteristics [72, 73]. Expansive soil mixed with NaCl solution or other solutions can be improved chemically to reduce the deformation of expansive soil [74].

The effect of rubber particles on improving expansive soil in the aspects of swelling and shrinkage characteristics and compressive strength is better. Rubber particles in expansive soil can weaken the interaction of expansive soil and water [75]. At the same time, it can reduce the content of hydrophilic minerals and swelling and shrinkage characteristics [76]. Rubber particles in expansive soil can improve its compression strength [77, 78] and decrease its stiffness. Freeze-thaw cycling can affect the compression strength of improved expansive soil. Under the same number of freeze-thaw cycling, the unconfined compression strength of improved expansive soil tends to increase first and then decrease with the increase of rubber particle content. When rubber particle content is 3%, the unconfined compression strength of improved expansive soil is maximum. Compression strength decreases as the number of freeze-thaw cycles increases. When water content is 20%, under the same condition of freeze-thaw cycles, it shows frozen shrinkage and thawed expansion in low rubber particle content; and it's opposite in high rubber particle content because of influence of ice-water interaction [79].

When the content of rubber particles in expansive soil is less than 23%, the cohesion of improved expansive soil is generally lower than that of pure expansive soil, which results in significant decrease in in shear strength [76]. The content of rubber particles used in this study ranged from 15% to 25%. The shear strength in the range of 0-15% has not been tested. Therefore, the overall change trend of shear strength of expansive soil with rubber particles needs to be further studied.

The swelling and shrinkage characteristics of improved soil is lower than that of pure expansive soil, which is the main purpose of improving expansive soil. However, the idea that the shear strength and dynamic characteristics of the improved expansive soil may meet the needs of practical engineering still needs to be studied.

4.3. Fly ash soil

The dynamic strength of fly ash soil mixed with rubber particles decreases with the increase of the cycle number of failure under the same confining pressure. At the same number of failure, the dynamic strength decreases with the increase of the confining pressure. The initial tangential modulus and average dynamic modulus of fly ash soil mixed with rubber particles are reduced, while the cohesion and internal friction angles are improved [80].

Recent years, fly ash soil is gradually widely used in engineering. If adding rubber particles into fly ash soil, the improved effect of its compression strength, deformation, compaction characteristics and other aspects need a lot of further research.

5. Conclusions

1. The strength, deformation, dynamic characteristics of the soil and the poor engineering characteristics of the special soil can be changed when the rubber particles of scrap tires are mixed into sand, clay, loess, expansive soil and fly ash soil. The influence on characteristics of soils mixed with rubber resulted by different rubber particle content, size, size ratio, strain and confining pressure is different.
2. When the sand is mixed with rubber particles, the cohesion of mixed soil can be improved. And the cohesion of mixed soil can reach its peak under the certain rubber particle content and size conditions. The

internal friction angle of the mixed soil may increase or decrease, which is related to the size ratio of rubber particles and sand.

3. Rubber particles can improve the shear strength of rubber particle sand mixed soil, but the variation of unconfined compressive strength and CBR of mixed soils with rubber particle content and size has not been studied in details. The rubber particle content affects the skeleton structure of mixed soil and the stress-strain relationship of mixed soil. At the same content of rubber particle, the skeleton structure of mixed soil is different when the size of rubber particle is different. The comprehensive influence of content and size on skeleton structure and stress-strain relationship of mixed soil is worth further study. When the sand is mixed with rubber particles, the dynamic shear modulus can be reduced and the damping ration can be increased, and the liquefaction resistance can be increased. It can be used in a seismic engineering. However, the study on the dynamic characteristics mechanism of rubber particle sand mixed soil is insufficient. Whether it is still related to the skeleton structure of mixed soil remains to be discussed. The rubber particles in rubber particle sand mixed soil also affects its deformation characteristics. In order to meet the engineering requirements to the utmost in terms of various characteristics, it is necessary to find suitable rubber particle content and size.
4. When the clay is mixed with rubber particles, the shear strength and compression modulus can be increased and the compression coefficient can be reduced to a certain extent. Rubber particles play a significant role in improving the strength and deformation characteristics of mixed soil.

The study of rubber particle clay mixed soil mainly focuses on some low liquid limit clay and different clay minerals such as kaolinite and montmorillonite. At present, there is no detailed study on the characteristics of silt and silty clay. Clay usually has small pores and poor water permeability. Rubber particles in mixed soil can cause changes of their pores, which affects the water permeability of clay. The specific law of change needs further study.

Loess is widely distributed in northwest China, and most loess has collapsibility. It is of great significance to have a further study on the effect of rubber particles on collapsibility of loess. The addition of rubber particles can improve the dynamic characteristics of loess to a certain extent. However, attention should be paid to the influence of confining pressure and rubber particle size on it. When loess is mixed with rubber particles, the changes of compressive strength, shear strength and CBR are lack of in-depth studies. The influence of rubber particles and barite powder on shear strength of loess should also consider the factors such as the size of rubber particle and barite particle. When the expansive soil is mixed with rubber particles, its swelling and shrinkage characteristics and compression strength can be improved. And its shear strength is also affected to some extent. However the influence of rubber particles on the compaction and dynamic characteristics of expansive soils and its mechanism are not well studied. It needs a further study on the improvement effect of rubber particles on deformation, compressive strength and compaction characteristics of fly ash soil.

(5) The durability of rubber particle mixed soil and its environmental influence on strength and deformation characteristics are not study in detail.

Acknowledgements

The authors would like to thank the National Natural Science Foundation of China (51669025) for their support for this study.

References

[1] Kong, D. S., Jia, T., Wang, X. M., Zhang, W. W. & Wu, Y. K.: Test on unconfined compressive strength of lightweight soil mixed with rubber chips of scrap tires. Journal of Central South University (Science and Technology). 47(1): 225-231(2016).

[2] Ding, L. Q. & Li, Y. Z.: Application and research status of scrap tire rubber particles. Sichuan Cement. 299: 85(2017).

[3] Anvari, Seyed, M. & Shooshpasha, I.: Influence of size of granulated rubber on bearing capacity of fine-grained sand. Arabian Journal of Geosciences. 9(18): (2016).

[4] Liu, J. H. & Song, S. M.: Effects of rubber particles treated surface on concrete damping capacity. Journal of Beijing University and Technology. 35(12): 1619-1623(2009).

[5] Fu, C. Q., Fan, S. F., Deng, X. B, Zhang, G. G., Li, J. & Lu, C. Y.: Experimental study on mechanical properties of rubber concrete with different curing age. Concrete. 324(10): 64-68(2016).

[6] Wang, J. J., Zhang, Y. H., Qin, W. X., Wang, S. J. & Zhang, H. B.: Mechanical properties of rubber concrete. Bulletin of Chinese Ceramic Society. 35(7): 2219-2223(2016).

[7] Ma, N. Z.: Experimental research on mechanical property of rubber concrete. Subgrade Engineering. 186(3): 79-82(2016).

[8] Ismail M. K. & Sherir, M. A. A.: Siad Hocine. Properties of self-consolidating engineered cementitious composite modified with rubber. Journal of Materials in Civil Engineering. 30(4): (2018).

[9] Liu, Y. R., Ge, S. G. & Han, Y.: Research progress of scrap rubber powder modified cement-based composites. Material Herald. 28(24): 422-426(2014).

[10] Ma, K. L., Long, G. C., Xie, Y. J., Chen, X. B., Qian, Z. M. & Tan, W. Y.: Effect of rubber particles on properties of self-compacting concrete. Bulletin of Chinese Ceramic Society. 42(8): 966-973(2014).

[11] Zhang, H. B., Guan, X. M., Liu, X. X. & Li, F.: Study on compressive strength and interface of rubberized concrete. Material Herald. 23(4): 65-67(2009).

[12] Huang, S. W., Xu, Y. H. & Luo, Q.: Research progress in rubber particles modified portland cement concrete. Material Herald. 23(1): 101-105(2019).

[13] Fu, R., Coop, M. R. & Li, X. Q.: Influence of particle type on the mechanics of sand-rubber mixtures. Journal of Geotechnical and Geoenvironmental Engineering. 143(9): 1-15(2017).

[14] Wei, H. B., Jiao, Y. B. & Liu, H. B.: Effect of freeze-thaw cycles on mechanical property of silty clay modified by fly ash and crumb rubber. Cold Regions Science and Technology. 116: 70-77(2015).

[15] Wang, Z. Y., Zhang, N. &Li, Q.: Dynamic response of bridge abutment to sand-rubber mixtures backfill under seismic loading conditions. Journal of Vibroengineering. 19(1): 434-446(2017).

[16] Dong, C., Li, D. Y. &Li. S. S.: Effects of scrap tire crumb size on shear strength of sand. Journal of Guangxi University (Science and Technology). 42(4): 1392-1398(2017).

[17] Liu, F. C., Ren, D. B., Liu, N. & Zhao, C. Q.: Numerical simulation on the isolation effect of geocell reinforced

rubber-sand mixture cushion earthquake base isolator. China Civil Engineering Journal. 48(S1): 109-118(2015).
[18] Wang, Z. Y., Zhang, N. &Jin, Y.: Experimental study on dynamic properties of sand-rubber mixtures in a small range of shearing strain amplitudes. Journal of Vibroengineering. 19(6): 4378-4393(2017).
[19] Zhang, T., Cai, G. J., Liu, S. Y., Duan, W. H. & Wang, P. C.: Experimental study on strength characteristics and micromechanism of rubber-sand mixtures. Chinese Journal of Geotechnical Engineering. 39(6): 1082-1088(2017).
[20] Perez, J. C., Lopera, Kwok, C. Y. & Senetakis, K.: Micromechanical analyses of the effect of rubber size and content on sand-rubber mixtures at the critical state. Geotextiles and Geomembranes. 45(2): 81-97(2017).
[21] Zhang, Y. F., Liu, F. C. & Ren, D. B.: Study on shear characteristics of rubber-sand mixtures by triaxial CD tests. Journal of Hunan University of Technology. 29(1): 17-23(2015).
[22] Anbazhagan, Panjamani, Manohar, D. R, Rohit & Divyesh.: Influence of size of granulated rubber and type chips on the shear strength characteristics of sand-rubber mix. Geomechanics and Geoengineering. 12(4): 266-278(2017).
[23] Perez, J. C. &Lopera, Kwok, C. Y.: Senetakis K. Effect of rubber size on the behaviour of sand-rubber mixtures: A numerical investigation. Computers and Geotechnics. 80(11): 199-214(2016).
[24] Liu, F. C. & Wu, M. T.: Micromechanics simulation of direct shear test of rubber-sand mixture with discrete element method. Journal of Hefei University of Technology (Science and Technology). 40(7): 944-951(2017).
[25] Ali, F. C.: Direct shear tests on waste tires–sand bixtures. Geotechnical and Geological Engineering. 29(4): 411-418(2011).
[26] Martin, C. & Jun-Boum, P.: Laboratory determination of strength properties of frozen rubber-sand mixtures. Cold Regions Science and Technology. 60(2): 183-192(2010).
[27] Changho, L. Q., Hung, T. & Woojin, L.: Characteristics of rubber-sand particle mixtures according to size ratio. Journal of Materials in Civil Engineering. 22(4): 323-331(2010).
[28] Deng, A. & Feng, J. R.: Experimental study on sand-shredded tire light fills. Journal of Building Materials. 13(1): 116-120(2010).
[29] Liu, F. C., Zhang, Y. F. & Ren, D. B.: Stress-strain characteristics of rubber-sand mixtures in united triaxial shear and simple shear tests. Rock and Soil Mechanics. 37(10): 2769-2779(2016).
[30] Kim, H. K. & Santamarina, J.: Sand-rubber mixtures (large rubber chips). Canadian Geotechnical Journal. 45(10): 1457-1466(2008).
[31] Zhang, T., Cai, G. J. & Duan. W. H.: Strength and microstructure characteristics of the recycled rubber tire-sand mixtures as lightweight backfill. Environmental Science and Pollution Research. 25(4): 3872-3883(2018).
[32] Perez, J. C., Lopera & Kwok, C. Y.: Senetakis K. Investigation of the micro-mechanics of sand-rubber mixtures at very small strains. Geosynthetics. 24(1): 30-44(2017).
[33] Deng, A. & Feng, J. R.: Effect of scrap tire bead addition on shear behavior of sand. Journal of PLA University of Science and Technology (Natural science Edition). 10(5): 483-487(2009).
[34] Li, B., Huang, M. S. &Zeng, X. W.: Dynamic behavior and liquefaction analysis of recycled-rubber sand mixtures. Journal of Materials in Civil Engineering. 28(11): 1356-1365(2016).
[35] Kostas, S., Anastasios, A. & Kyriazis, P.: Dynamic properties of dry sand/rubber (SRM) and gravel/rubber (GRM) mixtures in a wide range of shearing strain amplitudes. Soil Dynamics and Earthquake Engineering. 33(1): 38-53(2012).
[36] Anastasios, A., Kostas, S. & Kyriazis, P. : Small-strain shear modulus and damping ratio of sand-rubber and gravel-rubber mixtures. Geotechnical and Geological Engineering. 30(2): 363-382(2012).
[37] Shang, S. P., Sui, X. X., Zhou, Z. J., Liu, F. X & Xiong, W.: Study of dynamic shear modulus of granulated rubber-sand mixture. Rock and Soil Mechanics. 31(2): 377-381(2010).
[38] Liu, F. C., Yan, J. & Wang, H. D.: Experimental study on dynamic characteristics of dry rubber-sand mixture at large strains. Chinese Journal of Rock Mechanics and Engineering. 35(2): 4265-4278(2016).
[39] Wang, Z. Y., Zhang, N. & Jin, Y.: Experimental study on dynamic properties of sand-rubber mixtures in a small range of shearing strain amplitudes. Journal of Vibroengineering. 19(6): 4378-4393(2017).
[40] Senetakis, K. & Anastasiadis, A.: Effects of state of test sample, specimen geometry and sample preparation on dynamic properties of rubber-sand mixtures. Geosynthetics International. 22(4): 301-310(2015).
[41] Liu, F. C., Chen, L. & Wang, H. D.: Evaluation of dynamic shear modulus and damping ration of rubber-sand mixture based on cyclic simple shear tests. Rock and Soil Mechanics. 37(7): 1903-1913(2016).
[42] Zhou, J.: Study on dynamic properties of composite soil mixing soil and scrap tire rubber particles. Hunan Communication Science and Technology. 44(3): 65-69(2018).
[43] Brara, A., Brara, A. & Daouadji, A.: Dynamic properties of dense sand-rubber mixtures with small particles size ratio. European Journal of Environmental and Civil Engineering. 21(9): 1065-1079(2017).
[44] Li, B. & Huang, M. S.: Dynamic triaxial tests on liquefaction characteristics of rubber-sand mixture. Rock and Soil Mechanics. 38(5): 1343-1349(2017).
[45] Xu, D., Li, Y. R & Huang, X. X.: Research on isolation properties of sand-rubber vibration isolation cushion. Journal of Anhui University of Science and Technology (Natural Edition). 37(3): 17-22(2017).
[46] Wang, Q. Q., Zheng, W., Shi, J. B.: Study on the optimal of sand and rubber for isolation cushion. Journal of Anhui University of Science and Technology (Natural Edition). 35(1): 16-18(2015).
[47] Madhusudhan, B. R., Boominathan, A. & Banerjee, S.: Static and large-strain dynamic properties of sand-rubber tire shred mixtures. Journal of Materials in Civil Engineering. 29(10): (2017).
[48] Pitilakis, K., Karapetrou, S. & Tsagdi, K.: Numerical investigation of the seismic response of RC buildings on soil replaced with rubber-sand mixtures. Soil Dynamics and Earthquake Engineering. 79(11): 237-252(2015).
[49] Changho, L., Hosung, S. &Jong-Sub, L.: Behavior of sand-rubber particle mixtures: Experimental observations and numerical simulations. International Journal for Numerical and Analytical Methods in Geomechanics. 38(16): 1651-1663(2014).
[50] Duan, W. H., Zhang, T. & Cai, G. J.: Experimental study on compressibility characteristic of rubber-sands mixture. Journal of Engineering Geology. 23(suppl.): 200-204(2015).
[51] Zhang, Y. F., Liu, F. C., Yue, H. T. & Gan, L.: Study on laterally confined compression test of rubber-sand mixture. Journal of Hunan University of Technology. 29(3): 1-9(2015).
[52] Anvari, Seyed, M., Shooshpasha & Issa.: Influence of size of granulated rubber on bearing capacity of fine-grained sand. Arabian Journal of Geosciences. 9(18): 1899-1911(2016).
[53] Liu, F. C., Zheng, Y. F., Liu, N. & Zhang, Y. F.: Influence of proportioning and relative density on static parameters of rubber-sand. Journal of Hunan University of Technology. 31(5): 24 -31(2017).

[54] Liu, F. C., Wu, M. T, Liu, N., Zhang, Y. F. & Chen, J. L.: Experimental study on poisson's ratio of rubber-sand mixtures. Chinese Journal of Rock Mechanics and Engineering. 36(1): 3596-3606(2017).

[55] Liu, N., Liu, F. C., Zhang, X. Q., Ren, D. B. & Zhang, Y. F.: Study of poisson's ratio of calculation method for mixture under the triaxial test. Journal of Hunan University of Technology. 29(6): 16-22(2015).

[56] Li, S. S & Li, D. Y.: Shearing properties of composite soil mixing clay with rubber particle of scrap tire. Journal of Yangtze River Scientific Research Institute. 34(7): 99-105(2017).

[57] Zhang, L., Li, D. Y., Li, S. S. & Huang, T.: Effects of scrap tire chips on shear strength of soft dredger fill. Journal of PLA University of Science and Technology (Natural science Edition). 34(4): 102-106(2015).

[58] Xin, L., Liu, H. L., Shen, Y. & He, J.: Unconfined compressive test of light weight soil mixed with rubber chips of scrap tires. Journal of PLA University of Science and Technology (Natural science Edition). 11(1): 79-83(2010).

[59] Xin, L., Gao, D. Q. & He, J.: Engineering characteristics of lightweight soil mixed with rubber chips of scrap tires (paper presented at 11th National Symposium on Rock Mechanics and Engineering, Wuhan, Peoples R. China. Oct19-24)(2010).

[60] Xin, L., Liu, H. L., Shen, Y. & He, J.: Consolidated undrained triaxial compression tests on light weight soil mixed with rubber chips of scrap tires. Chinese Journal of Geotechnical Engineering. 32(3): 428-433(2010).

[61] Yadav, J. S. & Tiwar, S. K.: Effect of waste rubber fibres on the geotechnical properties of clay stabilized with cement. Applied Clay Science. 149: 97-110(2017).

[62] Li, S. S., Li, D. Y. & Zhang, Y. S.: Effects of scrap tire crumbs on compression behavior of clay. Journal of Shandong University of Science and Technology. 35(5): 55-62(2016).

[63] He, J., Li, Y., Ruan, X. C. & Hu, X. J.: Compaction performance of ground rubber and clay mixtures. Journal of Engineering Geology. 23(5): 1013-1019(2015).

[64] Li, Y., He, J., Ruan, X. C. & Hu, X. J.: Adsorption performance of phenol by waste tire rubber particles and clay. Journal of Hubei University of Technology. 30(5): 113-116(2015).

[65] Hu, Z. P., Liu, Z. H., Zhang, Z. Q. & Xu, J. W. & Yan, X. B.: Test on influence of rubber power on dynamic mechanic properties of manipulated loess. Journal of Chang'an University (Natural Science Edition). 33(4): 62-67(2013).

[66] Li, Z. H. & Zhang. H. Y.: Compaction properties of granulated rubber and loess. Rock and Soil Mechanics. 31(12): 3715-3726(2010).

[67] Xu, J. W., Hu, Z. P., Ma, S. L., Yan, X. B. & Liu, Z. H.: Effect of barite powder and rubber powder on the shear strength of manipulated loess. Journal of Xi'an University of Science and Technology. 33(5): 565-570(2013).

[68] Guo, L. Y., Zhang, Y., Zhou, T. P, Yang, X. Y & Han, C.: Experiment study on expansive soil improved by coal gangue powder. Journal of Inner Mongolia Agricultural University. 34(4): 127-130(2013).

[69] Yang, X. Y. & Zhang, Y.: Mechanism analysis of coal gangue powder improving shear strength of expansive soil. Coal Engineering. 46(9): 123-125(2014).

[70] Zhang, Y., Liu, B. B., Kang, X. C., Guo, L. Y., Yu, G. P., Dong, W. & Liang, J.: Research on CBR of expansive soil improved by coal gangue. Journal of Inner Mongolia Agricultural University. 36(2): 77-81(2015).

[71] Zhang, Y., Yin, X. X. & Liu, T.: Strength properties of solidified expansive soil with coal gangue and its pore structure characterization under condition of optimum dosage. Transactions of the Chinese Society of Agricultural Engineering. 34(22): 267-274(2018).

[72] Li, W. S, Zhang, Y., Guo, L. Y., Meng, F. F. & Yu, X. H.: Research on mechanism of compaction expansive soil with coal gangue. Journal of Inner Mongolia Agricultural University (Natural Science Edition). 35(4): 107-110(2014).

[73] Zhang, Y., Kang, X. C. & Guo, L. Y.: Engineering properties of expansive soil improved by lime and coal gangue. Bulletin of the Chinese Ceramic Society. 34(9): 2720-2724, 2730(2015).

[74] Li, W. S., Zhang, Y., Zhao, R. & Feng, X. B.: Effect of pore solution on deformation of chemical modified expansive soil. Non-Metallic Mines. 41(5): 92-95(2018).

[75] Zuo, C. Y. & Zhou, J. Deng W.: A evaluate summarizing on reform effect of expansion soil admix rubber particles. Shanxi Architecture. 36(25): 83-84(2010).

[76] Zhou, W. L., Xie, P., Ma, Q., Yang, Y. & Zuo, C. Y.: Experiment on characteristics of expansive soil modified with waste tire rubber particles. Journal of Sichuan University (Engineering Science Edition). 43(3): 44-48(2011).

[77] Yang, Q. G. & Wang, Y. F.: Study on road performance of waste rubber tire particles mixed expansive soil. Shanxi Architecture. 43(36): 99-101(2017).

[78] Shen, Z., Wang, Y. F., Kang, X. C., Fu, H., Wang, Z. Q., Guan, S. S., Wang, C. & Wu, Z. Z.: A Study of road performance on soil mixed with waste rubber tire particles. Journal of Nanjing Institute of Technology (Natural Science Edition). 16(2): 44-50(2018).

[79] Zong, J. M., Song, Y. J., Lu, Y., Xu, L. & Zhang, Y. Z.: Unconfined compressive strength test on expansive soil improved by waste tire rubber particles under freeze-thaw cycles. Journal of Yangtze River Scientific Research Institute. 34(9): 110-114(2017).

[80] Li, C. Y., Liu, H. B. & Wei, H. B.: Experimental research on dynamic characteristics of fly ash soil improved by rubber particles. Rock and Soil Mechanics. 32(7): 2025-2028, 2033(2011).