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Experimental and numerical investigations on the shear behaviour of recycled railway ballast

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Abstract

Ballast degradation is frequently observed under cyclic loading, and results in bearing capacity and drainage problem of ballast track. To keep the stability and safety, periodical maintenances are needed, such as cleaning and replacement, which produce a huge amount of wasted ballast. Thus, reusing the deteriorated ballast can become a considerable method for sustainable railway development and environment protection. One applications is adding the cleaned deteriorated ballast (i.e. recycled ballast) into fresh ballast. Furthermore, it is common situation that applying the mixture of fresh and deteriorated ballast during the railway operation. To study the mechanical behaviour of this mixture and find out the criterion weight proportion of the recycled ballast, a series of large direct shear tests were performed with different weight proportions (0%, 10%, 20%, 30%, 40%, and 50%) of recycled ballast mixed into fresh ballast under different normal stresses (50, 100 and 200 kPa). In addition, a numerical simulation based on discrete element method (DEM) was used to illustrate the shear strength, contact forces, coordination numbers and displacements of ballast particles. Results show that the shear strength reduction of the mixture is insignificant, when mixed with less than 30% recycled ballast. With the recycled ballast proportion increasing, the shear strength and coordination number reduce and the displacements get larger. This research provides a foundation for the application of recycled ballast, and on the other hands, adding fresh ballast can be a solution to reinforce deteriorated ballast bed.

Keywords：Railway ballast; Recycled ballast; Direct shear tests; Discrete element method

1. Introduction

Railway ballast is generally specified as a crushed, angular hard rock with particle size distributes from 20 mm to 65 mm [1]. The performance of ballast bed is influenced by several characteristics, thus several procedures are performed to check them before track construction. For instance, the LAA loss is applied to qualify the abrasion resistance, and the particle size distribution (PSD) is obtained by sieving to fulfil the characteristics of drainage and elastics [2]. With these characteristics, the main functions of ballast layer can provide a solid and elastic foundation for the sleepers, bear and transmit the stress from rails to subgrade which caused by passing trains and good drainage ability [3-4].

However, the function of ballast bed will deteriorate along with the ballast degradation under the heavier axle and higher speed train load, including particle breakage, abrasion, translation and rotation. In this process, ballast particles turn to less angularity, and the surface texture is worn from coarse to smooth, where the particle size also diminishes which affect the PSD and produces fine particles, which are the main fouling composition [5]. Finally, differential settlement, poor drainage and capacity reduction are occurred [6-7]. Especially with the heavier axle and higher speed loading is nowadays emerging, those problems are severer [8].

It needs to be noted that with the development of railway, maintenance is more and more frequent, a large amount of fresh ballast is exploited and deteriorated ballast is produced as wastes. In Europe, the maintenance cost varies from 30000 to 100000 Euros per kilometre per year [9], causing both excessive economic consumption and environment problems. Besides, the construction continues growing with the expectation of completing the Trans-European Transport Network (TEN-T) core network by 2030 and the TEN-T comprehensive network by 2050 [10]. Thus, enhancing the performance and prolong the lifespan of ballast track, and sustainable development of ballast track is needed to be found out.

The deteriorated ballast behaviour has been studied with a variety of researches using laboratory tests or numerical simulations. For instance, Ebrahimi et al [11] conducted triaxial tests focusing on the behaviour of ballast mixed with fine particles from coal or angular breakage, and results show that under high confine pressure the deformation of fouling ballast is similar with clean ballast. However, ballast is in track bed is under nearly no confine pressure. For this, Indraratna et al [12] studied the deformation and degradation of recycled ballast under simulated field loading on both fresh and recycled ballast with cyclic triaxial tests, and results show that the settlement of recycled ballast is 2 times higher than fresh ballast. The drainage problem was analysed by Tennakoon et al [13], and the results show the drainage changes from good to very poor when the ballast is deteriorated.

Because of the considerable effects of ballast degradation, some researches were carried out to qualify the status of ballast. For example, Qian et al [14] employed image analysis method to qualify ballast deterioration corresponding with fouling index (FI) after Los Angeles Abrasion (LAA) tests, and Guo et al [15] also analysed the ballast degradation based on 3-D image analysis method focusing on the influence of particle size and shape.

More importantly, several methods were proposed for deteriorated ballast bed performance improvement, including the geogrid, elastic materials (rail pad, ballast mat and crumb rubber), and polyurethane. The geogrid can increase the shear strength of ballast layer by strengthening the interlock between ballast particles [16], and the study in [17] shows that geogrid can decrease the permanent settlements under cyclic loading. Elastic materials can adjust stiffness and decrease vibration and noise, further prolonging the service life of ballast track [18-20]. For example, the crumb rubber applied in ballast particles was studied in [21] and [22], finding that the 10% (by weight) and 3~5 mm crumb rubber plays a significant role in reducing ballast degradation. Polyurethane reinforcement can also improve the ballast bed performance by bonded granular ballast together as a whole structure, through this method, the capacity and stability can be largely improved, and it also can be used for stiffness adjustment in transition zones [23-25].

Although these methods have their reinforcing effects, periodical maintenance is still needed to keep the high performance of ballast track, including, tamping, geometry adjustment and ballast renewal [16], thus the fresh ballast consumption is staying at a high level. Besides, some maintenance problems occur along with the reinforcement methods mentioned above. For example, after spraying polyurethane, ballast is bonded by high tensile strength, tamping maintenance is hard to be employed, because the tine of tamping machine cannot insert into ballast layer, and the problem has occurred after geogrid installing, where the geogrid can cause higher settlement on recycled ballast [26-28]. With the shortage of those reinforcement methods, a new method for reinforcement and the way to treat deteriorated ballast become a hot topic.

In addition, these studies illustrated the behaviour of deteriorated ballast, proposed a standard to distinguish the deteriorated ballast, or suggested methods for performance improvement. The ballast bed in operation commonly consists of deteriorated and fresh ballast because of ballast degradation or ballast renewal. The behaviour of the mixture is still not clear at present, and further works need to be carried out.

The ballast renewal operation is a method using fresh ballast to reinforce deteriorated ballast bed, in reverse, adding cleaned and re-sieved deteriorated ballast (i.e. recycled ballast) into fresh ballast also can be a reuse method. However, in this aspect, the current research is limited, and the proportion of recycled ballast which does not influence the whole required performance is not clear. Thus, except for the performance of the mixture of deteriorated and fresh ballast, the criterion proportion is also needed to be found out.

Towards this research gap, the performance of deteriorated ballast mixed with fresh ballast is studied with experimental tests and numerical simulation. The direct shear test is utilised to measure the mixture shear strength, and DEM direct shear test model is applied to study the mesoscopic behaviour, including the contact forces, coordination numbers and displacements of ballast particles. This research assists in disposing the waste ballast and proposing the guidance for ballast bed maintenance.

2. Experimental tests

2.1 material specifications

The deteriorated ballast was mixed with fresh ballast in different ratio of 10%, 20%, 30%, and 50% by weight. Moreover, fresh ballast only (0%) and deteriorated ballast only (100%) is concluded as reference groups. The strength and deformation behaviour is tested by a series of large-scale direct shear tests.

The fresh ballast, used in this research, was obtained from crushed basalt, which is in accordance with the Code for Design of High Speed Railway (TB/T2140-2008, China [29]). Tab. 1 shows the particle size distribution (PSD), and Tab.2 shows the main mechanical properties of ballast particles.

Tab. 1 PSD of ballast particles

Sieve Size (mm)	5-31.5	22.4	31.5	40	50	63
Ballast % Passing	71	0	7	33	71	100
TB/T2140-2008 % Passing	⩾50	0	1-25	30-65	70-99	100

Tab. 2 Characteristics of ballast

Properties	Test value	Standard value
LAA (%)	17.8	⩽18
Aggregate Crushing Test (%)	6.9	＜8
Bulk Unit Weight kg/m^3	2630	＞2550
Ratio of flat particle	5	⩽18
Ratio of elongated particle	7	⩽18

The deteriorated ballast was obtained from LAA machine using the fresh ballast. According to standard LAA test procedure (by BS EN 1097-2:2010 [30] and ASTM C-131-01[31]), the abrasion process was conducted at a speed of 32 r/min and for 500 rolling turns. After the tests, all of the deteriorated ballast was washed, dried, which defined as the recycled ballast. Five deteriorated ballast particles are shown in Fig. 1. Afterwards, the recycled ballast particles were sieved and mixed according to the PSD as shown in Tab. 1.

Fig.1 Recycle ballast after cleaning

In this paper, 7 different specimens were used, which is fresh ballast only, 10% recycled ballast and 90% fresh ballast; 20% recycled ballast and 80% fresh ballast; 30% recycled ballast and 70% fresh ballast; 50% recycled ballast and 50% fresh ballast; recycled ballast only. The specimens are shown as Fig.2.


a) fresh ballast only


b) 10% recycled ballast


c) 20% recycled ballast


d) 30% recycled ballast


e) 40% recycled ballast


f) 50% recycled ballast


g) recycled ballast only

Fig. 2 7 specimens depending on the mixing ratio of recycled ballast

2.2 Direct shear test

The direct shear test is a basic mechanical test for granular materials and can present several proprieties of the material, such as shear strength, cohesion and friction angle. The properties influence the interaction between particles, which is the main concern when applying the deteriorated-fresh ballast mixture.

The large-scale strain-controlled direct shear apparatus is shown as Fig.4. It consists of one lower and one upper shear box with different sizes. Where the inner size of lower box is 600mm×700mm in plane and 250mm in height, while the upper box is 600mm×600mm in plane and 300 mm in height a cover plate with size at 595 × 595 mm (providing the normal stress). Behind the lower box and the foundation, serval cylinder bearings are set to decrease the friction.

Direct shear test is a basic mechanical test for granular materials, it can present several proprieties of the material, such as shear strength, cohesion and friction angle which influence the interaction between particles. In this paper, the mechanical behaviour of degraded-fresh ballast is evaluated by the direct shear test, and the large-scale strain-controlled direct shear apparatus is shown as Fig.3. It consists of one lower and one upper shear box with different sizes. Where the inner size of lower box is 600mm×700mm in plane and 250mm in height, while the upper box is 600mm×600mm in plane and 300mm in height with a cover plate in 595mm×595mm to transmit the normal stress. Behind the lower box and the foundation, serval bearings are set to decrease the friction, and 4 bearings are installed in the side in case the box rotation when pushing.

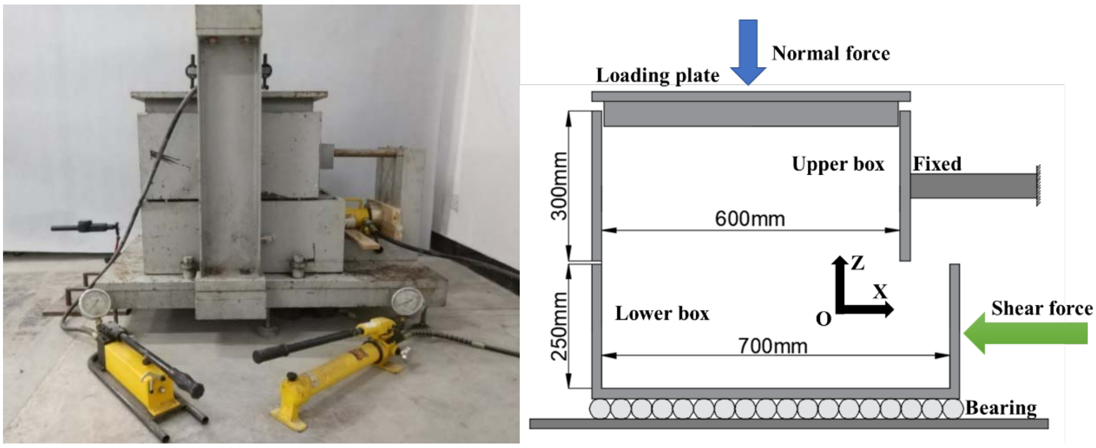


Fig.3 Large-scale direct shear apparatus

The recycled-fresh ballast mixture was filled in the shear box and compacted by layers using a vibrating compactor. Each layer is 100mm height, and the total weight of 359kg was controlled to reach the same porosity (0.3) in every specimen. A certain normal stress (50kPa, 100kPa or 200kPa) was applied to the mixed sample using hydraulic jack, and the weight of the loading plate is considered as a part of normal stress. Under the consistent vertical pressure, the sample was sheared with a loading rate of 0.3mm/min by horizontally pushing the bottom shear box. The lateral displacement and vertical displacement were recorded by LVDT with the accuracy at 0.001 mm, and a pressure sensor connected with data logger INV3018A was used to measure the lateral shearing forces during the test. The maximum horizontal displacement was set to 60 mm, which equals to 10% strain in total. Every condition was tested 3 times, and the results were presented by the average value.

3. Test results

3.1 Shear strength

Fig.4 shows the shear stresses of different proportion of recycled ballast: 0%, 10%, 20% 30%, 50%, 100% under different normal stresses.

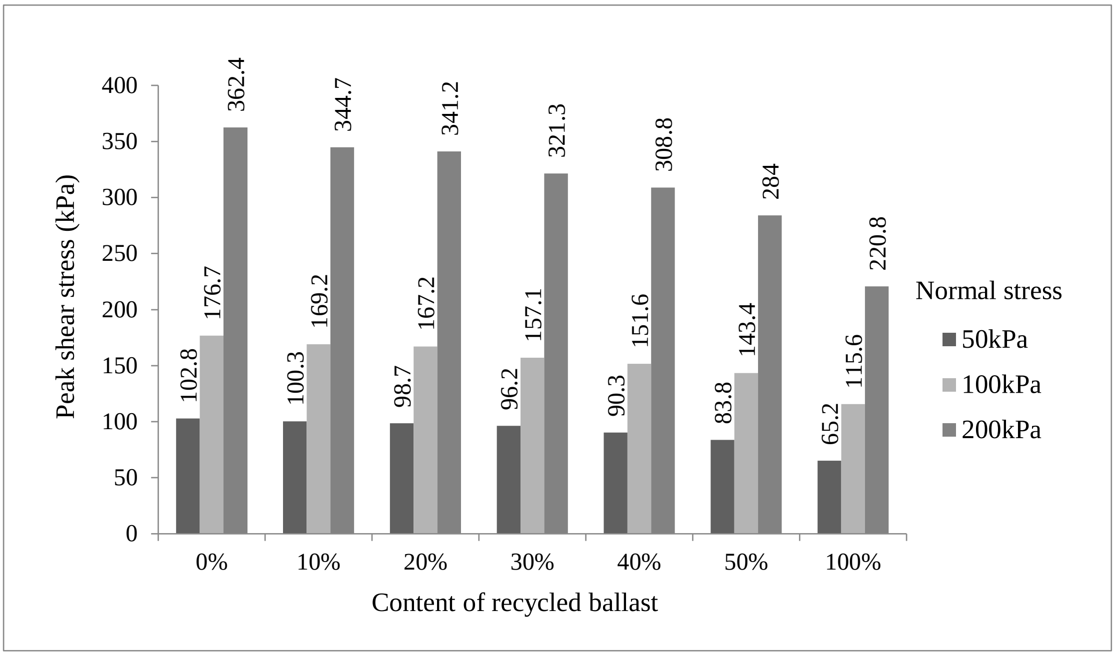


Fig. 4 Shear strength under different normal stresses

In the case of normal stress of 50kPa, 100kPa and 200kPa, the shear strength of recycled ballast is only 65.2 kPa, 115.6 kPa and 220.8 kPa, respectively. Comparing to the data of pure fresh ballast, the strength is significantly decreased by 34.6%, 36.5%, 39.1%, respectively. As for 10% recycled ballast mixture compared with pure fresh ballast, 2%, 4%, and 5% reduction can be observed. When the proportion of recycled ballast increases to 20%, the decreasing percentage is 4%, 5%, 6%. Those reductions are all below or near 5% which can be defined as insignificant influences. For 30% recycled ballast, the decreasing ratio is a little larger with 6%, 11% 11%, respectively. Thus, in the aspect of the shear stress, the mixtures which below 30% recycled ballast can be regarded as well-function. However, when the mixing proportion of recycled ballast is larger than 30%, the reduction ratio exceeds 20%, which strongly influences the shear strength of ballast.

The main differences between fresh and recycled ballast are the angularity and surface texture, and those two parameters influence the cohesion and friction of ballast particles, Fig.5 shows the linear fitting of data and referring to Eq.1, the cohesion and friction angle can be acquired [32], and the results are shown in Tab.3.

$$\tau_f = c + \sigma_n \tan\psi \qquad \text{Eq.1}$$

where: c——cohesion; ψ——friction angle

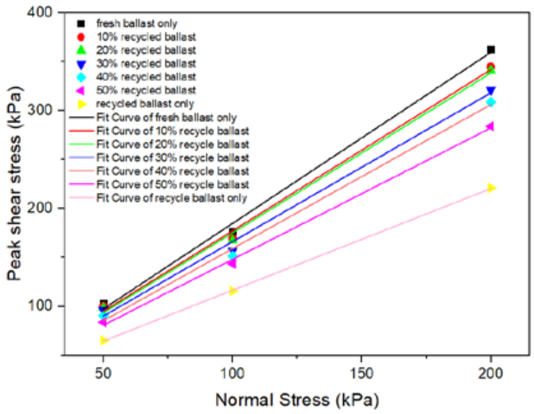


Fig.5 Linear fitting between normal stress and shear stress

Tab.3 Cohesion and friction angel by linear fitting

Content of recycled ballast	Cohesion (kPa)	Friction angle (degree)	R^2
fresh ballast only (0%)	9.95	60.27	0.99426
10% recycled ballast	12.55	58.77	0.99361
20% recycled ballast	11.7	58.56	0.99374
30% recycled ballast	14.1	56.71	0.99053
40% recycled ballast	11.7	55.85	0.99327
50% recycled ballast	13.5	53.39	0.99690
recycled ballast only (100%)	12.6	46.13	0.99978

It can be seen that the friction angle of pure fresh ballast is 60.27°. When mixed with 10% and 20% recycled ballast, the friction angles are slightly lower but very close to that of pure fresh ballast. When the proportion of recycled ballast is over 30%, the friction angle reduces considerably, and the lowest value is observed form pure recycled ballast (46.13°). Comparing to fresh ballast, recycle ballast has less angularity and smoother surface texture due to abrasion. Those changes influence the contacts between particles, thus the interlock between ballast particles is weakened and the rounder particles are easier to rotate.

3.2 Deformation characteristics

Fig.6 shows the average evolution of ballast shear dilatancy for 7 different proportion of recycled ballast. Under 100kPa, the shear dilatancy of fresh ballast is 5.0223 mm, and the value increases to 5.32~5.93 when mixing with 10%, 20%, and 30% recycled ballast, and 6.2208 mm with 40% recycled ballast. A similar trend can be seen under the normal stress of 50kPa and 100kPa. That is to say, with the mixing proportion of recycled ballast under 30%, the shear dilatancy increases within 1 mm, thus the deformation characteristic is in the same level. However, when the proportion of recycled ballast is no less than 30%, it has significant influences on the shear dilatancy, the data was increased by more than 20% and even by 70% for the pure recycled ballast, comparing with fresh ballast. In addition, with the normal stress increasing, the displacements at the peak shear force decreases for the specimen with same mixing proportion. Moreover, it appears that the higher proportion of fresh ballast is used, the lower shear dilatancy is observed. It demonstrates that the addition of fresh ballast can reduce ballast shear dilatancy.

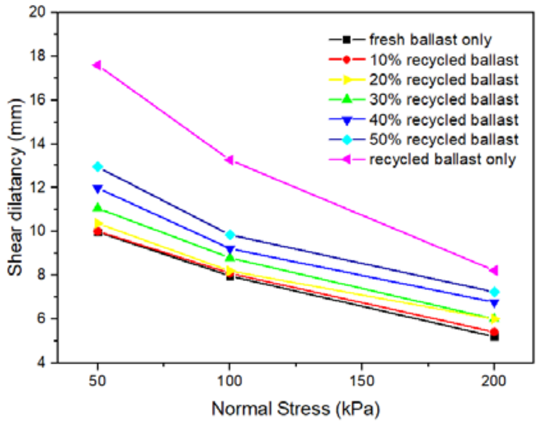


Fig.6 Shear dilatancy

4. DEM simulation

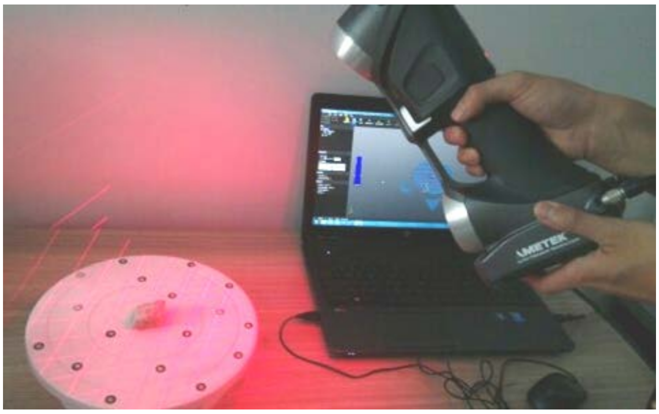
As a conventional test, the direct shear test is widely applied for characterising the mechanical properties of granular materials [33-36]. However, the experimental tests can only obtain macroscopic behaviour of ballast, and the interlock of particles cannot be observed or recorded. The discrete element method (DEM) has been widely used to simulate granular materials. In this method, the discrete nature of ballast particles can be simulated accurately by providing an insight into the mechanical characteristics. Thus, the contact number, contact force distributions, etc., which are difficult to measure in laboratory can be obtained. In this paper, DEM simulations are carried out with PFC^{3D} corresponding to experimental test.

4.1 Ballast particles

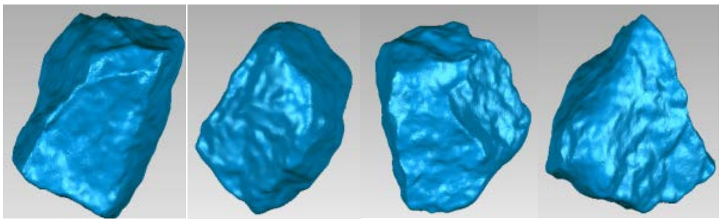
Particle shape is one important factor influencing the ballast characteristics in the DEM stimulation [37-39]. To generate the irregular particles, Tutumluer et al [40] employed the BLOCKS3D in deformation analysis, and Ngo et al [41-42] used non-overlapping spheres to present ballast particles in dynamic analysis and overlapping spheres in direct shear simulations. All of them stressed the importance of ballast particle shape.

Therefore, 3-D scanning based on laser equipment was used for shape obtaining in this research. One ballast particle is firstly placed on a white pedestal with black dots and then scanned by the laser lights. The white pedestal rotates slowly to help to get a whole particle vision. The point cloud data of ballast surface were obtained in this stage. Then, according to the point data, a closed curve surface of scanned ballast was built. The precision of this curve surface is related to the accuracy of scanning devices. With laser scanner, a very close morphology can be obtained and saved as a shape file [43].

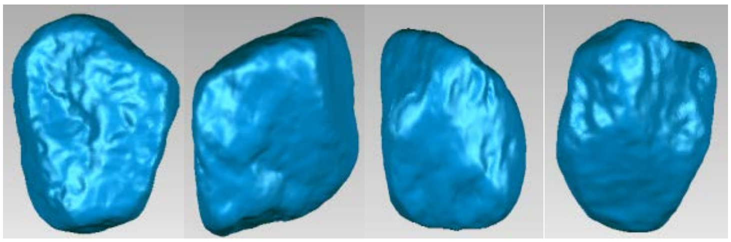
In this study, 50 fresh ballast and 50 recycled ballast particles were selected randomly, afterwards, scanned by the hand-held laser scanner (Handy Scan 700TM) with an accuracy of 0.030 mm. the scanning process is shown in Fig.7 (a), and the shape of fresh and recycled ballast is shown in Fig.7 (b) and (c). Further, those shape files are imported in PFC^{3D} as a template to generate ballast particles.



a) The hand-held laser scanner



b) Fresh ballast

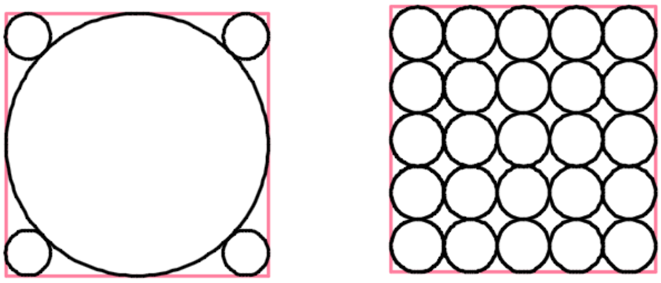


c) Recycled ballast

Fig.7 3D scanning setup

In the present method, clump is model in PFC which can generate irregular shape. After importing the template of a real shape of ballast, the volume of that is filled optimally with overlapping spheres at different sizes and those spheres are bonded as a whole particle. When the number of spheres inside the clump is enough, it can accurately present the shape of ballast particles. However, such a clump could hardly be usable in a DEM simulation as it would require huge amount of calculation time [39]. Therefore, different settings need to be included in the template to intentionally simplify the particle shape and limit the number of spheres for one clump, finally reducing the computational time.

In the process of clump generation in PFC^{3D}, two main parameters are used, i.e. the Ratio and the Distance [44]. The Ratio is corresponding to the radius of the smallest to largest spheres kept in the clump with the value of 0 to 1. Fig.8 illustrates the simplified definition of the Ratio in 2D, where the square is a template for clump generation, and the disks are basic elements. With the Ratio increase, the template is filled with more disks to reach a similar filling status in a corner, but the more disks are used, the more contacts are generated, thus causing the reduction in calculation efficient.

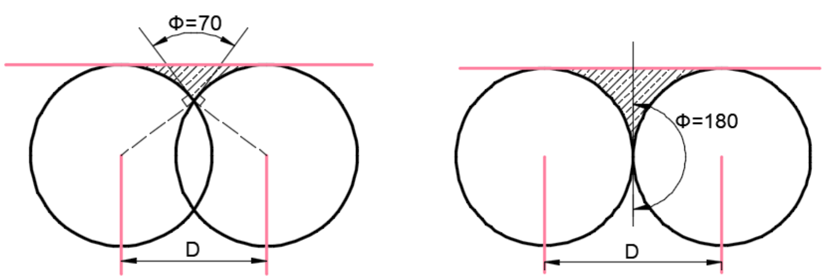


a) Ratio=0.2 b) Ratio=1

Fig.8 Simplified definition of the Ratio

The Distance is corresponding to an angular measure of smoothness which can be used to present the angularity changes between deteriorated and fresh ballast. the value of it varies from 0 to 180, corresponding to the angle of the tangent line in the point of intersection, which is simplified in 2D and illustrated as Fig.9.

As the definition, the Distance is a parameter which can control the filling status of the border, with the value decrease, the blank in the border (the shadow in Fig.9) is smaller. Small Distance value leads to the higher calculation cost by more disks filled in the template. It should be noticed that those 2 parameters cannot by applied severally. For example, the Distance in Fig.8 is 180, and the Ratio in Fig.9 is 1. Besides, in a ballast template, the border is roughness with surface texture, and the corner is irregular with angularity.

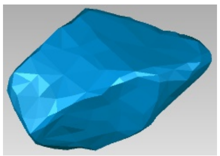
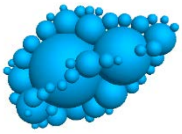
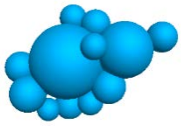
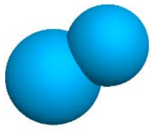
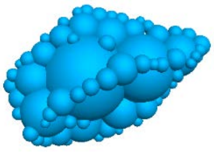
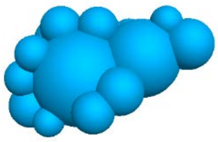
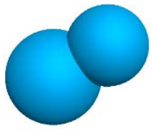
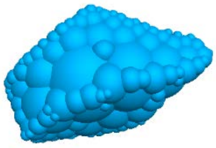
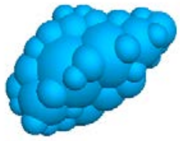
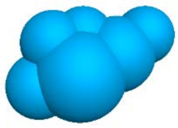
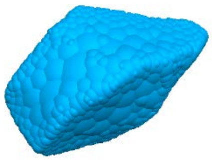
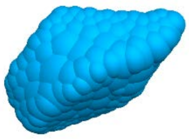
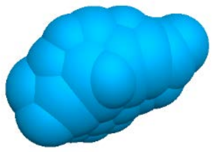


a) Distance=70 b) Distance=180

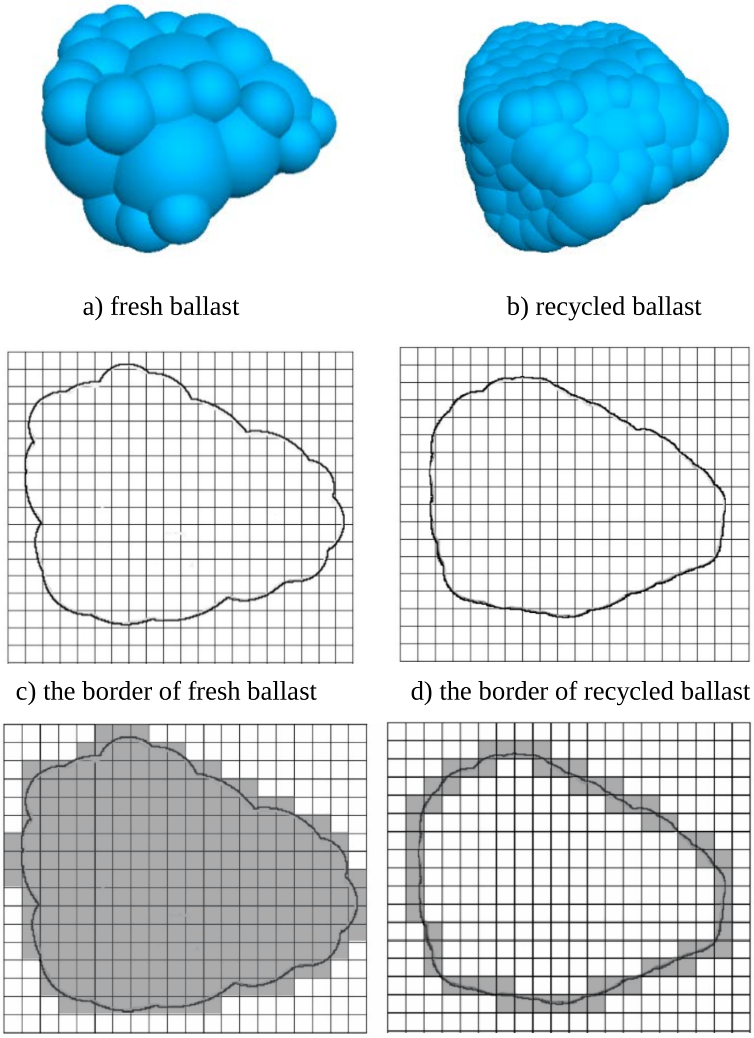
Fig.9 Simplified definition of the Distance

Furthermore, the combination of Distance and Ratio is analysed aiming to generated reasonable ballast particles. As shown in Tab.4, several ballast particles with different parameters are created using the same scanned ballast template. From those outputs, the Ratio less than 0.3 and Distance bigger than 120 can be regarded as reasonable parameters to present ballast shape.

Tab.4 The combination of Distance and Ratio

	Ratio 0.1	Ratio 0.3	Ratio 0.6
Distance 60			
Distance 90			
Distance 120			
Distance 150			

In addition, image analysis as an advanced method that can determine the degradation status of ballast [5] is employed in this part. To qualify the influence of the parameters, two clumps are generated with one template, where the clump in Fig.10 (a) is set with more angularity with Distance 120, Ratio 0.3 to present fresh ballast, and the clump in Fig.10 (b) is smoother with Distance 150, Ratio 0.3 to present recycled ballast. The border of those 2 ballast models is exported in 2D image as Fig.10 (c) and (d) for roundness calculation.



a) fresh ballast   b) recycled ballast

c) the border of fresh ballast   d) the border of recycled ballast

e) the sketch map of A f) the sketch map of p

Fig. 10 Ballast particle models in DEM simulations

By the method of Janoo et al [45], the roundness can be calculated with the following Eq. 2

$$R_n = \frac{4\pi A}{p^2} \qquad \text{Eq. 2}$$

In Eq.2, R_n is the Roundness Index (RI), and the value for a perfect circle is 1, which means the most rounded shape. With the value closer to 1 the shape is rounder and less angularity. A is the area of the particle projection corresponding to the number of pixels (0.2639mm/pixel) within the border, as shown in Fig. 10(e), and p is the perimeter of the particle corresponding to the number of pixels surrounding the ballast, as shown in Fig.10 (f). According to Eq.2, the RI of fresh ballast is 0.6737, and the value for recycled ballast is 0.7729. In this regard, the difference between those two kinds of ballast can be presented.

Another characteristic of deteriorated and fresh ballast, different frictional coefficient is used to present the wear of the surface texture. The linear contact model is selected for ballast particles due to its cohesion-less physics [46] and the mechanical parameters of the ballast particles and the shear box in PFC^{3D} are summarised in Tab.5, which are referred from former studies [47-48] and verified corresponding to laboratory tests. The influence of ballast breakage and abrasion in direct shear test is negligible, to enhance the efficiency of calculation, those behaviour was not included in the simulation.

Tab. 5 Parameters of linear contact model in simulations

Parameters	Fresh Ballast	recycled ballast	Shear box
Distance	120	150	-
Ratio	0.3	0.3	-
Tangential stiffness(N/m)	$1e^8$	$1e^8$	$6e^8$
Normal stiffness(N/m)	$1e^8$	$1e^8$	$6e^8$
Friction coefficient	0.5	0.47	0.2
Mass density(kg/m^3)		2630	
Damping coefficient		0.7	

4.2 Direct shear test model

The modelled ballast particles are fill in the shear box model (wall element) with porosity of 0.3 by the method of particle replacement and radius expanding (McDowell et al [49]). In the first stage, balls were filled in the shear box with required PSD and cycled to a relevant dense state using self-gravity. Then record the radius and the address of sphere centre, and using clump replace those balls with the recorded information. After this procedure, the clump in shear box has reached a dense state. However, the contact forces between clumps are not balanced, for this radius expending method was used to adjust the size of clump. Specifically, a random very small expansion coefficient such as 0.9971 or 1.0043 was applied to clump radius, thus modifying the contact status between particles, finally reaching the stabilised state. During this procedure, the radius is expanded slightly and the PSD has slight change, but it still stays at the setting curve with the unbalance force well-settled.

The direct shear was achieved by moving the lower boundary walls with a constant velocity of 6 mm/s until a total lateral displacement of 60 mm (10% strain). Meanwhile, a constant normal stress was provided by servo system. The DEM model is shown in Fig. 11, where the different colours are corresponding to various particle sizes.

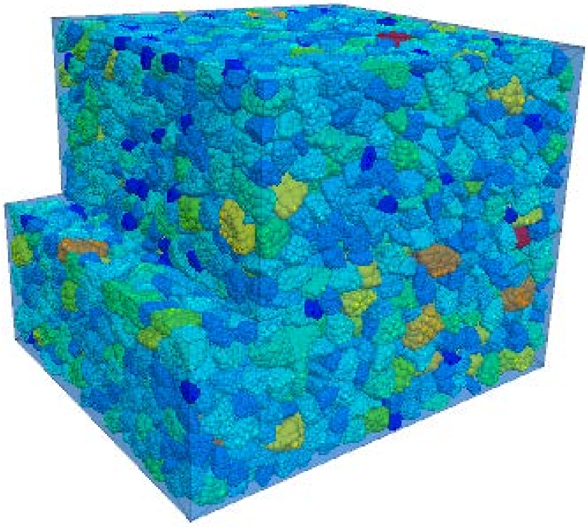
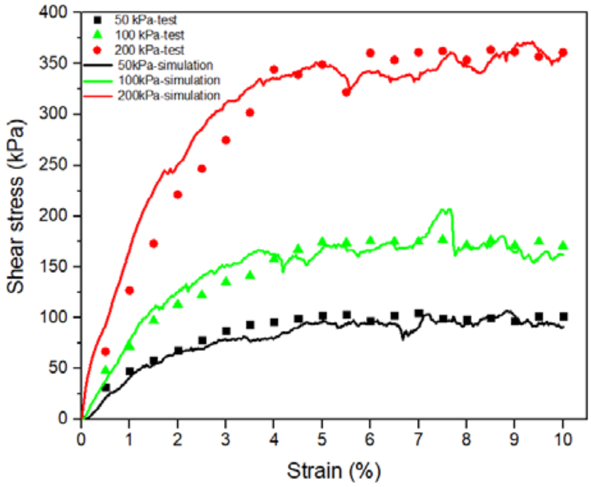


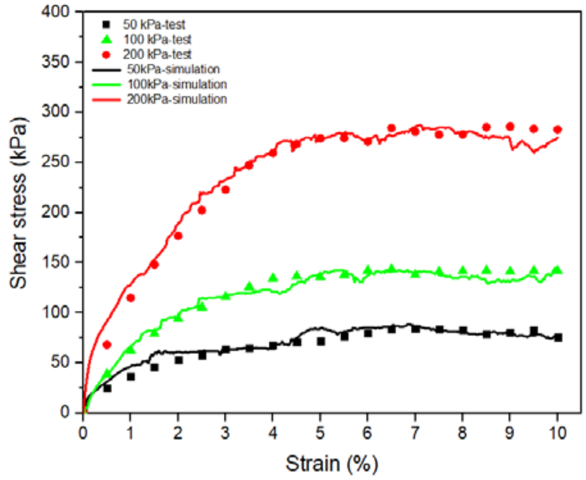
Fig. 11 The DEM numerical model of ballast direct shear test

4.3 Verification

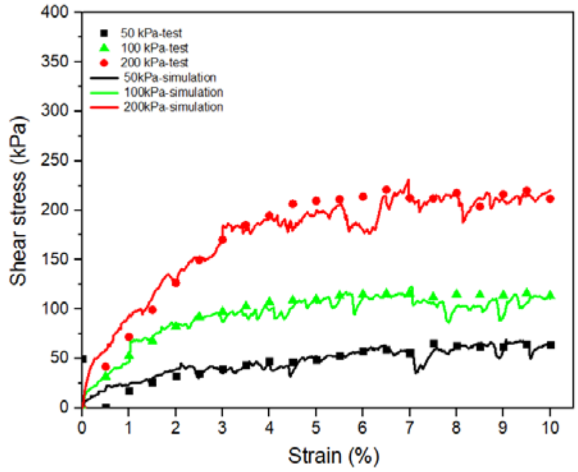
The strain-stress curve of simulations and laboratory test of pure fresh ballast, 50% recycled ballast and pure recycled ballast are shown in Fig.12, where the peak data and changing trend is highly matched. Therefore, the simulation method used in this paper can be regarded as valid and reliable.



a) fresh ballast only



b) 50% recycled ballast



c) recycled ballast only

Fig.12 Comparison of the simulation and the laboratory test results

5. Results of numerical simulation

Fig.13 shows the average coordination number (CN) of ballasts with different proportion of recycled ballast subjected to different normal stresses (50, 100 and 200kPa). Results present that the CN increased with the normal stress, and it increased with the proportion of fresh ballast due to tighter interlock between fresh ballast. Comparing with fresh ballast only, the CN of recycled ballast only has 1.1-1.7 reduction, which also means that recycled ballast has lower capacity and stability. While, The CN for 10%-30% recycled ballast is similar to fresh ballast, especially under high normal stress. The maximum contact force is shown in Fig.14, fresh ballast only presents higher contact force than mixed with recycled ballast during the shear procedure, and smaller maximum displacement was observed which is shown in Fig. 15. The coarser surface texture of fresh ballast contributes more friction thus making particles harder to rotate and displace. Combining these results, it can be concluded that the contact characteristics of fresh ballast are advantage over recycled ballast, and fresh ballast can bear higher stress and generate smaller deformation. With the present of recycled, those data are decreased, but with the percentage of 10%-30% recycled ballast, the reduction is insignificant.

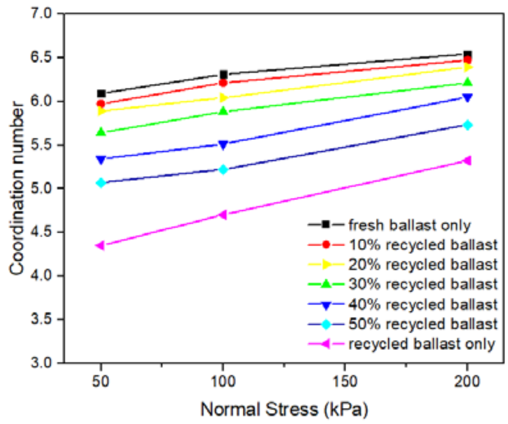


Fig.13 Average coordination number

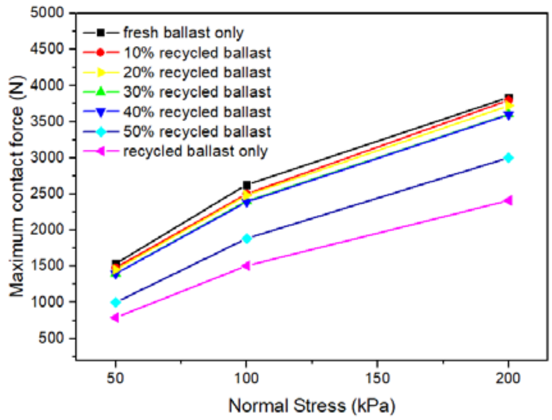


Fig.14 Maximum contact force

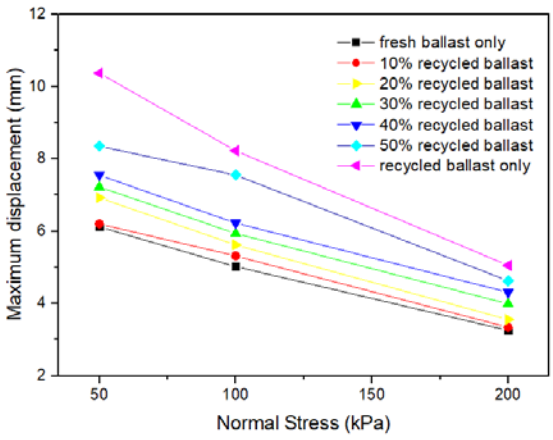


Fig.15 Maximum displacement

6. Conclusion

In this paper, the fresh-recycled ballast mixture was analysed by series of experimental direct shear tests and numerical simulations based on the DEM, with the aim to investigate mechanical characteristics of recycled ballast. The DEM simulations were in good agreement with laboratory results, and the conclusions were given as follows:

- Due to the angularity loss and surface texture reduction, the interlock between recycled ballast is weaker than fresh ballast. With increase of mixing proportion of recycled ballast, the mixture shear strength and friction angle is decreased, and shear dilatancy is increased. Especially for mixture of more than 50% recycled ballast, those changes are significant. However, when the proportion of recycled ballast is smaller than 30%, the reduction in shear stress is negligible.
- In the numerical simulations, clump was used to present ballast particels based on 3D scanning method and different setting of the Ratio and Distance in ballast generation can distinguish the fresh ballast and recycled ballast, making the result more reliable. Both the coordination number and maximum contact force have a downward trend when recycled ballast volume ratio increase, while result in an increase in maximum displacement of ballast particles.
- Recycled ballast behaves with lower level of capacity and stability than fresh ballast, however, it should be highly noted that adding recycled ballast with less than 30% dose not influence the total performance. Thus, adding recycled ballast into fresh ballast could be a method for reusing deteriorated ballast bed under the criterion ratio, also this result can be a guidance for maintenance which using fresh ballast to reinforce recycled ballast.

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References

[1] Hudson A, Watson G, Le Pen L, et al. Remediation of Mud Pumping on a Ballast Railway Track. Procedia Engineering. 2016, 143: 1043-1050.

[2] Selig E T, Waters J M. Track geotechnology and substructure management. Thomas Telford, 1994.

[3] D Angelo G, Thom N, Presti D L. Bitumen stabilized ballast: A potential solution for railway track-bed. Construction and Building Materials. 2016, 124: 118-126.

[4] Wang Z, Jing G, Yu Q, et al. Analysis of ballast direct shear tests by discrete element method under different normal stress. Measurement. 2015, 63: 17-24.

[5] Yunlong Guo, Valeri Markine, Xuehui Zhang, Weile Qiang, Guoqing Jing. Image analysis for morphology, rheology and degradation study of railway ballast: A review. Transportation Geotechnics. 2019(18):173-211.

[6] Indraratna B, Tennakoon N C, Nimbalkar S S, et al. Behaviour of clay-fouled ballast under drained triaxial testing. Geotechnique: international journal of soil mechanics. 2013, 5(63): 410-419.

[7] Indraratna B, Nimbalkar S, Rujikiatkamjorn C. Enhancement of rail track performance through utilisation of geosynthetic inclusions. Geotech. Eng. Jl. of the SEAGS & AGSSEA. 2014, 45(1): 17-27.

[8] Xuecheng Bian, Wei Li, Jing Hu, Hongming Liu, Xiang Duan, Yunmin Chen. Geodynamics of high-speed railway. Transportation Geotechnics. 2018(17):69-76.

[9] N. Jimenez-Redondo, N. Bosso, L. Zeni, A. Minardo, F. Schubert, F. Heinicke, A. Simroth, Automated and cost effective maintenance for railway (acem-rail), Transport Res. Arena 48 (2012) 1058–1067.

[10] UIC- International Union of railways 2015. Rail Transport and Environment Facts and Figures.

[11] Ebrahimi A, Tinjum J M, Edil T B. Deformational behaviour of fouled railway ballast. Canadian Geotechnical Journal. 2014, 52(3): 344-355.

[12] Indraratna B, Salim W. Deformation and degradation mechanics of recycled ballast stabilised with geosynthetics. Soils and Foundations. 2003, 43(4): 35-46.

[13] Nayoma Tennakoon, Indraratna Buddhima, Cholachat Rujikiatkamjorn. The Role of Ballast-Fouling Characteristics on the Drainage Capacity of Rail Substructure. Geotechnical Testing Journal, 2012(35): 629-640

[14] Qian Y , Boler H , Moaveni M , et al. Characterizing Ballast Degradation Through Los Angeles Abrasion Test and Image Analysis. Transportation Research Record: Journal of the Transportation Research Board, 2014, 2448(2448):142-151.

[15] Yunlong Guo, Valeri Markine, Song J, et al. Ballast degradation: Effect of particle size and shape using Los Angeles Abrasion test and image analysis. Construction & Building Materials, 2018, 169:414-424.

[16] M. Sol-Sánchez., G. D'Angelo. Review of the design and maintenance technologies used to decelerate the deterioration of ballast railway tracks. Construction and Building Materials, 2017, 157:402-415.

[17] Atalar C, Das B M , Shin E C , et al. Settlement of geogrid-reinforced railroad bed due to cyclic load. Proc.int.conf.on Soil Mech. & Geothch.engrg, 2001(3):2045-2048.

[18] Egana J I , Vinolas J , Seco M . Investigation of the influence of rail pad stiffness on rail corrugation on a transit system. Wear, 2006, 261(2):216-224.

[19] Jayasuriya C, Indraratna B, Trung Ngoc Ngo. Experimental study to examine the role of under sleeper pads for improved performance of ballast under cyclic loading.Transportation Geotechnics.

2019 (19): 61-73.
[20] Kaewunruen S , Remennikov A . An Experimental Evaluation of the Attenuation Effect of Rail Pad on Flexural Behaviour of Railway Concrete Sleeper under Severe Impact Loads. Australasian Structural Engineering Conference: Engaging with Structural Engineering. Meeting Planners, 2008.
[21] Y. Guo, V. Markine, W. Qiang, H. Zhang, G. Jing, Effects of crumb rubber size and percentage on degradation reduction of railway ballast, Construction and Building Materials 212 (2019) 210-224.
[22] M. Sol-Sánchez, N. H. Thom , F. Moreno-Navarro, et al. A study into the use of crumb rubber in railway ballast[J]. Construction and Building Materials, 2015, 75:19-24.
[23] PK Woodward, Kennedy J, Medero GM, Banimahd M. Application of in situ polyurethane geocomposite beams to improve the passive shoulder resistance of railway track. Proceedings of the Institution of Mechanical Engineers Part F Journal of Rail & Rapid Transit. 2011;3(226)：294-304.
[24] Kruglikov AA, Yavna VA, Ermolov YM, Kochur AG, Khakiev ZB. Strengthening of the railway ballast section shoulder with two-component polymeric binders. Transportation Geotechnics. 2017(11)：133-43.
[25] Lakušić S, Ahac M, Haladin I. Track stability using ballast bonding method. The 10th Slovenian Road & Transportation Congress. Portoroz, Slovenia2010.
[26] Indraratna B, Shahin M A, Salim W. Use of geosynthetics for stabilizing recycledd ballast in railway track substructures. Proceedings of NAGS2005/GRI 19 Cooperative Conference. 2005: 1-15.
[27] Indraratna B, Nimbalkar S, Christie D. The performance of rail track incorporating the effects of ballast breakage, confining pressure and geosynthetic reinforcement. Geotechnical engineering for transportation projects. 2009: 617-626.
[28] Indraratna B, Nimbalkar S, Christie D, et al. Field assessment of the performance of a ballast rail track with and without geosynthetics. Journal of Geotechnical and Geoenvironmental Engineering. 2010, 136(7): 907-917.
[29] TB/T2140-2008. Railway ballast. China, Ministry of Railways, 2008.
[30] British-Adopted European Standard. Tests for mechanical and physical properties of aggregates. Methods for the determination of resistance to fragmentation. BS EN 1097-2:2010
[31] ASTM. Standard Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine, ASTM Designation C-131-01. Philadelphia American Society for Testing Materials, 2006.
[32] Huang H, Tutumluer E, Dombrow W. Laboratory Characterization of Fouled Railroad Ballast Behaviour. Transportation Research Record Journal of the Transportation Research Board, 2009, 2117(2117):93-101.
[33] Simoni A, Houlsby G T. The direct shear strength and dilatancy of sand–gravel mixtures. Geotechnical & Geological Engineering. 2006, 24(3): 523.
[34] Suhr B, Six K. On the effect of stress dependent interparticle friction in direct shear tests. Powder Technology. 2016, 294: 211-220.
[35] Infante D J U, Martinez G M A, Arrua P A, et al. Shear Strength Behaviour of Different Geosynthetic Reinforced Soil Structure from Direct Shear Test. International Journal of Geosynthetics and Ground Engineering. 2016, 2(2): 1-16.
[36] Ngo N T, Indraratna B, Rujikiatkamjorn C. Study on the interface behaviour of a geosynthetics-reinforced fouled ballast using the discrete element method. 2016, 730-738.

[37] Lu M, Mcdowell G R. The importance of modelling ballast particle shape in the discrete element method. Granular matter. 2007, 9(1-2): 69.

[38] Shin H, Santamarina J C. Role of particle angularity on the mechanical behaviour of granular mixtures. Journal of Geotechnical and Geoenvironmental Engineering. 2012, 139(2): 353-355.

[39] Ferellec J, Mcdowell G R. A method to model realistic particle shape and inertia in DEM. Granular Matter. 2010, 12(5): 459-467.

[40] Tutumluer, E., Qian, Y., Hashash, Y.M.A., Ghaboussi, J. and Davis, D.D. Discrete element modelling of ballasted track deformation behaviour. International Journal of Rail Transportation, 2013,1(1-2), pp: 57-73.

[41] Ngo, N.T., B. Indraratna, and C. Rujikiatkamjorn, Simulation Ballasted Track Behavior: Numerical Treatment and Field Application. ASCE-International Journal of Geomechanics, 2017,17(6): p. 04016130.

[42] Ngo, N.T., Indraratna, B. and Rujikiatkamjorn, C. DEM simulation of the behaviour of geogrid stabilised ballast fouled with coal." Computers and Geotechnics, 2014,55: 224-231.

[43] Zhang X , Zhao C , Zhai W . DEM Analysis of Ballast Breakage Under Train Loads and Its Effect on Mechanical Behaviour of Railway Track. International Conference on Discrete Element Methods. Springer Singapore, 2016.

[44] PFC3D User's Mamual (Version 5.0). Minnesota Itasca Consulting Group Inc, 2015.

[45] V. Janoo. Quantification of shape, angularity, and surface texture of base course materials. Hanover (NH): Cold Regions Research and Engineering Lab; 1998.

[46] J. Liu, P. Wang, J. Liu. Macro-and micro-mechanical characteristics of crushed rock aggregate subjected to direct shearing. Transportation Geotechnics. 2015, 2: 10-19.

[47] Lim W L, Mcdowell G R. Discrete element modelling of railway ballast. Granular Matter. 2005, 7(1): 19-29.

[48] Ferellec J, Mcdowell G. Modelling realistic shape and particle inertia in DEM. Geotechnique. 2010, 60(3): 227-232.

[49] McDowell, G.R., Harireche, O., Konietzky, H., Brown, S.F. and Thom, N.H. Discrete element modelling of geogrid-reinforced aggregates. Proceedings of the ICE - Geotechnical Engineering 2006,159(1): 35-48.