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Sd K Karimullah Hussaini
University of Wollongong

Buddhima Indraratna
University of Wollongong, indra@uow.edu.au

J S. Vinod
University of Wollongong, vinod@uow.edu.au

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Performance of geosynthetically-reinforced rail ballast in direct shear conditions

Sd K Karimullah Hussaini[1], Buddhima Indraratna[2] and J.S. Vinod[3]

[1] PhD Student, Centre for Geomechanics and Railway Engineering, University of Wollongong, Wollongong 2522 NSW, Australia Email: kkhs545@uowmail.edu.au
[2]Professor Professor of Civil Engineering and Research Director, Centre for Geomechanics and Railway Engineering; Program Leader, ARC Centre of Excellence for Geotechnical Science and Engineering; University of Wollongong, Wollongong, NSW 2522, Australia; PH (+61) 2 4221 3046; FAX (+61) 2 4221 3238; email indra@uow.edu.au
[3] Senior Lecturer, Centre for Geomechanics and Railway Engineering, University of Wollongong, Wollongong, NSW 2522, Australia; PH (+61) 2 4221 5852; FAX (+61) 2 4221 3238; Email: vinod@uow.edu.au

ABSTRACT
In the recent past the use of geosynthetic-reinforcement to stabilise the rail tracks has been on the rise. The performance of such reinforced track is governed by the shear behavior of the ballast-geosynthetic interface. In view of this, large-scale direct shear tests were performed to explore the shear behaviour of rail ballast-geogrid interfaces. Fresh Latite ballast with an average particle size (D_{50}) of 35 mm, and geogrids with different aperture sizes and shapes were used for this purpose. The laboratory experimental results indicate that the shear strength of ballast can be improved significantly when reinforced with geosynthetics, but the degree of effectiveness depends on the aperture to particle size ratios. It is expected that this study will assist rail engineers in selecting suitable geosynthetics for stabilising a given ballast gradation, to reduce track maintenance costs.

Keywords: Ballast, geosynthetic-reinforcement, ballast-geosynthetic interface, average particle size (D_{50}), large-scale direct shear tests, geosynthetics.

1 INTRODUCTION
In order to meet the demand of increasing number of rail commuters, railways face the challenge of increasing the competitiveness and attractiveness of rail transport in terms of speed, increased tonnages, higher frequency and reliability. This in turn necessitates enhanced quality of track that depends on the better functioning of ballast, an important component of rail track. However, there have been numerous track problems caused by the densification, degradation and lateral spreading of ballast. Track maintenance costs across Australia are substantial, and are now estimated at about 14-15 million dollars per annum in the state of NSW alone. Therefore, it is important to inhibit the lateral spreading of ballast to optimise the track performance and reduce the maintenance costs.

One of the promising approaches to improve the track performance is to reinforce the ballast with geosynthetics. Once in place, the geogrid-reinforcement offers the following major benefits to the rail industry (i) Firstly, it holds the ballast in place by restraining its lateral movement thereby preventing the track settlement and rail misalignment (ii) Secondly, it increases the confining pressure on ballast thereby reducing particle degradation that helps maintaining the ballast angularity and track shear strength. With regards to the position of reinforcement, several researchers have argued that the beneficial effects of reinforcement in the form of reduction in track settlement could be enhanced considerably by placing the geogrid within the ballast (Brown et al., 2007; Indraratna et al., 2007). However, the effectiveness of reinforcement in providing the aforementioned benefits depends on the level of interaction between ballast and geogrid. In such a scenario, the ballast-geogrid interface shear strength could be treated as a measure of the ability of geogrid to inhibit the lateral spread of particles; thus, providing guideline about its suitability as reinforcing material for stabilising ballast. In view of this, large-scale direct shear tests were performed to explore the shear behaviour of rail ballast-geogrid interfaces.

2 MATERIALS AND METHOD OF TESTING
Laboratory tests were carried out using large-scale direct shear apparatus. It consists of two 300 x 300 mm square boxes, the upper immovable box being 100 mm deep and the lower, moveable box being 90 mm deep. Fresh Latite ballast from Bombo quarry, NSW, Australia, conforming to the

standards specified by Technical Specification TS 3402 of RIC, and a particle size distribution (PSD) conforming to AS 2758.7 was used for the investigation (Figure 1).

Two geogrids with different aperture sizes (labelled G2 and G3) were used in this current study, and their physical characteristics and technical specifications are listed in Table 1. Tests were also conducted for ballast-geotextile (GT) interface to compare with the use of geogrids. The specimens were prepared by thorough mixing of sieved ballast as per the selected gradation curve shown in Figure 1. The mixed sample was placed and compacted in three layers to achieve the desired field density of 1550 kg/m^3. The compaction was carried using an electric vibrator. To minimize particle breakage during vibration, a 5 mm thick rubber pad was placed underneath the vibrator. Geogrid was placed at the interface of upper and lower boxes and then tests were conducted at normal pressures of 26.3, 38.5, 52.5 and 61.0 kPa, at a constant shear rate of 2.75 mm/min. Fresh samples of aggregates and geosynthetics were used for each test. All the tests were conducted up to a shear displacement of 36 mm.

Table 1 Physical characteristics and technical specifications of the geogrids used for the study

Geosynthetic type	*Aperture type*	*Rib thickness (mm)*	*Aperture size (mm)*	*T_{ult}^{a} (kN/m)*
G2	Triangular	2.0	36 x 36	19
G3	Square	1.7	65 x 65	30

[a]ultimate tensile strength

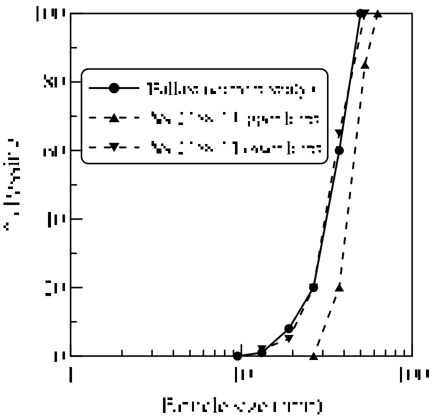

Figure 1 Particle size distribution of ballast used in the current study

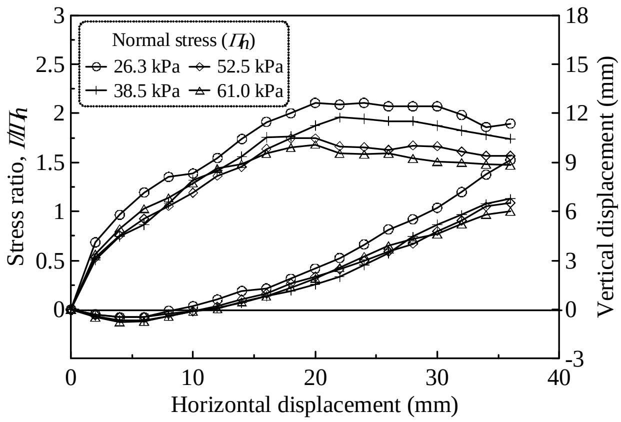

Figure 2 Plots of stress ratio (τ/σ_n) and vertical displacement versus horizontal displacement for unreinforced ballast (data from Indraratna et al.2012)

3 RESULTS AND DISCUSSION

The shear behaviour of the interfaces with respect to the normal stress (σ_n) is plotted in the form of stress ratio (τ/σ_n) and vertical displacement versus horizontal displacement for unreinforced and reinforced (G3) conditions (Figures 2 and 3). It is observed that τ/σ_n increases with horizontal displacement and attains a peak value at 18-21 mm horizontal displacement and exhibit slight strain softening thereafter. Moreover, it is clear that τ/σ_n decreases with σ_n for both unreinforced and reinforced ballast. The volumetric behaviour shows an initial compression of the specimen until horizontal displacement of about 9 mm followed by dilation, and a decrease in vertical displacement with increasing σ_n. Figure 4 shows the effect of geogrid type on the shear behaviour of the interfaces. It is observed from Figure 4 that the use of geogrid G3 increases τ/σ_n ratio in comparison to unreinforced ballast. However, ballast reinforced with G2 and GT exhibit lower values of τ/σ_n compared to unreinforced ballast. The fluctuations in the post peak shear strength could be attributed to the subsequent loss and gain of interlock.

Interface efficiency factor (α)

The effectiveness of reinforcement could be evaluated based on the interface efficiency factor (α), which is defined as the ratio of the shear strength of the interface to the internal shear strength of the soil and given by Equation 1 (Koerner 1998),

$$\alpha = \tan\delta/\tan\varphi \qquad (1)$$

Where, δ is the apparent friction angle of the interface and φ is the friction angle of the soil.

The interface efficiency factor (α) for various ballast-geosynthetic interfaces are summarised in Table 2.

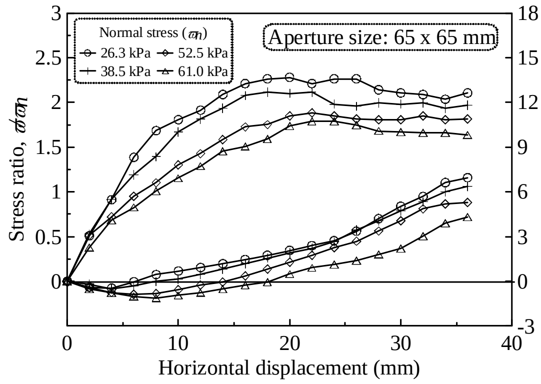

Figure 3 Plots of stress ratio (τ/σ_n) and vertical displacement versus horizontal displacement for reinforced ballast (G3)

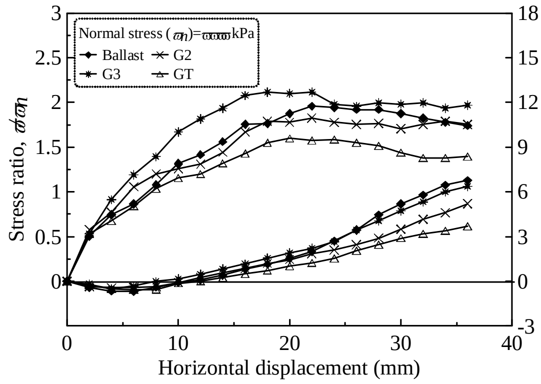

Figure 4 Comparison of stress ratio (τ/σ_n) and vertical displacement versus horizontal displacement for unreinforced and reinforced ballast

The increase in shear strength of ballast-G3 interface in comparison to the internal shear strength of ballast is attributed to the particle-geogrid interlock that prevents the free sliding of particles. In practical sense, the interlocking of particles in the geogrid apertures depicts the ability of geogrid to arrest the lateral spreading of ballast and impose non-displacement boundary conditions under the track operating conditions. In this view, an efficiency factor of greater than unity highlights the beneficial effects of reinforcement in keeping the ballast in its place; thus, preventing excessive vertical settlement, avoiding rail misalignment and potential derailment.

The very low interface shear strength in case of ballast-geotextile interface ($\alpha = 0.8$), due to the lack of interlocking, indicates that geotextile is not suitable for inhibiting the lateral spreading of ballast; and thus is not a good choice for the track reinforcement. In this context, it can be said that the use of geotextile is analogous to the introduction of a weak interface within the otherwise strong ballast assembly.

Table 2 Efficiency factors for the ballast-geosynthetic interfaces

Geosynthetic type	*Interface efficiency factor (α)*
G2	0.9
G3	1.08
GT	0.8

4 FACTORS INFLUENCING THE BALLAST-GEOGRID INTERFACE SHEAR STRENGTH

The various factors that influence the shear strength at the ballast-geogrid interface are identified and presented in the following section.

4.1 Geogrid aperture size (*A*)

The role of geogrid aperture size (*A*) on the ballast-geogrid interface shear strength is presented in the form of variation of average interface efficiency factor (α) with A/D_{50} ratio (Figure 5). It is seen that the value of α for ballast-geogrid interfaces is always greater than that for ballast-geotextile interface. This is because of interlocking of particles in case of ballast-geogrid interfaces, which is completely absent in case of geotextile reinforcement of ballast. For ballast-geogrid interfaces it is further noted that the interface shear strength attained depends on the degree of interlock between ballast and the geogrid, which is a function of A/D_{50} ratio. A closer observation of Figure 5 reveals that the effect of larger geogrid aperture size for a given particle gradation is neutral, if not beneficial, in contrast to the smaller geogrid aperture size which is detrimental in terms of the interface shear strength. Based on the degree of interlock attained, Indraratna et al. (2012) has classified the ratio A/D_{50} into three primary zones, as described below.

Feeble interlock zone (FIZ): For $0 < A/D_{50} < 0.95$, relatively smaller particles interlock and hence, the values of α are less than unity. In this zone, the particle-grid interlock is weaker than the inter-particle interaction achieved without geosynthetics as the particle-grid interlock here is attributed to smaller particles alone ($< 0.95\ D_{50}$) in comparison to the inter-particle interlock with respect to all sizes.

Optimum interlock zone (OIZ): For $0.95 < A/D_{50} < 1.20$, interlocking of relatively larger particles occurs thereby leading to the values of α exceeding unity. The value of α attains a maximum of 1.16 at an optimum A/D_{50} ratio of about 1.20.

Diminishing interlock zone (DIZ): For $A/D_{50} > 1.20$, the values of α are greater than unity but the degree of interlocking decreases rapidly leading to a reduction in α with increasing A/D_{50} ratio. With the increasing A/D_{50}, the free movement of relatively small particles within the aperture boundary approaches the displacement condition of unreinforced ballast and hence the value of α decreases gradually and becomes approximately unity at A/D_{50} of 2.50.

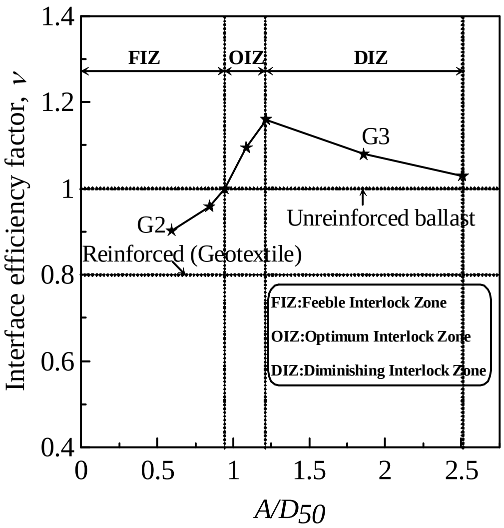

Figure 5 Interface efficiency factor (α) versus A/D_{50}, a dimensionless parameter (data from Indraratna et al. 2012)

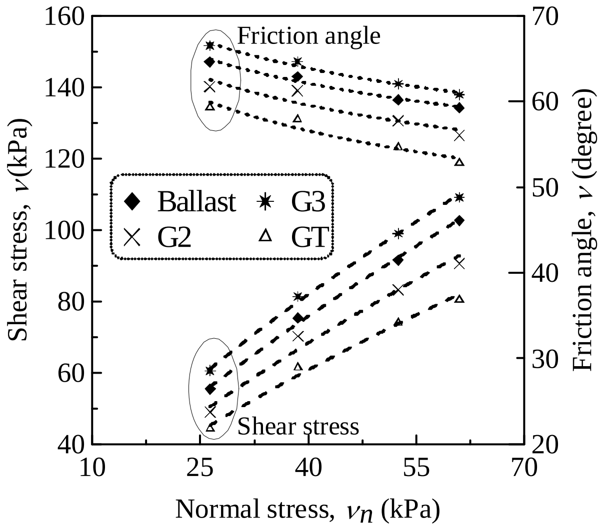

Figure 6 Variation of shear stress, and friction angle of ballast and ballast-geosynthetic interfaces with normal stress

4.2 Applied normal stress (σ_n)

The effect of applied normal stress, σ_n on the shear strength and friction angle of ballast and ballast-geosynthetic interfaces is shown in Figure 6. It is seen that the shear strength of both ballast and ballast-geosynthetic interfaces increases non-linearly with the increase in σ_n. This is mainly due to the decrease of dilation at higher values of σ_n. A significant reduction in the apparent friction angle (δ) of ballast-G3 interface from about 66^o to 60^o is observed when the applied normal stress is increased from 25 to 61 kPa. The apparent friction angle of other ballast-geosynthetic interfaces follows a similar trend with normal stress.

The effect of applied normal stress (σ_n) on the interface efficiency factor (α) is shown in Table 3. It is seen that the efficiency factor for a given ballast-geosynthetic interface is almost constant with the applied normal stress (σ_n), suggesting that the attained interface shear strength or the degree of ballast-geogrid interlock is primarily a function of the ratio A/D_{50} alone. Therefore, it can be said that the degree of interlocking achieved is primarily a function of geometrical dimensions/sizes of materials at the interface, i.e. both geogrid and ballast. This implies that the extent of reduction in dilation due to the increase in normal stress is constant irrespective of whether the ballast is in the unreinforced or reinforced state. In other words, both ballast and ballast-geosynthetic interfaces exhibit similar degree of non-linearity at low normal stresses. This fact is further substantiated by the similar range of *n* values computed as per the normalised shear stress-normal stress relationship given by Indraratna et al. (1998) for unreinforced and reinforced ballast (Indraratna et al., 2012).

Table 3 Efficiency factors of ballast-geosynthetic interfaces with normal stress (σ_n)

Geosynthetic type	*Interface efficiency factor (α)*			
	σ_n= 26.3 kPa	σ_n= 38.5 kPa	σ_n= 52.5 kPa	σ_n= 61.0 kPa
G2	0.89	0.92	0.9	0.88
G3	1.09	1.08	1.08	1.06
GT	0.8	0.81	0.8	0.79

4.3 Geogrid aperture shape

The effect of aperture shape on the shear strength of ballast-geogrid interfaces, for a given aperture size, could not be established owing to the limited range of geogrids with triangular apertures commercially available in the market. The only available geogrid with triangular apertures gave an interface efficiency factor of less than unity owing to its relatively small aperture size (A/D_{50} of 0.6 in this case). However, in case of $0.95 < A/D_{50} < 2.5$ it is anticipated that triangular apertures would lead to better and stable interlock as any interlocked particle needs only three contacts to attain stability (one with each side of the aperture), the least for any aperture shape. Once the desired interlock is attained the triangular geometry of the aperture gives less room for the particle movement; thus, enhancing the stability of interlocked particles. Also, the geogrid with triangular apertures would lead to isotropic stress distribution (Dong et al., 2010). However, further research is needed to establish the effect of aperture shape on the stability of the interlocked particles and hence on the interface shear strength.

5 CONCLUSIONS

The behaviour of various ballast-geosynthetic interfaces has been explored in the current study. It is shown that the shear strength of both ballast and ballast-geosynthetic interfaces increases non-linearly with the increase in σ_n. The apparent friction angle of ballast-G3 interface decreases non-linearly from about 66^o to 60^o as the applied normal stress increases from about 25 to 60 kPa. The apparent friction angle of other ballast-geosynthetic interfaces follows a similar trend with normal stress.

It is shown the shear strength of ballast can be improved significantly when reinforced with geosynthetics, but the degree of effectiveness depends on the aperture to particle size ratios. The study highlights the importance of proper selection of geogrid aperture size to stabilise the ballast of given gradation. With regards to the aperture size, the effect of bigger geogrid aperture size for a given particle gradation appears to be neutral, if not beneficial, in contrast to the smaller geogrid aperture size which is detrimental in terms of the interface shear strength and hence in arresting the lateral spread of ballast in a typical rail track. Owing to the absence of interlocking, geotextile is not suitable for inhibiting the lateral spread of ballast and thus is not a good choice for the track reinforcement. For the range of normal stresses used in this current study, it is shown that the value of α for a given ballast-geosynthetic interface is independent of applied normal stress, which suggests that both ballast and ballast-geosynthetic interfaces exhibit similar degree of non-linearity at relatively low confining pressures ($\sigma_n < 100$ kPa).

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