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Improvement of recycled ballast using geosynthetics

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ABSTRACT: Railway ballast degrades and deteriorates progressively under heavy cyclic loading. The degraded ballast is usually replaced by fresh ballast in routine track maintenance schemes. The waste ballast may be cleaned and re-used in the track. However, the settlement and lateral deformation of recycled ballast are generally excessive, which cannot be tolerated considering the safety, high speed of new trains, and passenger comfort. This paper presents the stabilisation and improvement of recycled ballast bed by inserting geosynthetic reinforcement at the ballast/capping interface. Laboratory model experiments were conducted simulating the field load and boundary conditions. Cyclic triaxial tests were carried out on recycled ballast with and without geosynthetic reinforcement. The test results are compared with those of fresh ballast. The research findings indicate that the recycled ballast stabilised with geosynthetic reinforcement has a good potential in rail track construction and maintenance.

1 INTRODUCTION

Increasing track maintenance cost is becoming a major concern for the railway authorities in Australia. A major portion of track maintenance cost is associated with ballast related problems (Indraratna et al. 1998). Ballast particles are degraded in track under heavy cyclic rail traffic loading, causing the degraded fine particles to fill the voids between larger aggregates, thereby reducing the drainage properties. Additionally, the crushed particles form a thin layer surrounding larger particles, hence, increase the compressibility. In severe cases, the fouled ballast needs to be cleaned or replaced with fresh ballast, in order to keep the track in its desired level and alignment.

In New South Wales (NSW), Australia, the ballast maintenance cost is considerably high compared to other national and international railways (Dowson, 1994). For example, in NSW, the ballast maintenance cost is over 15 million dollars per year. In order to reduce this huge cost, Rail Infrastructure Corporation (RIC) of NSW, in collaboration with the University of Wollongong, has initiated a major research programme to investigate the potential use of recycled ballast with various geosynthetics in rail track construction. The purpose of adding a geosynthetic layer in recycled ballast is to compensate for the loss of bearing capacity, shear strength and dynamic resiliency occurred during the previous degradation and fouling process in track.

In the past, the behaviour of ballast under dynamic loading was studied using large triaxial chamber with rigid cell walls. Some investigators in the recent days (Atalar et al. 2001) are still using rigid wall box in simulating railway foundations. In actual railway tracks, lateral displacement of ballast is not fully restrained (Indraratna et al. 2001). The confinement due to the rigid walls is, therefore, a major shortcoming in modelling ballast degradations and associated settlements. In the recent past, semi-confined devices have been used by several investigators (Jeffs & Marich, 1987; Norman & Selig, 1983). In order to simulate lateral movement of ballast properly under dynamic rail traffic loading, a large-scale cubical triaxial rig with movable walls was designed at the University of Wollongong, and built with the assistance of Rail Services Australia. Recently, Indraratna et al. (2001) reported the behaviour of freshly quarried ballast under static and dynamic loading conditions. In this study, the behaviour of recycled ballast and its improvement using geosynthetic reinforcement has been investigated under cyclic loading conditions using the cubical triaxial apparatus. Two types of reinforcement (geogrid and geogrid-geotextile composite) were used in the current study. Two cyclic load tests were conducted on fresh and recycled ballast without any reinforcement. Two tests were carried out on dry recycled ballast stabilised with a geogrid and a geogrid-geotextile composite. Additional two tests were conducted on saturated recycled ballast stabilised with a geogrid and a geogrid-geotextile composite, in order to simulate the track under flooded condition. This paper presents the findings of these model experiments, and the results are being discussed to characterise the potential benefits of using different geosynthetics in stabilising recycled ballast.

2 ROLE OF BALLAST

A conventional ballasted track foundation comprised of several graded layers of aggregates placed above compacted sub-grade. The sleepers or ties (made of timber or concrete) are firmly embedded in the top aggregate (ballast) layer. The primary functions of the ballast layer are to:
(1) provide minimal plastic deformation of the track vertically, longitudinally and laterally,
(2) provide the necessary degree of elasticity and resilience for the other track components,
(3) transmit the imposed wheel loading to the formation layer at an acceptable stress level,
(4) facilitate track installation and maintenance operations,
(5) provide adequate drainage of the track structure and,
(6) retard the possible growth of weeds.

Additional functions include tolerable degradation due to cyclic loads and its environment, and resisting external entry of fine particles so that maintenance and renewal cycles are acceptable (Jeffs, 1989).

Good quality fresh ballast when compacted, can often perform most of the above functions satisfactorily. Due to breakage of sharp angles and corners in the previous cycles of loading, recycled ballast usually offers less frictional resistance, hence higher settlement and lateral deformation compared to those of fresh ballast. Therefore, the performance of recycled ballast in the light of the above functions and its potential improvement using geosynthetics need to be investigated before using it in rail track construction and maintenance.

3 MATERIAL PROPERTIES

3.1 *Ballast characteristics*

The recycled ballast used in the current study was collected from Chullora (Sydney) stockpile. Physical examination indicates that about 90% of the recycled ballast sample is comprised of semi-angular crushed rock fragments, while the remaining 10% consists of semi-rounded river gravels and other impurities (cemented materials, sleeper fragments etc.). The fresh ballast was collected from Bombo quarry (NSW). It represents angular particles of crushed volcanic basalt (latite). A capping layer was used beneath the ballast specimen to act as a filter and separator between the subgrade and ballast bed. A thin layer of compacted clay was used beneath the capping layer. The grain size distribution of ballast and capping layers used in the current investigation is shown in Fig. 1. All ballast specimens (fresh and recycled) were prepared following the same gradation curve (Fig. 1). Table 1 shows the physical characteristics of fresh ballast, recycled ballast and capping materials.

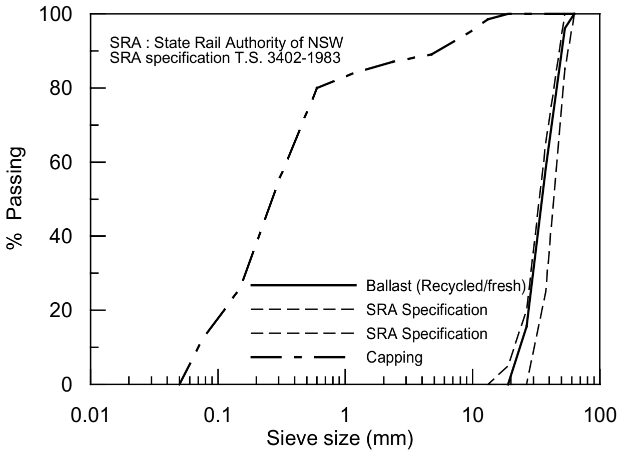

Figure 1. Particle size distribution of ballast and capping layer

Table 1. Grain size characteristics of ballast and capping materials

Material	Particle shape	d_{max} (mm)	d_{min} (mm)	d_{10} (mm)	d_{30} (mm)	d_{50} (mm)	d_{60} (mm)	C_u	C_c
Fresh ballast	Highly angular	63.0	19.0	24.0	30.0	35.0	38.0	1.6	1.0
Recycled ballast	Semi-angular	63.0	19.0	24.0	30.0	35.0	38.0	1.6	1.0
Capping	Angular to rounded	19.0	0.05	0.07	0.17	0.26	0.35	5.0	1.2

3.2 *Properties of geosynthetics*

Two types of geosynthetics were used in the current study to stabilise recycled ballast. One is a geogrid and the other is a geogrid-geotextile composite, both made of polypropylene. The properties of these geosynthetics are given below.

3.2.1 *Geogrid*

The physical and strength characteristics of the geogrid used in the current investigation are given in Tables 2 and 3.

Table 2. Physical properties of geogrid

Characteristics	Unit	Data
Material	-	Polypropylene
Structure	-	Bi-oriented geogrid
Mesh type	-	Rectangular apertures
Aperture size MD	mm	40
Aperture size TD	mm	27
Mass per unit area	g/m^2	420

Note: MD: machine direction; TD: transverse direction

Table 3. Strength characteristics of geogrid

Characteristics	Unit	MD	TD
Tensile strength at 2% strain	kN/m	10.5	10.5
Tensile strength at 5% strain	kN/m	21.0	21.0
Peak tensile strength	kN/m	30.0	30.0
Yield point elongation	%	11.0	10.0

3.2.2 *Geogrid-geotextile composite*

The geogrid-geotextile composites used in the current study are geogrids (Tables 2 and 3) bonded with non-woven polypropylene geotextiles. Use of geocomposite in rail track can provide reinforcement to the ballast layer, as well as providing filtration and separation functions simultaneously. The physical and strength characteristics of the composite are given in Table 4.

Table 4. Characteristics of geogrid-geotextile composite

Characteristics	Unit	Data
Material	-	Polypropylene
Geogrid structure	-	Bi-oriented
Geogrid mesh type	-	Rectangular
Mass of geotextile	g/m^2	120
Mass of composite	g/m^2	560
Peak tensile strength	kN/m	30
Yield point elongation	%	11.0

4 LABORATORY MODEL EXPERIMENTS

4.1 *Large-scale cubical triaxial apparatus*

Ideally, ballast testing should be conducted in the track under actual operating conditions (Jeffs & Marich, 1987). However, the costs involved in such tests are excessive and many variables are difficult to control in the field to enable the formulation of definitive ballast relationships. Therefore, laboratory model experiments are usually performed on railway ballast. To model the cyclic loading response of ballasted track, a large-scale cubical triaxial rig (800 x 600 x 600 mm) was fabricated at the University of Wollongong. In actual railway tracks, the confining pressure is not sufficient to restrict lateral movement of ballast, hence, the cubical triaxial rig (Fig. 2) with unrestrained sides provides an ideal facility for physical modelling of ballast deformation under dynamic loading. In the laboratory model, the vertical cyclic load (σ'_1) is provided by a servo-hydraulic actuator, and the load is transmitted to the ballast through a 100 mm steel ram and rail/sleeper arrangement. A system of hydraulic jacks and load cells attached to the vertical walls of the rig provides the intermediate and minor principal stresses (σ'_2 and σ'_3).

4.2 *Specimen preparation*

In order to model a real track, the cubical triaxial chamber was filled with four layers of subgrade and ballast. The bottom layer consisted of compacted clay of 50 mm thick, to simulate subgrade soil layer of the track. The capping layer (100 mm) was formed of compacted mixture of gravel and sand, to represent sub-base layer. The load bearing ballast (300 mm) and crib ballast (150 mm) layers consisted of fresh or recycled ballast. A timber sleeper and rail segment was placed above the compacted load bearing ballast. The space between the sleeper and the walls was filled with crib ballast. A geosynthetic reinforcement layer was placed, where necessary, at the ballast/capping interface (i.e. the weakest interface), to optimise the performance of recycled ballast. Two pressure cells were installed at the sleeper/ballast and ballast/capping interfaces, to monitor the vertical stresses on the ballast specimen. Eight settlement plates were installed at each of sleeper/ballast and ballast/capping interfaces. The ballast and capping layers were compacted with a vibratory hammer in several layers, each about 75 mm thick, to achieve representative field densities. A 5 mm rubber pad was used beneath the vibrator to minimise the risk of particle breakage during compaction. The bulk unit weights of the compacted ballast layer and capping layer were about 15.3 kN/m^3 and 21.3 kN/m^3, respectively. The initial void ratio (e_o) of ballast layer was about 0.74. All six-test specimens were compacted to the same initial density. The vertical deformations of the sleeper and settlement plates, and the lateral movements of vertical walls were measured using digital vernier callipers and dial gauges.

Figure 2. Large cubical triaxial rig built at the University of Wollongong

4.3 *Test procedure*

After preparing the test specimen, small lateral loads (σ'_2 = 10 kPa and σ'_3 = 7 kPa) were applied to the vertical walls of the triaxial chamber through hydraulic jacks, to simulate field confining stresses. An initial vertical load of 10 kN was applied to stabilise the sleeper and ballast, and to serve as the reference for all settlement and lateral movement measurements. The cyclic load was applied with a maximum load intensity of 73 kN to produce the same average contact stress at the sleeper/ballast interface in the track for a typical 25 tonnes/axle traffic load. The dynamic amplification was calculated following Broadley et al. (1981). The tests were conducted at a frequency of 15 Hz, simulating a train speed of 80 km/hour for a distance of 1.5 m between two axles. The total number of load cycles applied in each test was half a million. The cyclic loading was halted at selected number of load cycles, and the readings of settlement, lateral movement of walls and loading magnitudes were recorded.

5 TEST RESULTS

5.1 *Settlement characteristics*

The behaviour of railway ballast under cyclic loading is highly non-linear, and depends on the stress state (Ionescu et al. 1998). The variation of sleeper settlement under cyclic loading is shown in Fig. 3 for six ballast specimens with and without geosynthetic reinforcement. As expected, fresh ballast specimen tested in dry condition produces the minimum settlement. Recycled ballast alone (without reinforcement) shows higher settlement compared to fresh ballast. Figure 3 also indicates that inclusion of geogrid-geotextile composite in recycled dry ballast improves the settlement characteristics to almost the same extent as of fresh dry ballast. Inclusion of geogrid reinforcement in recycled dry ballast improves the settlement behaviour moderately, but not to the same extent as of the geogrid-geotextile composite. Given that the geogrid apertures (40 mm) are larger than the d_{50} of ballast, (35 mm), it may be anticipated that grids with smaller apertures would reduce the settlements even more. It is expected that the geogrid-geotextile composite would reduce the settlement further in comparison with a geogrid, because, (a) the lateral and out of plane stiffness is greater and (b) the geotextile provides effective separation between the ballast and capping layer. As expected, saturated (wet) specimens show higher settlement compared to the dry specimens, irrespective of type of reinforcement. Saturation of recycled ballast stabilised with geogrid reinforcement increases the settlement considerably. In contrast, saturation of recycled ballast stabilised with geogrid-geotextile composite does not increase the settlement significantly. The filtering function of the geocomposites in preventing the upward migration of saturated subgrade fines under cyclic loading is believed to be one of the key reasons for this behaviour. As shown in Fig. 3, all specimens show an increasing settlement at the initial stages of loading, and stabilise within about 100,000 load cycles, beyond which the settlement increases at a diminishing rate.

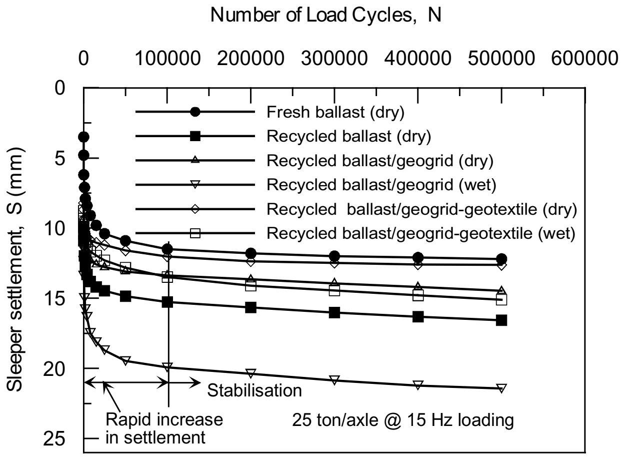

Figure 3. Variation of settlement with number of load cycles

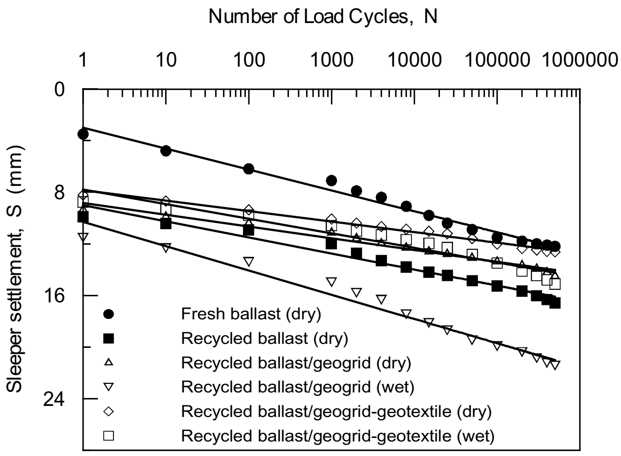

Figure 4. Prediction of sleeper settlement under cyclic loading

Usually, the rail track settlement is related to the number of load cycles by a semi-logarithmic relationship (Raymond et al. 1976; Jeffs and Marich, 1987). Figure 4 shows the settlement-load cycle data plotted in a semi-logarithmic scale, which indicates that the ballast settlement may be represented by the following logarithmic function:

$$s = a + bLog(N) \quad (1)$$

where, s = sleeper settlement; N = number of load cycles; *a* and *b* are empirical constants depending on the initial compaction, type of ballast, type of reinforcement and degree of saturation. The predictions by Equation (1) are also plotted in Fig. 4 (solid lines) for comparison. Figure 4 indicates that the rate of settlement of recycled ballast (i.e. slope of lines) with logarithm of number of load cycles decreases due to geosynthetics. However, the decrease in the rate of settlement is more pronounced in the case of geogrid-geotextile composite inclusion. As expected, when saturated with water, the rate of settlement of recycled ballast stabilised with geosynthetics increases.

5.2 *Ballast strain characteristics*

The sleeper settlement data and the measurements of settlement plates placed at the ballast/capping interface were used to calculate the vertical strain (major principal strain, ε_1) of the ballast specimen. Figure 5 shows the vertical strain of ballast against the logarithm of number of load cycles for all six test specimens. As expected, recycled ballast produces higher vertical strain compared to fresh ballast. Figure 5 verifies that the geogrid-geotextile composite is more effective in reducing ε_1, than the geogrid on its own. The saturation of geogrid stabilised recycled ballast increases the rate of vertical strain significantly. In contrast, the rate of vertical strain of recycled ballast stabilised with geogrid-geotextile composite does not increases significantly upon saturation. In this context, the geogrid-geotextile composite will work better in rail track under wet weather condition.

As indicated in Fig. 5, the vertical strain of ballast is also related linearly with the logarithm of number of load cycles, irrespective of the type of ballast, reinforcement and saturation. Thus, the vertical strain of ballast can also be described by a logarithmic function as given below:

$$\varepsilon_1 = c + dLog(N) \qquad (2)$$

where, ε_1 = ballast vertical strain; N = number of load cycles; and *c* and *d* are empirical constants. The predicted vertical strains using Equation (2) are also plotted in Fig. 5 (solid lines) for comparison.

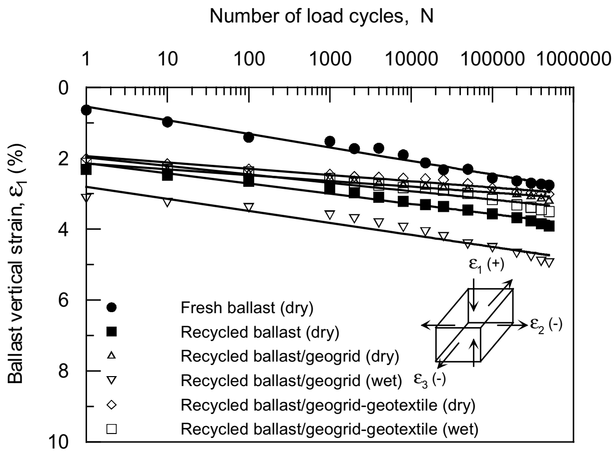

Figure 5. Variation of ballast vertical strain under cyclic loading

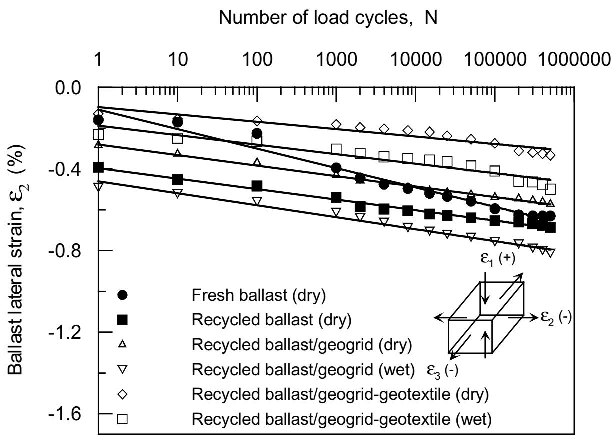

Figure 6. Intermediate principal strain of ballast under cyclic loading

The lateral strains (intermediate principal strain, ε_2, and minor principal strain, ε_3) of ballast were calculated from the average lateral movements of the vertical walls and initial lateral dimensions of the specimen. The strain perpendicular to the sleeper is the intermediate principal strain, while the strain parallel to the sleeper is the minor principal strain. Figure 6 shows the variation of intermediate principal strain (ε_2) with increasing number of load cycles plotted in a semi-logarithmic scale. As expected, recycled ballast specimen (without reinforcement) gives higher lateral strains due to its less angularity and friction angle, compared to fresh ballast. The magnitude of lateral strain (ε_2) of recycled dry ballast decreases significantly with the inclusion of geogrid-geotextile composite, and the value of ε_2 becomes even less than that of fresh ballast with increasing number of load cycles. In contrast, the inclusion of geogrid in recycled dry ballast decreases ε_2 only slightly. The reason for this is that the high aperture geogrid provides less frictional contact area with ballast, thereby, not generating sufficient shear interlock. It is noted that the aperture of geogrid (40 mm) is larger than the mean size of ballast (d_{50} = 35 mm), as stated earlier. If a smaller aperture geogrid had been used (e.g. less than 30 mm), the effect of geogrid in stabilising recycled ballast is expected to be much greater. Figure 6 also indicates that saturation increases the intermediate principal strain of recycled ballast stabilised with either type of geosynthetics. However, inclusion of geogrid-geotextile composite in saturated recycled ballast provides significantly less lateral strain (ε_2), compared to geogrid inclusion.

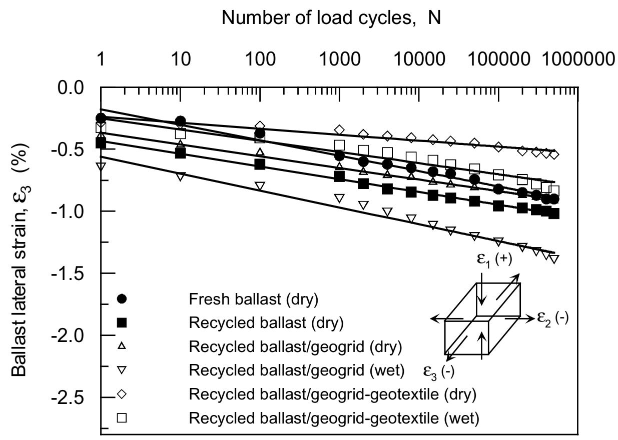

Figure 7. Minor principal strain of ballast under cyclic loading

The variation of minor principal strain (ε_3) of ballast against the number of load cycles is shown in Fig. 7 in a semi-logarithmic scale. Similar to intermediate principal strain, the minor principal strain of recycled ballast (without stabilisation) is higher than that of fresh ballast. Inclusion of geogrid in recycled dry ballast decreases the minor principal strain slightly. However, the inclusion of geogrid-geotextile composite decreases the minor principal strain to even less than that of fresh ballast at higher number of load cycles. Upon saturation, the geogrid-geotextile composite performs better than the pure geogrid.

Figure 8 shows the variation of volumetric strain (compression +ve) of ballast with the increasing number of load cycles. As shown in Fig. 8, dry fresh ballast produces the least volumetric compression, while saturated recycled ballast stabilised with geogrid shows the highest volumetric compression amongst all test specimens. Volumetric strain of recycled ballast is higher than that of fresh ballast, due to less angularity and friction. Inclusion of geogrid in recycled dry ballast decreases the volumetric strain considerably. Surprisingly, inclusion of geogrid-geotextile composite in recycled ballast has negligible effect on the volumetric strain, both in dry and wet condition. In spite of using geogrid-geotextile composite, the overall volumetric strain

($\varepsilon_v = \varepsilon_1 + \varepsilon_2 + \varepsilon_3$) of recycled ballast seems to remain the same (Fig. 8). The composite decreases the lateral strains as well as the vertical strain of ballast in such proportions that the summation of the three principal strains converge to a very similar value. Consequently, the performance of a geogrid-geotextile composite cannot be assessed using the overall volume change, but rather its performance is clearly reflected by the reduction of the individual principal strain. Figure 8 also indicates that saturation of recycled ballast stabilised with geogrid increases the volumetric compression significantly. In contrast, saturation has negligible effect on the volumetric strain of ballast, when stabilised with geogrid-geotextile composite.

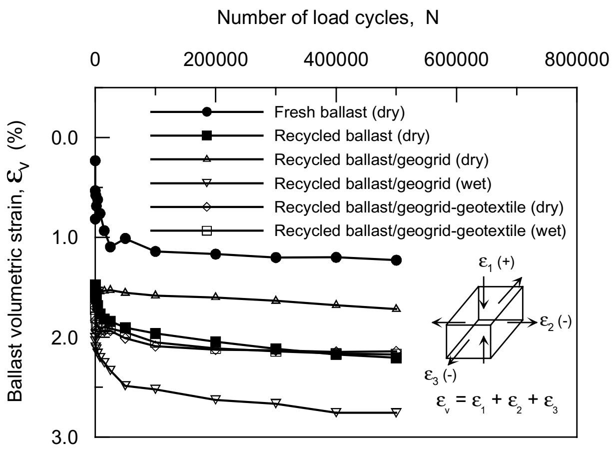

Figure 8. Volumetric strain of ballast during cyclic loading

5.3 *Particle degradation*

The degradation of ballast particles influences the deformation characteristics of railway track (Selig and Waters, 1994, Indraratna et al. 1998). The breakage of ballast particles under cyclic loading is a complex mechanism that starts at the interparticle contacts, followed by complete crushing of the weaker particles upon further loading. The breakage of ballast causes differential track settlement and lateral movement. Accumulation of pulverized fine particles in the void spaces between larger aggregates decreases permeability of ballast, and in many cases, may cause localised undrained failure in rainy seasons. In overstressed railway foundations, rapid fragmentation of particles and subsequent clogging of ballast voids with fines is commonly observed (Ionescu et al. 1998). Chrismer and Read (1994) reported that the primary cause of ballast contamination is the degradation of aggregates, which accounts for up to 40% of fouled material.

In order to evaluate the degradation characteristics of ballast with and without geosynthetics, the load bearing ballast was isolated from the crib ballast and capping materials by placing a very thin loose geotextile interface, which prevented migration of pulverized particles in between these layers, but not sharing any lateral load. Before and after the test, each ballast specimen was sieved carefully, and the changes in ballast grading were recorded. Since the small changes in particle size due to degradation of ballast cannot be illustrated clearly in conventional particle size distribution plots (Fig. 1), therefore, an alternative method was developed by Marsal (1973), where the difference in percentage by weight of each grain size fraction before and after the test (ΔW_k) is plotted against the aperture of the lower sieve corresponding to that fraction. In this method, an index of particle breakage (B_g) was introduced, which is equal to the sum of positive values of ΔW_k expressed as a percentage.

Figure 9 shows the variations of ΔW_k with different grain sizes of ballast. It is clear from Fig. 9 that fresh ballast suffers least degradation, while recycled ballast is more vulnerable to breakage. Inclusion of geosynthetics (geogrid or geogrid-geotextile composite) decreases the deformations of recycled ballast (Figs. 5-7), and thereby, reduces particle degradation, as indicated in Fig. 9. It is also noticed in Fig. 9 that saturation of recycled ballast stabilised with geosynthetics does not increase particle breakage significantly. For fresh ballast, particles of size 45 to 60 mm are most susceptible to degradation, while for recycled ballast (with or without geosynthetics), particles of size 30 to 50 mm are the most vulnerable to breakage (Fig. 9). The values of breakage indices (B_g) for different test specimens used in the current study are shown in Table 5.

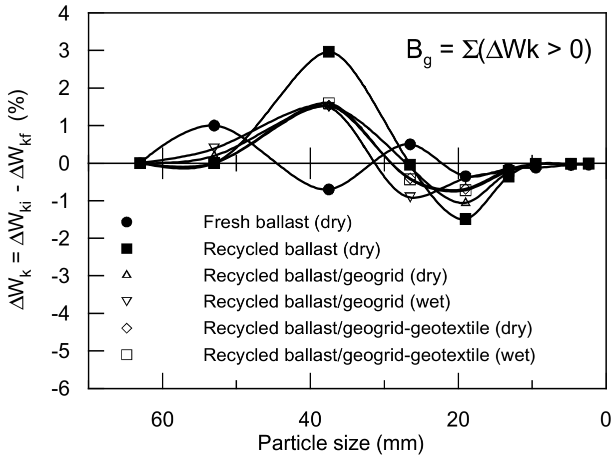

Figure 9. Change in particle size of ballast under cyclic loading

Table 5. Particle degradation of ballast

Type of ballast	Breakage Index, B_g
Fresh ballast (dry)	1.50
Recycled ballast (dry)	2.96
Recycled ballast with geogrid (dry)	1.70
Recycled ballast with geogrid (wet)	1.88
Recycled ballast with geogrid-geotextile (dry)	1.54
Recycled ballast with geogrid-geotextile (wet)	1.60

The test results indicate that recycled ballast undergoes 97% more breakage compared to fresh ballast under similar loading conditions. The presence of micro-cracks in recycled ballast under the previous loading cycles is believed to be a major reason for its higher particle degradation. Inclusion of geogrid and geogrid-geotextile composite in recycled ballast decreases particle breakage by about 42% and 48%, respectively.

6 CONCLUSIONS

The investigations covered in this study indicate that the deformation of railway ballast, both fresh and recycled, is non-linear with the number of load cycles. The settlement of ballast may be described by a logarithmic function of the number of load cycles. The study confirms that recycled ballast produces higher settlement compared to fresh ballast. Inclusion of geosynthetic layer at the ballast/capping interface decreases the rate of settlement of recycled ballast significantly. Saturation increases the settlement of recycled ballast stabilised with geosynthetics by about 3-7 mm. All ballast specimens irrespective of type of ballast, reinforcement and saturation, stabilise within about 100,000 loading cycles, beyond which settlement increases at a diminishing rate.

The vertical and lateral strains of ballast may also be represented by a logarithmic function of load cycles. The vertical strain of recycled ballast is higher than that of fresh ballast. In dry recycled ballast, the geogrid-geotextile composite works slightly better than the pure geogrid, in terms of minimising vertical strain. Upon saturation, the composite performs clearly better than the pure geogrid, with respect to settlement context.

Inclusion of geogrid-geotextile composite in recycled dry ballast produces lateral strains (ε_2, and ε_3) even less than that of fresh ballast. This has tremendous implications in the maintenance cycle of rail tracks. Moreover, the reduction in the lateral movement of ballast due to using the composite decreases the need for crib and shoulder ballast replacement, i.e. the track will benefit from minimum confinement. Saturation increases the lateral strains of geogrid stabilised recycled ballast significantly. In contrast, saturation does not increase the lateral strains of recycled ballast significantly, when stabilised with geogrid-geotextile composite. Saturation increases the volumetric strain of geogrid stabilised recycled ballast, while it has a negligible effect in case of geogrid-geotextile composite.

The study indicates that fresh ballast particles of size 45 – 60 mm are most susceptible to breakage, while recycled ballast particles of size 30-50 mm are most vulnerable to degradation. Recycled ballast shows about 97% more breakage compared to fresh ballast. By inclusion of geogrid or geogrid-geotextile composite in recycled ballast, particle breakage could be reduced by about 42-48%.

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