A Laboratory Investigation on the Advancement of Railway Ballast Behavior Using Artificial Inclusions

S. Venuja, S. K. Navaratnarajah, T. H. V. P. Wickramasinghe, and D. S. A. Wanigasekara

Abstract Ballasted rail tracks are the most popular and conventional rail track foundation system primarily consists of ballast as a major portion by weight and volume. Ballast is a highly angular, coarser material with high bearing capacity, shear strength, and non-water absorbent, which is obtained by crushing rocks. The ballast layer absorbs and widely distributes the moving train loads from sleepers to the ground. With time, the ballast is deteriorated because of frequent cyclic and impact loads from train movements, which ended up with high-cost maintenance. Artificial inclusions are renowned remedial action to the above-mentioned issue. In this laboratory-based study, the effect of rubber pads and geogrids on the shear and deterioration behavior of ballast was evaluated by conducting large-scale direct shear tests under 30, 60, and 90 kPa normal loads with a shearing rate of 4 mm/min. Based on the experimental results, a combination of shock mats and geogrid is suggested which enhanced the stress, dilation, and deterioration behavior of railway ballast.

Keywords Ballast · Shear strength · Deterioration · Rubber pads · Geogrids

1 Introduction

Ballast is produced by crushing accessible natural rocks such as granite, basalt, dolomite, gneiss, and rheolite. These coarse aggregates are packed below and around the crossties to transmit the stresses from sleepers to the underneath layer such as the capping layer and subgrade. Stresses transferred from the superstructure to the ballast layer depend on dead and live loads from the superstructure, spacing, and properties of sleepers, gradation, and level of compaction of ballast, ballast depth as well as subgrade conditions. These repeated dynamic and impact loads cause ballast deterioration. Ballast aggregates undergo breakage and these crushed materials clog the voids in the ballast layer causing drainage hindrance. Ballast may penetrate the formation and blow away due to excessive loads. This may lead to

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differential track settlement and loss of track geometry thus leads to safety issues. Therefore, regular monitoring and maintenance are required which involves high expenses [9, 15, 17, 25].

Degradation behavior of ballast and enhancement of ballast performance with artificial inclusions were analyzed in many ways such as conducting laboratory tests like direct shear tests, triaxial tests, impact load tests, truncated pyramid load tests, and dynamic load tests [1, 6, 14, 16, 18, 27, 28], numerical simulations using *PLAXIS 2D*, *PLAXIS 3D*, *ABAQUS*, *Midas*, and *DEM* [2, 3, 5, 13, 23] and field tests such as plate load test, single tie push test, static load test, field instrumentation and monitoring [4, 10, 24]. Rubber mats and geosynthetics are the major types of artificial inclusions in the railway industry. Nowadays, rubber elements from the recycling of waste tires also have been studied for the suitability in rail track performance enhancement through absorbing energy and reducing ballast breakage [12, 22].

Rail pads (RPs), under sleeper pads (USPs), and under ballast mats (UBMs) are examples of rubber mats used in the rail track. Rubber mats create a softer interface between various parts of the rail track structure. Also, it increases the contact area and distributes load through a wider area [11, 16, 18, 21]. USP is placed on top of the ballast under the sleepers where UBM is placed below the ballast bed. Geogrid reduces the lateral movement of ballast aggregates via mechanical interlocking and it reduces subgrade stresses through acting as a tensile element. Soft subgrade condition encourages the higher mobilization of tension in the geogrid thus leads to lower sleeper displacement [7, 10, 19, 20, 29].

In this study, a series of large-scale direct shear tests were conducted on ballast with and without rubber mats and geogrid. All samples were tested under 30, 60, and 90 kPa static normal loads with a constant shearing rate of 4 mm/min up to 15% shear strain. Shear, dilation, and breakage behavior of ballast with and without artificial inclusions were discussed in this paper.

2 Materials and Test Mechanism

2.1 Materials

Fresh biotite gneiss ballast material was collected from Nawalapitiya stockyard. The basic physical properties such as bulk specific gravity, water absorption, aggregate crushing value, aggregate impact value, flakiness index, and elongation index were tested and concluded that the ballast sample is a composition of highly rock fragments. Ballast was sieved using 63, 50, 37.5, 25, and 20 mm sieves to separate particles by size to prepare a test sample according to Indian standard limits for ballast gradation which is adapted by Sri Lankan railways. Then, aggregates were washed thoroughly to remove dust or other coatings from its surface and left for drying. Artificial inclusions used in this study are rubber mats and geogrid shown in Fig. 1. The mechanical properties of the rubber mats (UBM and USP) can be found

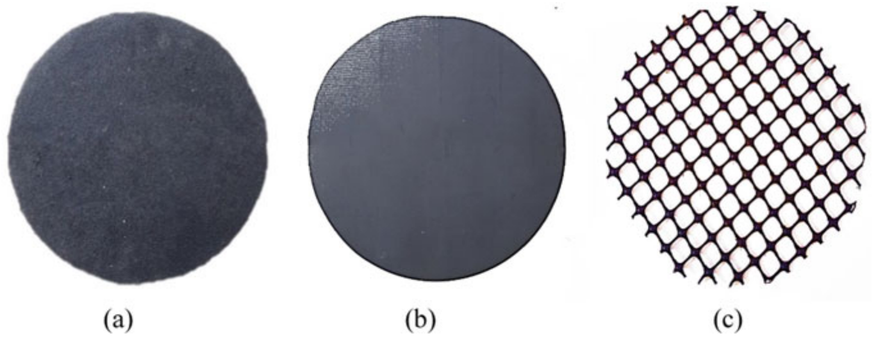

Fig. 1 Artificial inclusions used in this study; **a** UBM; **b** USP; **c** Geogrid

Table 1 Mechanical properties of rubber mats

Material properties	Under ballast mat (UBM)	Under sleeper pad (USP)
Thickness (mm)	10	10
Weight (per unit area) (kg/m^2)	9.2	4.2
Young's modulus (MPa)	6.12	6.0
Bedding modulus, C_{stat} (N/mm^3)	0.20	0.22

in Table 1 [17]. Geogrid has a shear strength of 50 kN/m in both longitudinal and transverse directions as it is an extruded bi-axial polypropylene type.

2.2 *Structure of the Large Scale Direct Shear Test Apparatus*

As ballast is a large size material, the conventional direct shear apparatus is not capable of analyzing the shear behavior of railway ballast. Therefore, a large-scale direct shear test apparatus was built at the Geotechnical Laboratory of the University of Peradeniya. There are different square-shaped and rectangular-shaped large shear boxes which are discussed by researchers from different countries. Figure 2 illustrates the various parts of the large-scale shear test apparatus used in this study. 400 mm diameter and 300 mm depth hollow cylinder is divided into two equal halves and the top half is fixed in position with the support frame where the bottom part is movable only in the horizontal direction. Shear displacement is applied to the bottom part through a manually operated hydraulic jack. The load cell is used to measure the resistance to shearing where the horizontal transducer is used to measure the shear displacement and both are connected to the bottom half of the apparatus. Surcharge pressure is applied on a top plate mounted on the sample using a lever arm technique.

Fig. 2 The large-scale direct shear apparatus

Another transducer attached to the top plate is used to measure the compression and dilation of the sample during shearing.

2.3 *Test Approach*

As the aim of this study is to analyze the shear, dilation, and breakage behavior of ballast various layer types of samples were tested under 30, 60, and 90 kPa surcharge stresses. Different layered samples include fresh ballast, ballast with only UBM, ballast with only USP, ballast with a combination of UBM and USP, and ballast with a combination of UBM and USP along with geogrid. The ballast was filled in three layers into the ballast box. Thus, ballast for each layer was prepared according to the particle size distribution (PSD) shown in Fig. 3 by adding the predetermined mass of different sized particles and mixing with a hand shovel. Each layer was compacted using a rubber-padded hammer to required density to attain a 100 mm overall height.

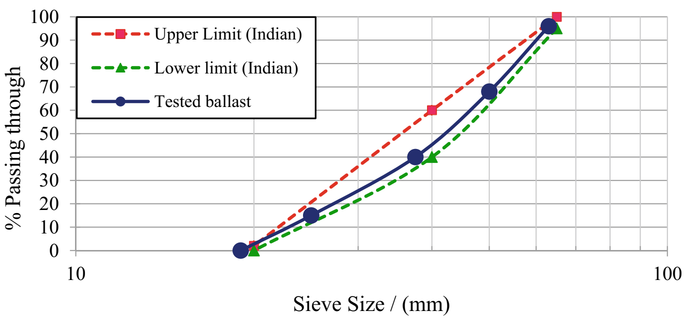

Fig. 3 PSD of tested ballast

UBM was placed at the bottom of the ballast, USP was placed at the top of the ballast, and geogrid was placed on top of the UBM for selected tests. A constant shearing rate of 4 mm/min up to a shear displacement of 60 mm was achieved. The outcomes were obtained from a computer connected with a data logger for automatic recording of shear load, vertical displacement, and shear displacement.

3 Analysis of Experimental Outcomes

3.1 Influence of Artificial Inclusions on Shear and Dilation Behavior of Ballast

Shear load, shear displacement, and vertical displacement were obtained from the data logger for each type of sample. Then, shear stresses of each sample were plotted against the corresponding shear strain (see Fig. 4). An increasing trend up to maximum shear stress was observed in all plots in between 13 and 15% shear strain. With the increase in surcharge load, shear stress increased as higher interlocking between granular particles under greater loads lead to improved frictional resistance.

Under all normal loads, fresh ballast had higher shear stress than the samples with rubber mats and geogrid. Fresh ballast with a combination of UBM, USP, and geogrid showed the second-highest shear stress as the geogrid provides mechanical interlocking to ballast particles [26]. Comparing UBM and USP installed samples, ballast with UBM showed higher shear stress than with USP due to the ballast particle gripping on the UBM and resulted in improved shear resistance. Further, Mohr–Coulomb failure envelopes were developed for each type of sample using the highest shear stress from each test as illustrated in Fig. 5. The friction angle of the ballast was 68° and the lowest value of 59° was obtained for ballast with USP.

3.2 Influence of Artificial Inclusions on Breakage Behavior of Ballast

Ballast particles experienced angular corner breakage, fracture, grinding, and breaking into minor particles as shearing and normal stress applied to the ballast sample. The method proposed by Indraratna et al. [8] was adopted in this study to calculate the ballast breakage index (BBI). The bar graph of BBI of various samples under three normal loads is elaborated in Fig. 6. Higher normal loads compress the ballast sample thus the possibility of higher breakage and higher BBI. BBI values indicated that the ballast breakage is minimal when a combination of USP and UBM is installed. Resilient rubber pads allow ballast particles to partially compress into the smooth surface and USP resulted in a uniform distribution of normal load to the

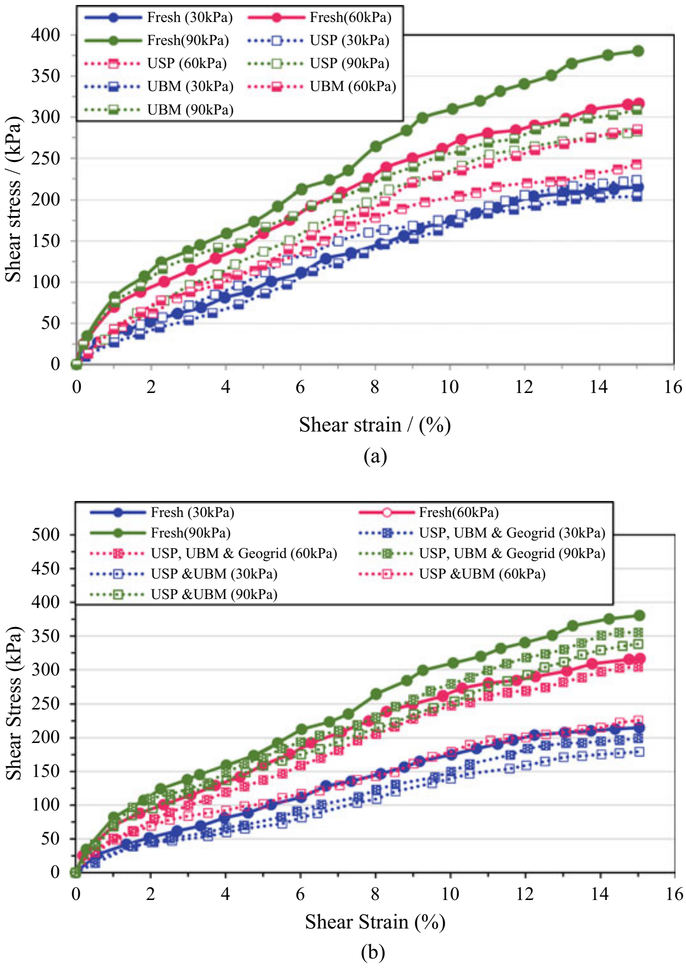

Fig. 4 Shear stress variation with shear strain of ballast; **a** only one artificial inclusion; **b** a combination of artificial inclusions

ballast in a wider area thus lower BBI [22]. The inclusion of geogrid on top of UBM did not influence the change in BBI compared to ballast with both USP and UBM.

As the shear displacement is applied at the bottom part and normal load varies with the depth, the variation in breakage potential was examined by calculating BBI of three layers like top, middle and bottom layers separated using painting each layer in different colors. Higher BBI was observed in the middle layer as the shear plane is fixed in the middle of the test apparatus.

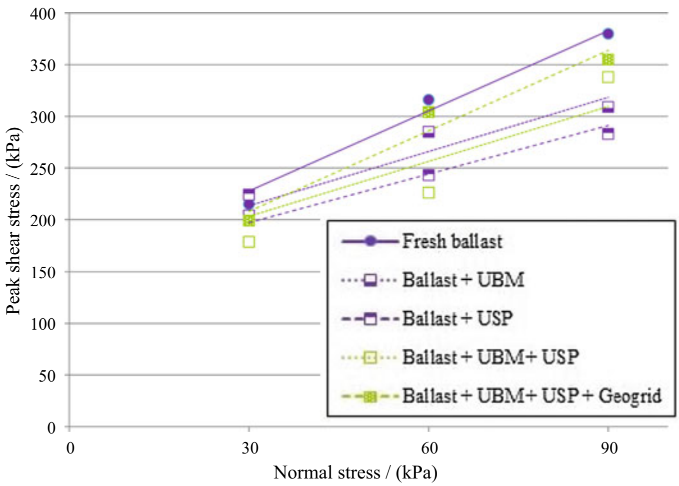

Fig. 5 Peak shear stress variation with normal stresses

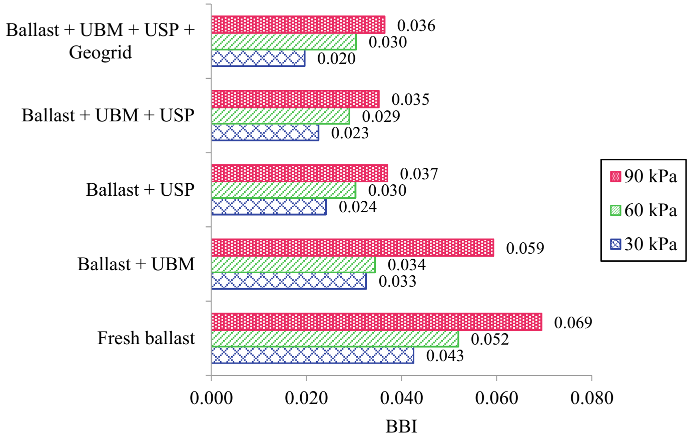

Fig. 6 BBI of various samples under different normal stresses

4 Conclusions

The conducted static load tests on ballast clearly showed that the artificial inclusions, as well as applied normal stress, have an impact on the shear and breakage behavior of ballast. Shear stress and friction angle of fresh ballast were greater than that for ballast with artificial inclusions. Ballast with a combination of rubber pads and geogrid showed closer shear stress values as of fresh ballast and reduced the ballast breakage nearly half of fresh ballast. Further, ballast breakage significantly reduced with a combination of artificial inclusions as the rubber element acted as a cushion and distributed the load more uniformly to the ballast. A combination of rubber mats along with geogrid is suggested as it gives nearly the same shear behavior as ballast and drastically reduces the ballast breakage. This study is limited to check the influence of artificial inclusions under static loads.

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References

1. Biabani MM, Indraratna B, Nimbalkar S (2016) Assessment of interface shear behaviour of sub-ballast with geosynthetics by large-scale direct shear test. Procedia Eng 143:1007–1015
2. Chawla S, Banerjee L, Dash SK (2018) Three dimensional finite element analyses of geocell reinforced railway tracks. In: Indian geotechnical conference, Bengaluru, India, pp 1–5
3. Chen C, McDowell GR, Thom N (2013) A study of geogrid-reinforced ballast using laboratory pull-out tests and discrete element modelling. Geomech Geoeng 8(4):244–253
4. Esmaeili M, Zakeri JA, Babaei M (2017) Laboratory and field investigation of the effect of geogrid-reinforced ballast on railway track lateral resistance. Geotext Geomembr 45(2):23–33
5. Fattah MY, Mahmood MR, Aswad MF (2017) Experimental and numerical behavior of railway track over geogrid reinforced ballast underlain by soft clay. In: International Congress and Exhibition Sustainable Civil Infrastructures: Innovative Infrastructure Geotechnology. Springer, Berlin, pp 1–26
6. Huang H, Tutumluer E, Dombrow W (2009) Laboratory characterization of fouled railroad ballast behavior. Transp Res Rec 2117(1):93–101
7. Hussaini SKK, Indraratna B, Vinod J (2018) A Critical review of the performance of geosynthetic-reinforced railroad ballast. Geotech Eng 49(4):31–41
8. Indraratna B, Lackenby J, Christie D (2005) Effect of confining pressure on the degradation of ballast under cyclic loading. Geotech Inst Civil Eng 55(4):325–328
9. Indraratna B, Navaratnarajah SK, Nimbalkar S, Rujikiatkamjiorn C (2014) Use of shock mats for enhanced stability of railroad track foundation. Austr Geomech J 49(4):101–110
10. Indraratna B, Navaratnarajah SK, Nimbalkar S, Rujikiatkamjorn C, Neville T (2015) Performance monitoring: case studies of tracks stabilised by geosynthetic grids and prefabricated vertical drains. In: Field measurements in geomechanics, Sydney, pp 233–246
11. Indraratna B, Qi Y, Tawk M, Heitor A, Rujikiatkamjorn C, Navaratnarajah SK (2020) Advances in ground improvement using waste materials for transportation infrastructure. In: Proceedings of the Institution of Civil Engineers—Ground Improvement, pp 1–44
12. Jayasuriya C, Indraratna B, Rujikiatkamjorn C, Navaratnarajah SK (2020) Application of elastic inclusions to improve the performance of ballasted track. In: Geo-Congress 2020: Engineering, Monitoring, and Management of Geotechnical Infrastructure. American Society of Civil Engineers Reston, VA, pp 364–373
13. Jiang Y, Nimbalkar SS (2019) Finite element modelling of ballasted rail track capturing effects of geosynthetic inclusions. Front Built Environ 5:69(1–11)
14. Leshchinsky BA (2011) Enhancing ballast performance using geocell confinement. In: Geofrontiers 2011: advances in geotechnical engineering, pp 4693–4702
15. Mishra A, Goyal S, Muttharam M, Nanthakumar S (2018) Study on the performance of railway ballasted track reinforced with geogrid. Indian J Sci Technol 11(23):1–4

16. Navaratnarajah S, Indraratna B, Nimbalkar S (2015) Performance of rail ballast stabilized with resilient rubber pads under cyclic and impact loading. In: International conference on geotechnical engineering, Colombo, pp 617–620
17. Navaratnarajah SK (2017) Application of rubber inclusions to enhance the stability of ballasted rail track under cyclic loading. Ph.D. thesis, University of Wollongong. Available at: https://ro.uow.edu.au/theses1/51
18. Navaratnarajah SK (2019) Resilient element attached under the concrete sleepers to improve the rail track performances. J Eastern Asia Soc Transport Stud 13:2506–2520
19. Navaratnarajah SK, Gunawardhana KRCM, Gunawardhana MASP (2020) Influence of type of interfaces on railway ballast behavior. In: ICSECM 2019, Lecture notes in civil engineering. Springer, Berlin, pp 243–251
20. Navaratnarajah SK, Indraratna B (2017) Use of rubber mats to improve the deformation and degradation behavior of rail ballast under cyclic loading. J Geotech Geoenviron Eng 143(6):1–15
21. Navaratnarajah SK, Indraratna B (2018) Application of under sleeper pads to enhance the sleeper-ballast interface behaviours. In: Indian geotechnical conference, Bengaluru, pp 1–8
22. Navaratnarajah SK, Indraratna B (2020) Stabilisation of stiffer rail track substructure using artificial inclusion. Indian Geotech J 50(2):196–203
23. Navaratnarajah SK, Indraratna B, Ngo NT (2018) Influence of under sleeper pads on ballast behavior under cyclic loading: experimental and numerical studies. J Geotech Geoenviron Eng 144(9):1–16
24. Ngo NT, Indraratna B, Bessa Ferreira F, Rujikiatkamjorn C (2018) Improved performance of geosynthetics enhanced ballast: laboratory and numerical studies. Proc Inst Civil Eng Ground Improve 171(4):202–222
25. Sun Q (2020) Numerical simulation of the dynamic response of ballasted track overlying a tire-reinforced capping layer. Front Built Environ 6:1–15
26. Sweta K, Hussaini SKK (2018) Effect of shearing rate on the behavior of geogrid-reinforced railroad ballast under direct shear conditions. Geotext Geomembr 46(3):251–256
27. Sweta K, Hussaini SKK (2019) Behavior evaluation of geogrid-reinforced ballast-subballast interface under shear condition. Geotext Geomembr 47(1):23–31
28. Tennakoon N, Indraratna B, Rujikiatkamjorn C, Nimbalkar S (2012) Assessment of ballast fouling and its implications on track drainage. In: 11th Australia–New Zealand conference on geomechanics: ground engineering in a changing world, pp 421–426
29. Venuja S, Navaratnarajah SK, Bandara CS, Jayasinghe JASC (2020) Review on geosynthetic inclusions for the enhancement of ballasted rail tracks. In: ICSECM 2019, Lecture notes in civil engineering. Springer, Berlin, pp 459–468