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Buddhima Indraratna

University of Wollongong, indra@uow.edu.au

H. Khabbaz

University of Wollongong, khabbaz@uow.edu.au

Wadud Salim

University of Wollongong, wadud@uow.edu.au

D. Christie

RailCorp, Australia

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Geotechnical properties of ballast and the role of geosynthetics in rail track stabilisation

B. INDRARATNA*, H. KHABBAZ[†], W. SALIM[‡] and D. CHRISTIE[‡]

*Faculty of Engineering, University of Wollongong, Australia; [†]Jeffery and Katauskas Consulting Geotechnical and Environmental Engineers, Sydney, Australia; [‡]Geotechnical Consulting Division, RailCorp (NSW), Sydney, Australia

The ballast and its engineering behaviour have a key role in governing the stability and performance of railway tracks. The deformation and degradation behaviour of ballast under static and dynamic loads was studied based on large-scale triaxial testing. The possible use of different types of geosynthetics to improve the performance of fresh and recycled ballast was also investigated. The research findings showed that the inclusion of geosynthetics improves the performance of ballasted tracks.

Keywords: geosynthetics; large-scale triaxial testing; railway ballast

Introduction

The need to maintain a competitive edge over other means of transportation has increased the pressure on the railway industry to improve its efficiency and decrease maintenance and infrastructure costs. In the case of ballasted railway tracks, the cost of substructure maintenance can be significantly reduced if a better understanding is obtained of the physical and mechanical characteristics of the rail substructure, and of the ballast layer in particular.

Accordingly, the University of Wollongong under the auspices of the Cooperative Research Centre for Railway Engineering and Technologies (RAIL-CRC) and in collaboration with other railway organisations in Australia has initiated a broad research programme to investigate the behaviour of rail track under cyclic loading. The following investigations have already been accomplished, and the findings of the study are presented in this paper:

- (a) studying the effect of ballast particle size distribution and confining pressure on ballast shear strength, settlement and degradation, based on static and dynamic tests using large-scale cylindrical triaxial apparatus
- (b) investigating the potential use of geosynthetics (geogrids, geotextiles and geocomposites) for enhancing the performance of ballasted tracks, and quantifying the effect of their inclusion for reducing ballast degradation and excessive track deformation, based on large-scale prismatic triaxial testing.

The conventional triaxial apparatus is one of the most

Le ballast et son comportement mécanique ont une influence importante sur la stabilité et la performance des voies ferrées. Nous avons étudié le comportement de détérioration et de déformation du ballast sous charge statiques et dynamiques en nous basant sur des essais triaxiaux à grande échelle. Nous avons également étudié la possibilité d'utiliser divers types de géosynthétiques pour améliorer la performance du ballast neuf et recyclé. Les résultats de cette recherche ont montré que l'adjonction de géosynthétiques améliorerait la performance des voies ballastées.

versatile laboratory methods for obtaining the deformation and strength properties of coarse- and fine-grained materials. However, the inconsistency between the actual particle sizes in the field and the greatly reduced particle sizes used in conventional laboratory equipment contributes to inaccurate deformation behaviour and failure modes observed in the laboratory. This is because of the inevitable size-dependent dilation and different mechanisms of particle crushing (Indraratna *et al.*, 1998). To overcome these size-dependent problems, 'large-scale' triaxial facilities for testing ballast have been designed and employed at the University of Wollongong. As expected, these testing rigs provide more realistic information on the ballast stress-strain and degradation characteristics, using the prototype rock fragments (i.e. correct size and angularity).

In this study, two large-scale triaxial chambers, a cylindrical rig and a prismatic rig, have been used to investigate ballast deformation and degradation under different conditions. A flowchart of the experimental programme, conducted by the authors on railway ballast based on large-scale triaxial testing, is shown in Fig. 1.

Ballast behaviour

Ballast is a free-draining granular material used as a load-bearing material in railway tracks. It is composed of medium to coarse gravel-sized aggregates (10–60 mm), with a small percentage of cobble-sized particles. Ballasted track is still the most common railroad structure, thanks to its relatively low cost of construction and the possibility of maintenance (Chrismer, 1985; Jeffs and Marich, 1987; Esveld, 2001). The thickness of the ballast should be such that the subgrade is

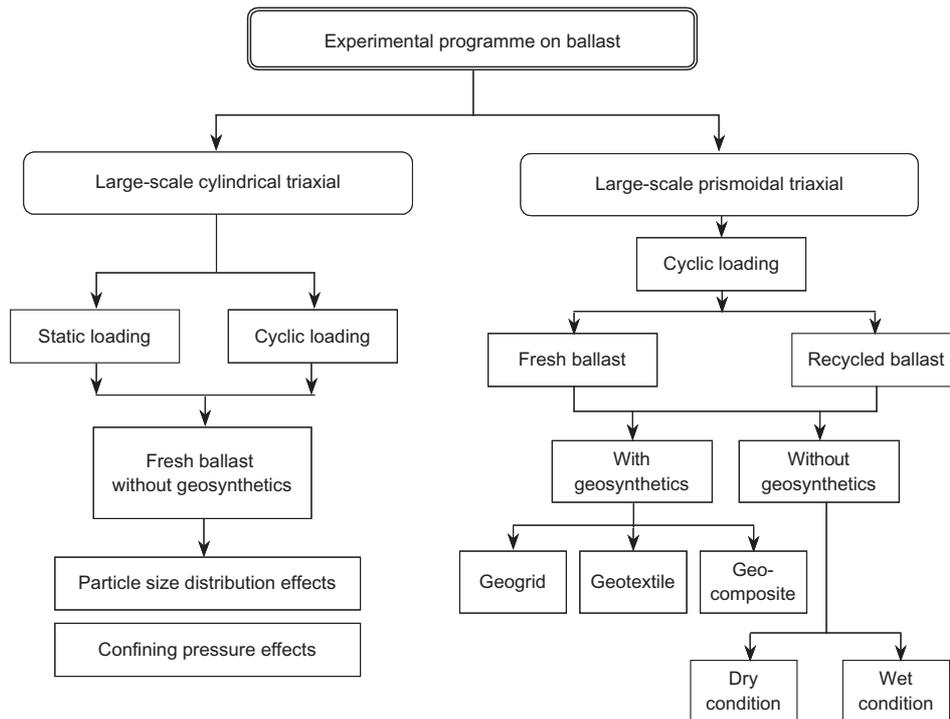


Fig. 1. The experimental programme on railway ballast based on large-scale triaxial testing

loaded as uniformly possible. The optimum thickness is usually 250–300 mm measured from the lower side of the sleeper (Esveld, 2001). Good-quality railway ballast should have angular particles, high specific gravity, high shear strength, high toughness and hardness, high resistance to weathering, rough surface and minimum hairline cracks (Chrismer, 1985; Jeffs and Marich, 1987; Indraratna *et al.*, 1998, 2000, 2003b; Esveld, 2001). However, the sources of high-quality ballast are limited, and under dynamic loading conditions most ballast properties change progressively because of breakage, deformation and fouling. Ballast fouling decreases permeability, and therefore causes hydraulic erosion, reduction in stability due to particle lubrication, subgrade attrition, and ballast deterioration due to the delay in dissipation of excess pore water pressures.

The main functions of ballast are to distribute the load from the sleepers, to damp dynamic loads, and to provide lateral resistance and rapid drainage. The characteristics required for these functions are clearly contradictory in some aspects, and thus a particular type of ballast cannot accomplish all of them completely (Profillidis, 1995). It could be argued that for high load-bearing characteristics and maximum track stability the ballast needs to be angular, well graded and compact, which in turn reduces the drainage of the track. Therefore a balance needs to be achieved between bearing capacity and drainage. To elucidate this point, the main geotechnical properties of ballast are briefly discussed in this section. In the following section it is shown that the use of geosynthetics with special characteristics in the track bed may supplement or further improve the various functions that ballast is required to perform.

Physical properties of ballast

The physical properties of ballast are largely responsible for successful ballast performance in the field. They can be divided into two categories. The first group is concerned with the properties of individual particles, and includes a petrological examination, durability test, and shape and

surface examination before the ballast can be declared suitable. The second category considers the physical properties of ballast particles that are in contact with each other, but not influencing deformation. These properties are permeability, void ratio, bulk density and specific gravity.

The extent to which a given aggregate is considered suitable is determined largely by its petrological examination. In this analysis, rock type, geological and chemical properties, texture and mineralogy of ballast particles are examined. After suitable rock types have been determined, durability testing is conducted. Individual particles are tested for toughness, wearing by attrition, resistance to crushing under static loading and resistance to sudden shock loading. Ballast that satisfies the durability requirements is then subjected to further examination to evaluate shape and surface characteristics, gradation, and detect the existence of impurities. These tests are concerned with establishing a quantitative estimate of the resistance to in-track instability and degradation under loading. They include flakiness, elongation, sphericity, angularity or roundness, fractured particles, surface texture, grain size, particle size distribution, fine particle content, clay lumps and friable particles.

A number of serious track problems, including fouling, pumping, subgrade failure and excessive ballast breakdown, are related to the lack of adequate drainage of the ballast layer. The permeability and void ratio are important factors that are ultimately responsible for long-term track drainage. It is well known that permeability decreases with increasing compaction and cementation, and increases with higher void ratio and coarser particles.

The specific gravity and bulk density of the ballast are two properties that play pivotal roles in rail track safety. Bulk density is a function of the particle specific gravity and the void ratio. Two methods can be employed to increase the bulk density: the use of denser particles, and a broader gradation. Ballast with higher specific gravity can improve the strength and stability of railway track, increase durability under cyclic loading, and minimise ballast settlement

(Jefferies and Marich, 1987; Indraratna *et al.*, 1998) It has been shown that the higher the specific gravity of the parent rock, the greater the holding capacity of the ballast and the lower the degradation. The lateral stability of curved tracks, which is essential for track safety, can be improved by the use of ballast with high specific gravity. The bulk density and specific gravity control the stability of the track, and should be maximised without significant reduction in drainage.

Mechanical properties of ballast

Three important aspects of mechanical properties of ballast, namely shear strength, settlement and degradation, are discussed in this paper. Further critical review and discussion on this topic can be found in Indraratna *et al.* (2000, 2003b).

Shear strength

Conventionally, the shear strength of granular materials is assumed to vary linearly with the applied stress, and the Mohr–Coulomb theory is used to describe the conventional shear behaviour. Recent research by Indraratna *et al.* (2000) and Ramamurthy (2001), among others, has shown that when soils at high stresses and rocks at low normal stresses are tested, a non-linear shear strength response is obtained. Hence one value set of cohesion intercept c , and the angle of shearing resistance ϕ , cannot be used to represent accurately the failure envelopes corresponding to the entire range of stresses. Indraratna *et al.* (1993) proposed a non-linear strength envelope obtained during the testing of granular media at low normal stress. This non-linear shear strength envelope is represented by the following equation:

$$\frac{\tau_f}{\sigma_c} = m \left(\frac{\sigma'_n}{\sigma_c} \right)^n \quad (1)$$

where σ_c is the uniaxial compressive strength of parent rock determined from the point load test, m and n are dimensionless constants, τ_f is the shear strength at failure, and σ'_n is the effective normal stress. The non-linearity of the strength envelope is governed by the coefficient n . For small confining pressures (below 200 kPa) representative of rail tracks, n takes values in the range 0.65 – 0.75. A large-scale cylindrical triaxial apparatus, which could accommodate specimens 300 mm in diameter and 600 mm high, was used by Indraratna *et al.* (1998) to verify equation (1). The results of that study associated with latite basalt in a normalised form are plotted in Fig. 2, with other results obtained for various sources of basalt (Marachi *et al.*, 1972; Marsal, 1973; Charles and Watts, 1980).

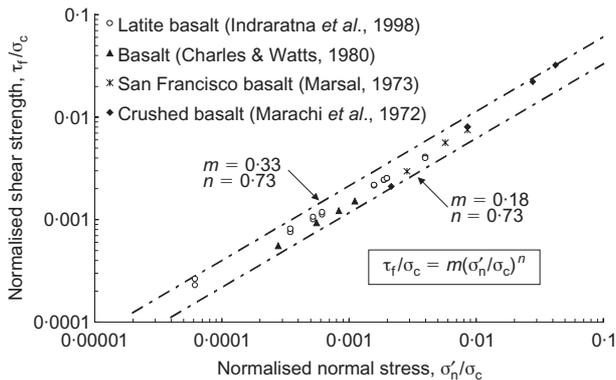


Fig. 2. Normalised shear strength for basalt aggregates (Indraratna *et al.*, 1998)

Ballast degradation

The main causes of ballast degradation are excessive cyclic loading and vibration, temperature and moisture fluctuation, and impact load on ballast due to severe braking. The degradation of ballast particles can occur in three ways (Raymond and Dyaljee, 1979):

- the breakage of particles into approximately equal parts (this is responsible for the long-term stability and safety of the track)
- the breakage of angular projections, which influences the initial settlement
- the grinding-off of small-scale asperities (the presence of fines can cause fouling and reduce drainage).

The main factors that have effects on ballast breakage can be divided into the following categories (Indraratna *et al.*, 2003b):

- ballast properties related to the characteristics of the parent rock (e.g. hardness, specific gravity, toughness, weathering, mineralogical composition, internal bonding and grain size)
- particle properties associated with the blasting, crushing and transportation processes (e.g. soundness, particle shape, particle size and surface smoothness)
- factors related to the field/experimental variables (e.g. confining pressure, initial density or porosity, thickness of ballast layer, ballast gradation, presence of water or ballast moisture content, dynamic loading pattern, including train speed and frequency).

Modelling of particle breakage The degree of particle breakage affects the strength characteristics of coarse aggregates. An analytical model has been developed by Indraratna and Salim (2002) to include the relationship of the deviator stress ratio (q/p'), the rate of dilation ($d\varepsilon_v/d\varepsilon_1$), the ultimate or critical state friction angle (ϕ_f), and the rate of energy consumption due to particle breakage. Based on the proposed model, the deviator stress ratio becomes:

$$\frac{q}{p'} = \frac{3(1 - d\varepsilon_v/d\varepsilon_1)\tan^2(45^\circ + \phi_f/2) - 3}{2 + (1 - d\varepsilon_v/d\varepsilon_1)\tan^2(45^\circ + \phi_f/2)} + \frac{3f(dB_g/d\varepsilon_1)(1 + \sin \phi_f)}{p[2 + (1 - d\varepsilon_v/d\varepsilon_1)\tan^2(45^\circ + \phi_f/2)]} \quad (2)$$

where $d\varepsilon_1$ and $d\varepsilon_v$ are the increments of major principal strain and volumetric strain respectively. The parameter p' is the mean effective stress, q is the deviator stress, and dB_g is the increment of breakage index associated with $d\varepsilon_1$. The function $f(dB_g/d\varepsilon_1)$ in equation (2) remains to be determined based on laboratory triaxial testing. Equation (2) was employed along with drained triaxial test results of fresh ballast, and the resulting effects of particle breakage and dilatancy on the friction angle of ballast are shown in Fig. 3. A constitutive model that can predict particle breakage under cyclic loads in an assembly of irregular shapes including the effects of anisotropy is currently being developed at the University of Wollongong.

Quantification of particle breakage The breakage of ballast causes differential track settlement and excessive lateral movement. Accumulation of crushed particles in the void spaces between larger aggregates decreases the permeability of ballast. In order to evaluate the degradation characteristics of ballast, the load-bearing ballast is isolated from the crib ballast and capping materials. Before and after the test,

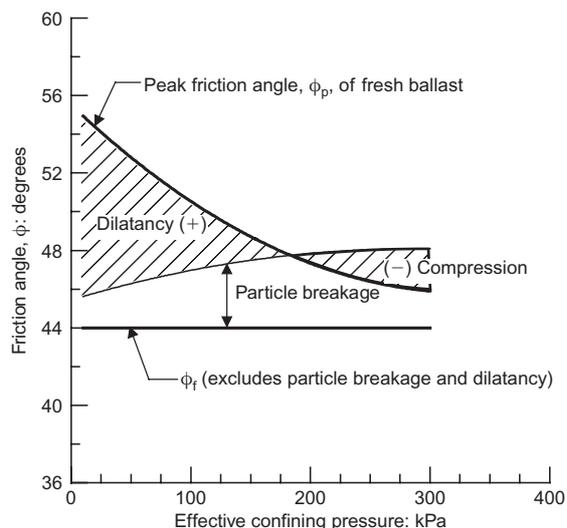


Fig. 3. Effect of particle breakage on friction angle of ballast at various confining pressures (Indraratna and Salim, 2002)

each ballast specimen is sieved, and the changes in ballast grading are recorded. As the changes in particle size due to degradation of ballast cannot be illustrated clearly in conventional particle size distribution plots, an alternative method was developed by Marsal (1967), wherein the difference in percentage retained by weight of each grain size fraction before (W_{ki}) and after (W_{kf}) the test is defined as $\Delta W_k (= W_{ki} - W_{kf})$. Marsal (1967) introduced an index of particle breakage B_g , which is equal to the sum of the positive values of ΔW_k , expressed as a percentage.

Effect of particle size distribution on particle breakage Using the large-scale cylindrical apparatus at the University of Wollongong (Fig. 4), which has recently been upgraded by installing a dynamic actuator to perform cyclic loading tests, a series of experiments have been conducted



Fig. 4. Cylindrical triaxial apparatus with dynamic actuator designed at University of Wollongong

to examine the effect of ballast particle size distribution on ballast degradation and settlement (Indraratna et al., 2003a). The four different particle size distributions tested, along with their respective C_u values (coefficients of uniformity), are illustrated in Fig. 5. The distributions are described as 'very uniform', 'uniform', 'gap graded' and 'well graded'. Past research has shown that the ballast particle sizes most prone to breakage are those around 38 mm (Indraratna et al., 2000, 2003b). The gap-graded distribution is very similar to the uniform graded distribution but contains no particles retained on the 37.5 or 40 mm sieves. This particular grading was incorporated into the testing schedule to examine what effect the removal of a vulnerable particle size has on ballast degradation.

Ballast samples were made of latite basalt from Bombo quarry near Wollongong. Samples were first compacted to a bulk unit weight of 15.5 kN/m^3 using a jack-hammer. There was a slight variation in initial specimen density due to the different compressibility of each distribution. The sample was subjected to a small confining pressure and consolidated overnight. A back-pressure was applied to allow saturation and to prevent negative pore water pressure development. Cyclic loading was applied with a maximum amplitude of 21 kN, and the tests were conducted at a frequency of 20 Hz to simulate high-speed freight trains. The total number of load cycles applied in each test was half a million.

Table 1 indicates the average breakage indices of several samples with different particle distribution size, based on Marsal's method (Marsal, 1967). The results show that well-graded distribution results in minimal ballast degradation. The results also indicate that by removing vulnerable particle sizes from the distributions currently used on railway lines, reductions in degradation can be achieved. It is expected that if the density of recycled ballast is increased by using well-graded aggregates (rather than uniformly

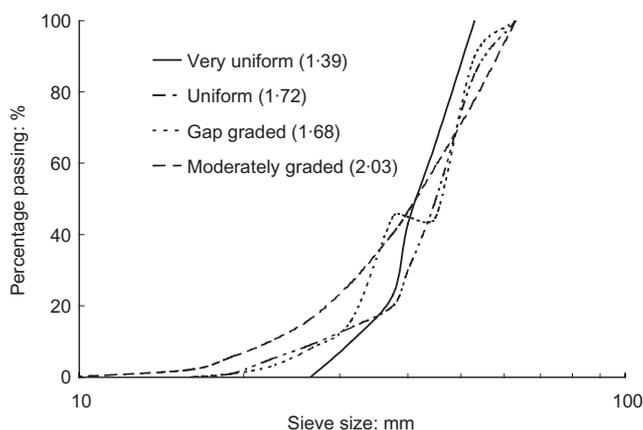


Fig. 5. Ballast particle size distributions and their uniformity coefficients (Indraratna et al., 2003a)

Table 1. Breakage index of ballast samples under cyclic loading

Sample type	Average breakage index
Very uniform	4.28
Uniform	2.31
Gap graded	1.41
Moderately graded	1.35

graded ballast as commonly used), the interparticle contact stresses will be reduced by the increased contact area around the particles, resulting in the reduction of particle breakage.

There are a number of problems associated with employing a very well-graded distribution in track. Two of the most important are size segregation and a reduction in drainage. Future tests using the large-scale cylindrical triaxial apparatus will study the interaction of the entire substructure, with and without the use of geosynthetics. The writers are currently evaluating the success of well-graded ballast with geosynthetics included to prevent substructure problems, such as clay pumping, loss of track resilience, ballast fouling, and delay in dissipating excess pore water pressures.

Effect of confining pressure on particle breakage Previous testing at the University of Wollongong has shown that the extent of particle breakage at a given vertical strain increases with higher confinement (Indraratna and Salim, 2002). Fig. 6 indicates the variation of ballast breakage with axial strain and confining pressure. The large-scale cylindrical triaxial apparatus, shown in Fig. 4, was used to conduct monotonic load testing on all initially identical ballast samples.

Settlement

The settlement of ballast can be both elastic (such as the initial settlement due to the compaction of ballast) and plastic (due to breakage of ballast particles). As identified by Selig and Waters (1994), settlement of ballast may not be a problem if it occurs uniformly along the length of the track. In fact, differential track settlement is more important than the total track settlement. In the long term, however, the subgrade is more influential.

The settlement of ballast is influenced by large trainloads, the number of load cycles, and high speed of trains. There is an initial stabilisation stage where settlement is rapid, followed by settlement over an extended period at a decreasing rate. Jeffs and Marich (1987) and Indraratna *et al.* (2003b) among others, based on their experimental studies, reported that the relationship between the number of load applications and settlement of ballast is non-linear. The rail

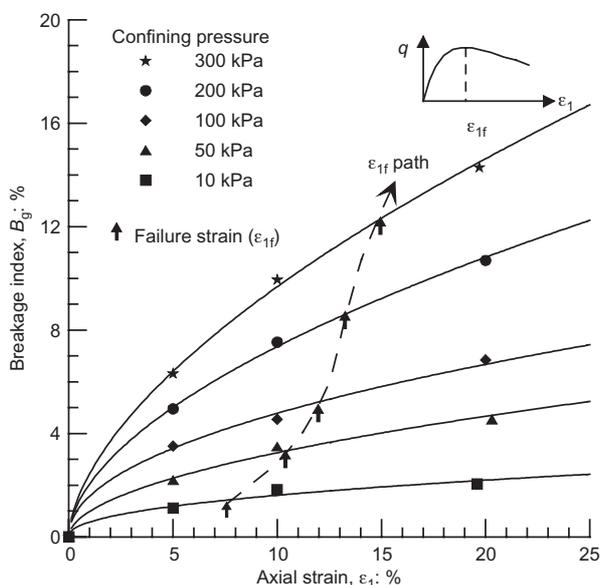


Fig. 6. Variation of particle breakage with axial strain and confining pressure (Indraratna and Salim, 2002)

track settlement is usually related to the number of load cycles by a semi-logarithmic relationship such as

$$S_N = a(1 + k \log N) \quad (3)$$

where S_N is the settlement of ballast at N load cycles, a is the settlement at the first cycle, and k is an empirical constant depending on the initial compaction, type of ballast, type of reinforcement and degree of saturation. Current data indicate a rapid initial settlement followed by gradual consolidation with increasing number of load cycles. Therefore a more accurate relationship for settlement under cyclic load could be presented as a power function of the number of load cycles (Indraratna *et al.*, 2000):

$$S_N = a \cdot N^b \quad (4)$$

where b is an empirical coefficient determined from non-linear regression analysis.

Indraratna *et al.* (2000) conducted several tests to investigate the effect of load cycles and axle loads on settlement. They employed equation (4) to model the ballast settlement, as shown in Fig. 7. It is important to note that the variation of the applied load affects only the coefficient a , while the coefficient b remains relatively unchanged (see Fig. 7).

The settlement behaviour of ballast with different particle size distribution was investigated by the authors under cyclic loading using the same equipment and procedures as explained earlier. Fig. 8 illustrates the settlement of the four ballast distributions against number of load cycles. The moderately graded samples display the least settlement, followed by the gap-graded specimens.

Improvement of rail track performance using geosynthetics

Geosynthetics have been used in various ways in new rail tracks and track rehabilitation for almost three decades. When appropriately designed and installed, geosynthetics provide a cost-effective alternative to more traditional techniques (Indraratna *et al.*, 2003b). There are several problems required to be corrected in railway tracks: increasing the bearing capacity of the subgrade soil; preventing contamination of the ballast by subgrade fines; and dissipating the high pore water pressures built up by cyclic train loading. The

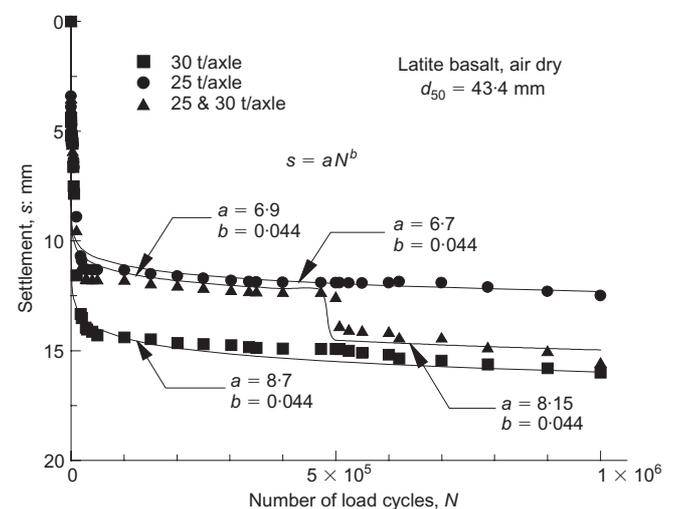


Fig. 7. Effect of load cycles and axle loads on settlement (Indraratna *et al.*, 2000)

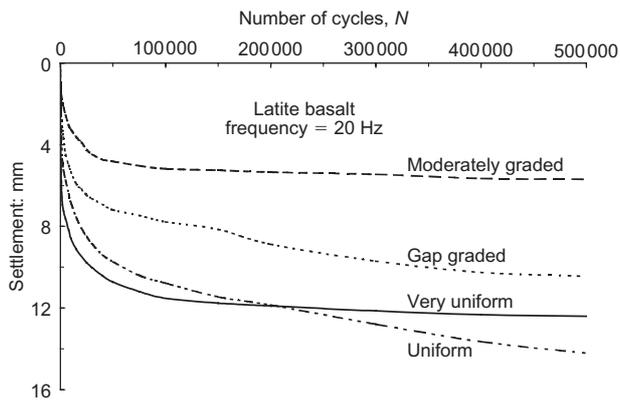


Fig. 8. Settlement of ballast specimens with different particle size distributions (Indraratna et al., 2003a)

purpose of the application of geosynthetics within railway construction, similar to other geotechnical engineering projects, can be subdivided into six categories:

- (a) separation
- (b) reinforcement
- (c) filtration
- (d) drainage
- (e) moisture barrier/waterproofing
- (f) protection.

Some applications of geosynthetics in rail track stabilisation are described below.

Ability of geotextiles to prevent pumping of fines into ballast Geotextiles can be placed under the ballast during construction or rehabilitation of rail track, for separation and filtration. When fine-grained material enters the ballast from the subgrade by the action of repeated loads, fouling of the ballast occurs. The separation function of geotextiles is to prevent this intrusion. Excess water in the subgrade, from seepage or cyclic loading effects, may flow upwards into the ballast. The filtration function of geotextiles is to permit this water movement, while at the same time preventing the percolation of fines.

Byrne (1989) evaluated the ability of the geotextile to prevent pumping of fines into ballast. The performance of the geotextile was compared with that of a sand filter loaded under similar conditions. Byrne (1989), based on laboratory cyclic testing, indicated that the use of geotextiles reduced the migration of fine-grained material into the upper ballast layer; however, they were not able to prevent pumping of soils consisting only of clay-size particles. He concluded that geotextiles were mostly suitable when used to prevent pumping of a fine soil that is broadly graded and contains significant amounts of sand-size particles. According to previous research, a geotextile placed on top of a sand filter could significantly reduce intermixing of the sand filter and the ballast (Byrne, 1989; Raymond, 2002).

Soft formation improvement using geosynthetic vertical drains Because of the rapid growth of infrastructure in the world, particularly in the coastal region of many countries, one is very likely to encounter the construction of embankments and railways on soft clay formations with high compressibility and low bearing capacity. The application of preloading over unconsolidated soft soil is regarded as one of the classical and popular methods in practice. However, in the case of thick soil deposits with low permeability, the consolidation time is very long, and hence a system of

vertical drains is often introduced to achieve accelerated radial drainage and consolidation. The performance of various types of vertical drain, including sand compaction piles, sand drains and geosynthetic (prefabricated) vertical drains (PVDs), has been investigated by a number of researchers (Bergado et al., 1991; Indraratna and Redana, 2000; Holtz et al., 2001; Indraratna and Bamunawita, 2002). It is found that, among the different techniques, the use of geosynthetic vertical drains is a very cost-effective method. The installation costs of prefabricated vertical drains are much lower than those of sand drains. As reported by Holtz et al. (2001), sand drains cost five to eight times more than PVDs. Furthermore, the maximum length of PVDs can be up to 60 m, which is twice as the maximum length of conventional sand drains.

In order to study the consolidation behaviour of soft soils stabilised by PVDs, a large-scale radial drainage consolidometer was designed and installed to investigate the different factors influencing the performance of PVDs. This apparatus, as shown in Fig. 9, consists of two half sections made of stainless steel. The internal diameter and the height of the cell are 450 mm and 950 mm respectively.

The presentation of extensive theoretical and experimental findings of our research on vertical drains at the University of Wollongong is beyond the scope of this paper. Thus only some results in relation to the determination of the smear zone around vertical drains based on the variation of horizontal and vertical permeability ratio (k_h/k_v) are shown in Fig. 10. According to Bergado et al. (1991), the k_h/k_v ratio in the smear zone was found to be close to unity, which is in agreement with the results of the study of Indraratna and Redana (2000).

The research at University of Wollongong has highlighted the effectiveness of using geosynthetic vertical drains to improve the geotechnical behaviour of soft formation of the track (Indraratna and Redana, 2000; Indraratna and Bamunawita, 2002). Prefabricated vertical drains can be used when an accelerated rate of consolidation and the improvement of soft formation soils are desired. However, the factors influencing the performance of PVDs, particularly the disturbance of soil surrounding the drains due to the installation process (smear effects), should be considered in design and practice.

Performance of fresh and recycled ballast stabilised with geosynthetics Based on relatively low cost and the proven performance of geosynthetics in a number of railway



Fig. 9. Large-scale consolidometer built at University of Wollongong (Indraratna and Redana, 2000)

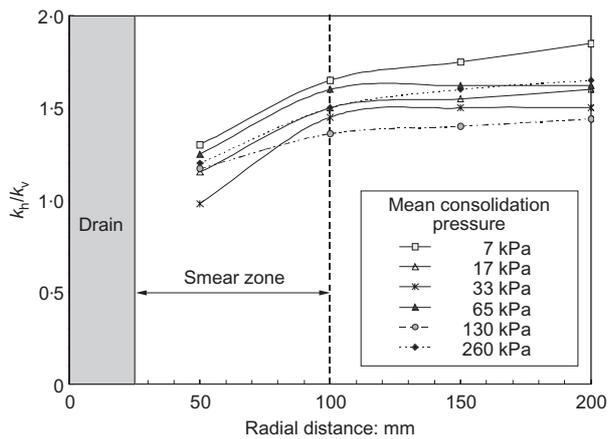


Fig. 10. Variation of permeability ratio along radial distance from the drain centre due to smear effect (Indraratna and Redana, 2000)

applications, the authors have conducted extensive research to investigate the effects of the different types of geosynthetic on the degradation and deformation of fresh and recycled ballast. In order to reduce the accumulation of discarded ballast, to minimise the cost of track maintenance and to reduce the environmental degradation by further quarrying for fresh ballast, the selected waste ballast may be cleaned, sieved and reused in the track. However, as the angularity of recycled ballast is decreased by the degradation of sharp corners in previous loading cycles, it is expected that recycled ballast will provide higher settlement and lateral deformation, compared with fresh ballast. Before utilising recycled ballast in the track, its behaviour and performance need to be investigated to ensure compliance with the stability and safety criteria stipulated by various rail authorities. The research findings associated with the inclusion of geosynthetics in enhancing the mechanical properties of recycled and fresh ballast specimens are presented in this section.

Material properties

The fresh ballast was collected from Bombo quarry near Wollongong. It represents sharp angular aggregates of crushed volcanic ballast (latite). Recycled ballast used in this study was collected from Chullora stockpile near Sydney. The recycled ballast consisted of semi-angular crushed rock fragments. The capping layer (also called the sub-ballast or intermediate layer) was used beneath the ballast specimen to act as a filter and separator between the subgrade and ballast bed. The capping layer consisted of 100 mm of compacted sand ($d_{50} = 0.26$ mm, $C_u = 5$). In order to simulate the real situation of railway track, a thick subgrade layer is required. However, because of limitations in laboratory testing, and in conducting a comparative study only on degradation and settlement of ballast under cyclic loading, a thin layer (50 mm) of compacted clay was used beneath the capping layer. For comparison of behaviour, all fresh and recycled ballast specimens were prepared according to the same gradation curve ($d_{50} = 35$ mm, $C_u = 1.6$).

Three types of geosynthetic were used in the current study to stabilise the recycled ballast:

- The geotextile was a high-strength woven polypropylene polymer with 0.25 mm pore size and 450 g/m² unit mass.
- The geogrid was a polypropylene in rectangular mesh (40 mm × 27 mm grid) with 420 g/m² unit mass.

- The geocomposite, with 560 g/m² unit mass, was the same geogrid bonded with a non-woven polypropylene geotextile.

Experimental procedures using a large-scale prismoidal triaxial rig

A large-scale prismoidal triaxial rig 800 mm long, 600 mm wide and 600 mm high was designed and installed at the University of Wollongong to model the cyclic loading response of ballasted tracks (Fig. 11). By allowing the lateral strain of ballast upon loading, this triaxial rig with unrestrained sides provides a reliable facility for the physical modelling of ballast under cyclic loading. In the laboratory model, a servo-hydraulic actuator provides the vertical cyclic load, and the load is transmitted to the ballast through a 100 mm steel ram and a 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. More details of this apparatus can be found in Indraratna *et al.* (1998, 2000).

In order to model a real track, the cubical triaxial chamber was filled with ballast and other materials in several layers. The bottom layer consisted of compacted clay 50 mm thick, to simulate the subgrade soil. The capping layer (100 mm) was formed of a compacted mixture of gravel and sand, to represent the sub-base layer. The load-bearing ballast (300 mm) and crib ballast (150 mm) layers consisted of fresh or recycled ballast. A timber sleeper (650 mm long and 220 mm wide) and rail segment were 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 at the ballast/capping interface. 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 sleeper/ballast and ballast/capping interface. The ballast and capping layers were compacted with a vibratory hammer in several layers, each about 75 mm thick, to achieve representative field densities. The bulk unit weights of the compacted ballast layer and capping layer were about 15.3 kN/m³ and 21.3 kN/m³ respectively. The initial void ratio of the ballast layer was about 0.74. All test specimens were compacted to the same initial density. The deformations of the ballast and the lateral movements of the vertical walls were measured using 18 LDVTs, which were then connected to a data acquisition system.

After preparing the test specimen, small lateral stresses

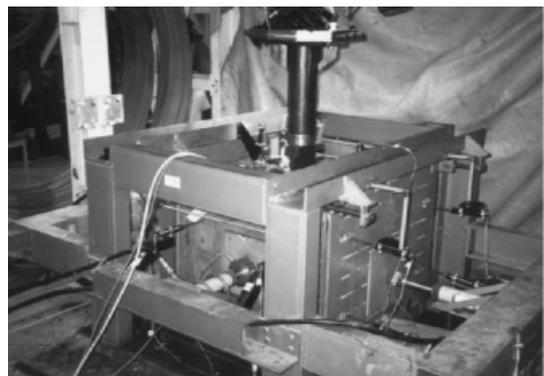


Fig. 11. Large-scale prismoidal triaxial equipment designed at University of Wollongong

($\sigma'_2 = 10$ kPa and $\sigma'_3 = 7$ kPa) were applied to the vertical walls of the triaxial chamber through hydraulic jacks, to simulate shoulder ballast and field confining stresses. 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 t/axle traffic load. The tests were conducted at a frequency of 15 Hz, simulating a train speed of 80 km/h. The total number of load cycles applied in each test was half a million. The cyclic loading was halted at selected numbers of load cycles, and the readings of settlement, lateral movement of walls and loading magnitudes were recorded.

Results and discussion

Ballast settlement and strains

The total settlement of fresh and recycled ballast samples (in wet and dry conditions) after 500 000 load cycles is shown in Fig. 12, accompanied by the settlement of the recycled ballast with geocomposite reinforcement. This figure indicates that the inclusion of a geocomposite (geogrid bonded with non-woven geotextile) decreases the settlement of recycled ballast to even less than that of fresh ballast (without geosynthetics).

The variation of the total settlement of fresh and recycled ballast specimens against number of load cycles is shown in Fig. 13 for samples with and without geosynthetic stabilisation. The settlement of fresh ballast specimens is illustrated in Fig. 13(a) and the settlement of recycled ballast specimens in dry and wet conditions is shown in Figs 13(b) and 13(c) respectively. These figures confirm that the behaviour of railway ballast under cyclic loading is highly non-linear. Similar behaviour was reported in the previous studies (Indraratna et al., 1998, 2000).

As expected, fresh ballast produces the minimum settlement, and recycled ballast without reinforcement shows much higher settlement than that of fresh ballast. Fig. 13 clearly shows that the inclusion of a geocomposite in recycled ballast improves its resistance to settlement, and compares well with that of fresh ballast. Inclusion of either a geotextile or a geogrid in recycled ballast improves the settlement behaviour moderately, but not to the same extent as that of the geocomposite.

The sleeper settlement data and measurements of settlement plates placed at the ballast/capping interface were used to calculate the vertical strain (ϵ_1) of the ballast specimens. The lateral strains of ballast ϵ_L (the strain parallel to the sleeper) were calculated from the average lateral

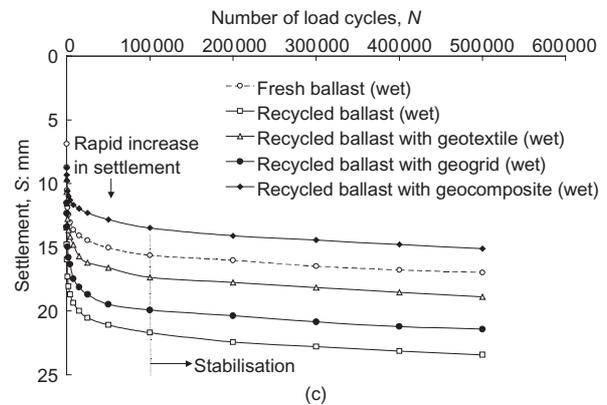
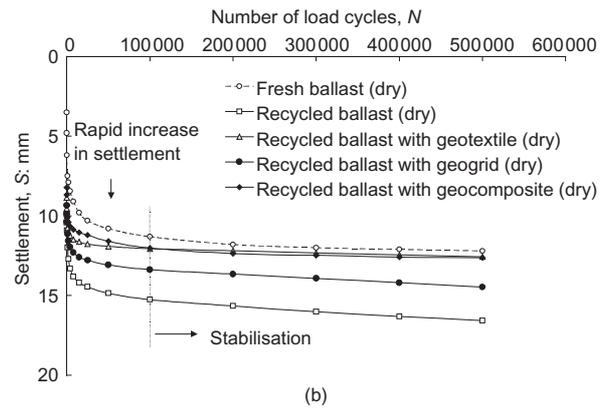
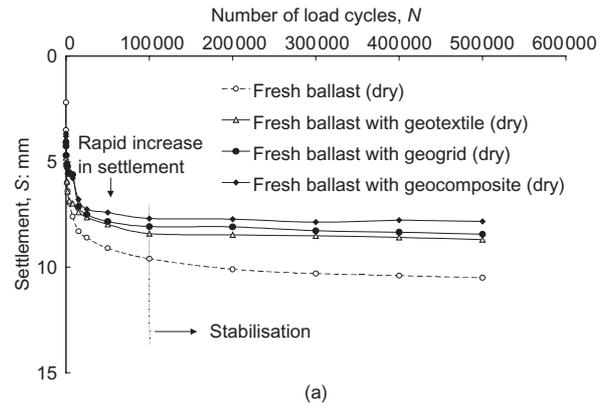


Fig. 13. Settlement of ballast under cyclic loading: (a) fresh ballast (dry specimens); (b) recycled ballast (dry specimens); (c) recycled ballast (saturated specimens)

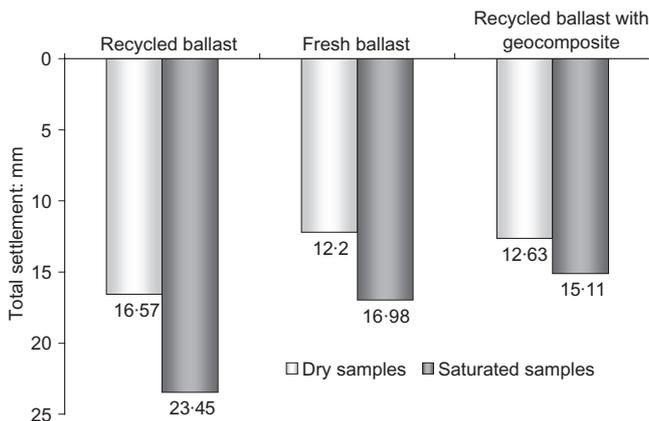


Fig. 12. Settlement of dry and wet samples after 500 000 load cycles

movements of the vertical walls and the initial lateral dimensions of the specimen. Fig. 14 shows the vertical strain of ballast against the number of load cycles for saturated and dry test specimens. This figure verifies that the geogrid-geotextile composite is more effective in reducing ϵ_1 than the geogrid or the geotextile used alone. Fig. 14 also indicates that, after the initial rapid deformation, the vertical strain of the ballast is related linearly to the number of load cycles, irrespective of the type of ballast and reinforcement.

The variations of strain parallel to the sleeper, ϵ_L (in the direction of the lowest confinement), with increasing number of load cycles are shown in Fig. 15. The lateral strain of recycled ballast with no stabilisation is higher than that of fresh ballast. Inclusion of the geogrid in the recycled ballast decreases the lateral strain slightly. However, inclusion of the geotextile or geocomposite decreases ϵ_L to even less than

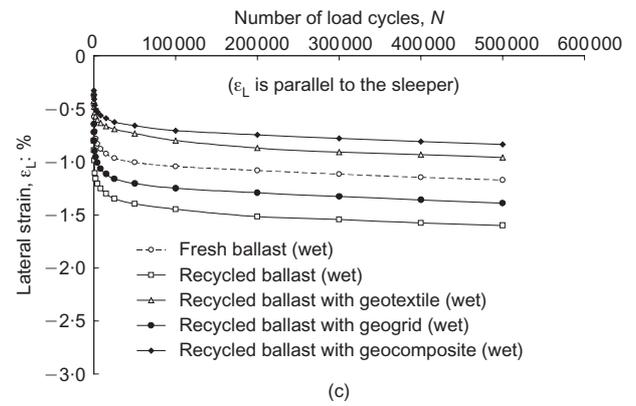
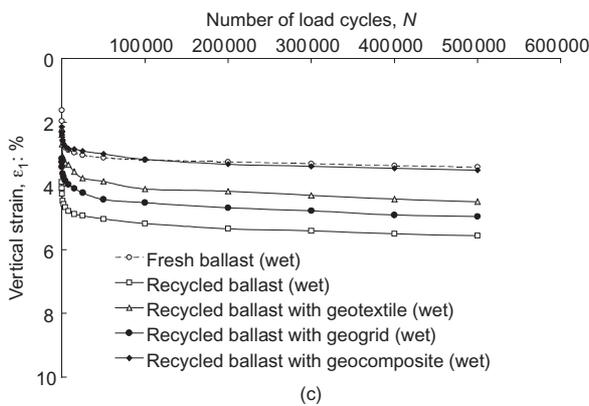
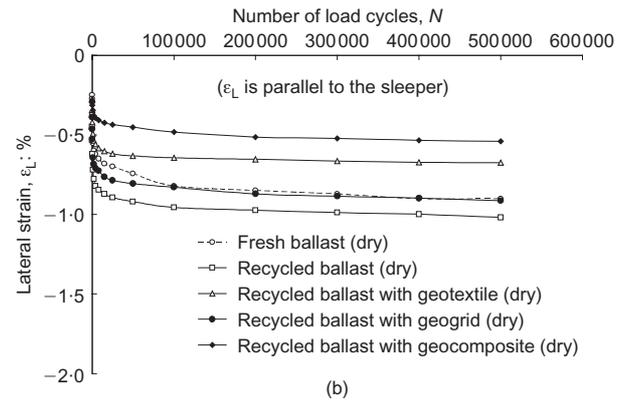
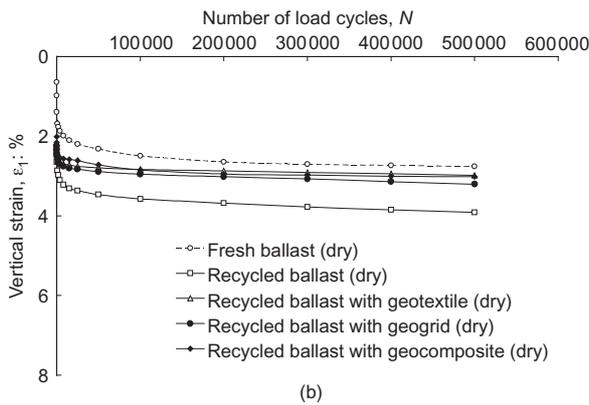
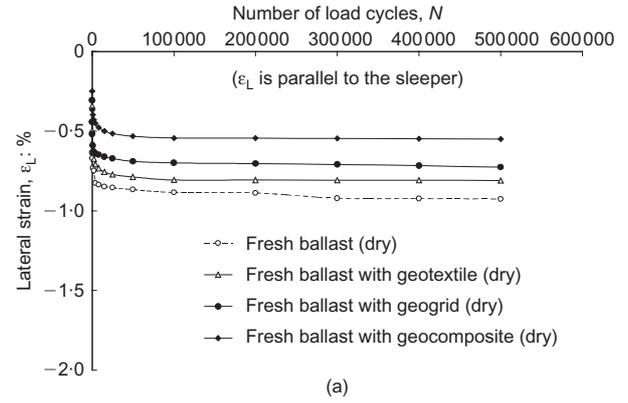
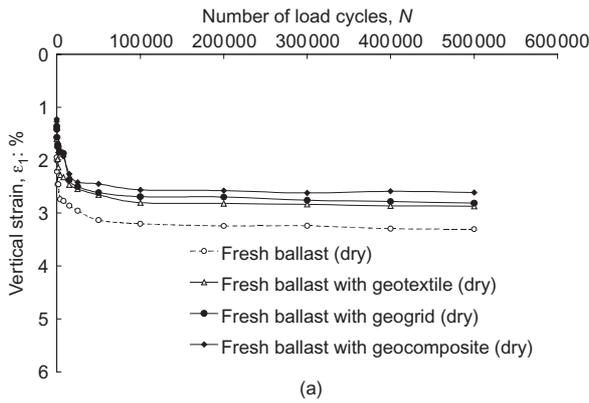


Fig. 14. Variation of vertical strain of ballast under cyclic loading: (a) fresh ballast (dry specimens); (b) recycled ballast (dry specimens); (c) recycled ballast (saturated specimens)

Fig. 15. Variation of lateral strain of ballast under cyclic loading: (a) fresh ballast (dry specimens); (b) recycled ballast (dry specimens); (c) recycled ballast (saturated specimens)

that of fresh ballast at a higher number of load cycles. As can be seen in Figs 13–15, the deformation results for ballast specimens tested in dry conditions were similar to those for saturated samples but indicating less settlement, vertical strains and lateral strains.

Particle breakage

In order to evaluate the breakage index (Marsal, 1967), each ballast specimen was sieved before and after the test, and the changes in ballast grading were recorded. Fig. 16 shows the variation of ΔW_k with different grain sizes of ballast. The breakage index values of different ballast specimens used in this study are given in Table 2 for comparison. It is clear that fresh ballast indicates the least degradation, whereas recycled ballast is more vulnerable to breakage. The

inclusion of geosynthetics in recycled ballast increases its resistance to degradation. However, the inclusion of geosynthetics in fresh ballast has insignificant effect on the reduction of ballast degradation.

The test results indicate that recycled ballast experiences 97% more breakage than fresh ballast under similar loading conditions. The presence of microcracks in the recycled ballast from previous loading cycles is believed to be a major reason for its higher particle degradation. The inclusion of a geogrid–geotextile composite layer in the recycled ballast decreases particle breakage by about 48% (in dry conditions) and 50% (in wet conditions). According to the experimental results, there is no doubt that recycled ballast stabilised with geocomposites ($B_g = 1.60$) is as good as fresh ballast ($B_g = 1.63$) in terms of breakage assessment.

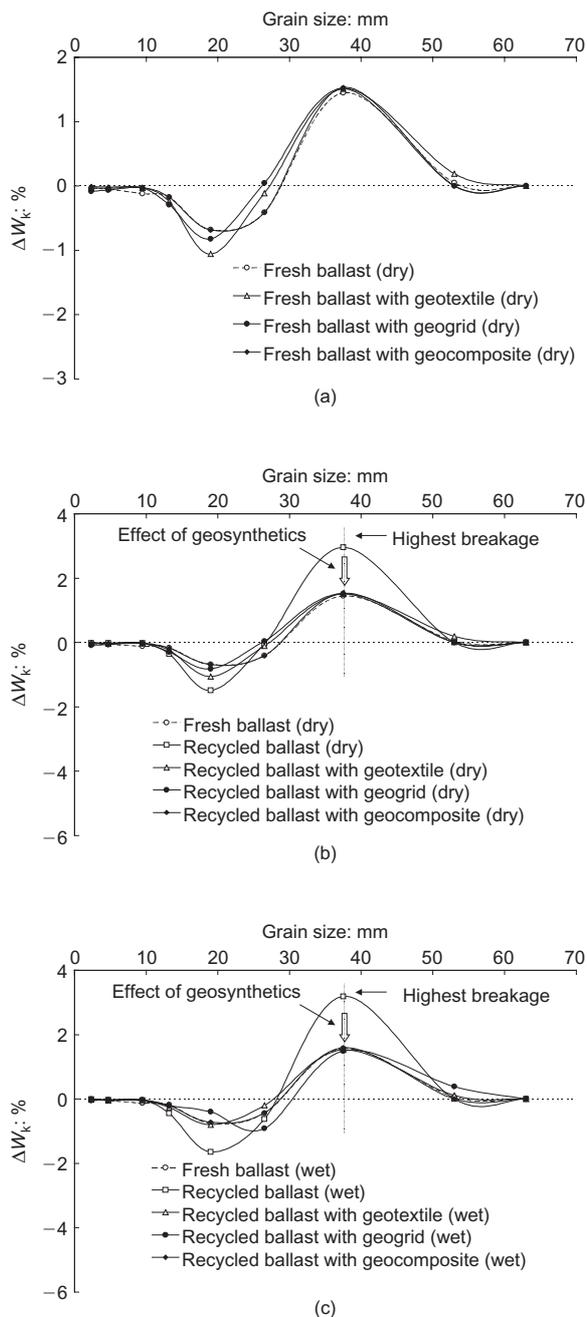


Fig. 16. Change in particle size of ballast under cyclic loading: (a) fresh ballast (dry specimens); (b) recycled ballast (dry specimens); (c) recycled ballast (saturated specimens)

Conclusions

Comprehensive research is being undertaken by the authors at the University of Wollongong to investigate the characteristics of railway substructure with the aim of providing better guidelines to construct stronger, safer and more economical tracks. For the design of railway track structures, the accurate geotechnical properties of the ballast layer are required. Because tests on scaled-down aggregates cannot be relied on for the prediction of ballast characteristics, and also to avoid size effects caused by coarse aggregates, the triaxial cell/chamber needs to be very large to establish a uniform stress-strain situation over the area where the actual measurements take place. The two large-scale triaxial rigs (cylindrical and prismatic) designed and installed at the University of Wollongong are ideal for simulating track conditions and for evaluating the properties of ballast.

Table 2. The role of geosynthetics in the degradation of ballast

Type of test	Breakage index, $B_g = \sum(\Delta W_k > 0)$	
	Sample in dry condition	Sample in wet condition
Fresh ballast	1.50	1.63
Recycled ballast	2.96	3.19
Recycled ballast with geotextile	1.56	1.64
Recycled ballast with geogrid	1.70	1.88
Recycled ballast with geocomposite	1.52	1.60
Fresh ballast with geotextile	1.54	—
Fresh ballast with geogrid	1.49	—
Fresh ballast with geocomposite	1.42	—

The physical and mechanical properties of ballast that affect the performance of rail tracks have been discussed. The results of cyclic tests on ballast, based on large-scale cylindrical triaxial testing, indicate that the ballast particle size distribution has a significant influence on ballast degradation, with the uniformly graded distribution being the most prone to breakage.

The findings of this study suggest that the deformations of fresh and recycled ballast vary non-linearly with the number of load cycles. Irrespective of the type of ballast, reinforcement and saturation, the settlement of ballast stabilises within about 100 000 load cycles. The experimental results of this study clearly showed that with the insertion of any type of selected geosynthetic the extent of degradation and settlement in fresh and recycled ballast were reduced. It is also recommended that a bonded geosynthetic be employed because of the need to prevent the ingress of liquefied mud into ballast voids under cyclic loads, and to maintain an efficient pore pressure dissipation layer. The effectiveness of geosynthetics in improving fresh ballast behaviour (deformation and degradation) was marginal, whereas it was more evident when used with recycled ballast in wet or dry conditions.

According to the results, the inclusion of geocomposites in recycled ballast reduces the breakage index almost to that of fresh ballast (without geosynthetics). Hence the use of recycled ballast stabilised with geosynthetics would be a cost-effective and environmentally attractive option.

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Discussion contributions on this paper should reach the editor by 3 January 2007