Sustainable Transport Infrastructure Adopting Energy - absorbing Waste Materials

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Abstract. Ballasted rail tracks are the most common type of transportation infrastructure. However, ballast progressively degrades under dynamic loads and impact loads. The degree of degradation will be accelerated due to the increasing demand for higher-speed passenger trains and heavier axle load freight transportation. It is therefore those novel technical methods are adopted to enhance track conditions. Over the past two decades, many studies have been conducted by the researchers of Transport Research Centre (TRC) at the University of Technology Sydney (UTS) to investigate the ability of recycled rubber mats/pads, as well as waste tyre cells and granulated rubber to improve the stability and longevity of rail track. This paper presents an overview of these novel methods and materials used in recent studies based on large scale laboratory tests (i.e. cubical triaxial tests and drop hammer impact tests) and numerical modelling. Moreover, in an effort to put theory into practice, the performance of under ballast shock mats placed at ballast-bridge deck interfaces has been investigated in field tests carried out at Singleton (near Newcastle, Australia). The test results and the numerical modelling show that rubber inclusions will greatly improve overall track performance.

Keywords: Recycled Rubber, Ballast degradation, Large-scale Laboratory Tests, Finite Element Modelling, Field Test.

1 Introduction

By 2018, the Australian rail network had more than 36,000 km of track and ranked seventh highest worldwide [1]. Until recently most of these tracks had been built with ballast, but ballasted tracks deteriorate progressively as the ballast breaks due to particle splitting and attrition and abrasion from dynamic loading during service. This process of degradation will exacerbate because faster and heavier trains are needed to cope with the growing population and increasing freight movements. In addition, the impact loading caused by rail and /or wheel imperfections and irregularities also inevitably intensifies ballast degradation [2], and this will lead to costly and more frequent track maintenance. It is, therefore, imperative to improve the design of rail track and concentrate more on the track substructure, including ballast, subballast and subgrade layers, to solve the geotechnical problem of ballast degradation.

The adoption of artificial geo-inclusions such as resilient rubber materials, geogrids and geocomposites has already proved to be a very efficient method of mitigating the degradation and deformation of ballast [2-28]. In recent years, the use of recycled rubber products such as rubber mat/pats, tyre cells, and granulated rubber has prevailed over other materials due to their high energy absorbing capacity and high damping property [9-15]. Esmaeili et al. [16] found that adding 5% of tyre derived aggregates could reduce the breakage of fouled ballast by 34%, while Signes et al. [17] proved that mixing 1-10% of rubber particles with subballast helps rail tracks resist degradation, and Indraratna et al. [18] found that installing under ballast mats at the ballast-deck interface attenuates the impact of dynamic train load imparted by the running stock.

Since there is no comprehensive scientific evidence on ballast degradation and its associated load-deformation responses under cyclic and impact loading when recycled rubber materials are incorporated in track embankment, this paper reviews current research in this area carried out by the researchers of the current Transport Research Centre (TRC) currently at the University of Technology Sydney (UTS) over the past decades. This research consists of a series of prototype cubical triaxial tests and drop hammer impact tests to examine the performance of under sleeper pads (USP), under ballast mats (UBM), rubber energy absorbing drainage sheets (READS), tyre cell reinforced track and a synthetic energy absorbing layer (SEAL; a matrix of rubber crumbs and mining rejects). It also consists of finite element modelling (FEM) for track reinforced with tyre cells and field tests for shock mats (UBM) with geogrids.

2 Large-scale Laboratory Tests

2.1 Large-scale Cubical Triaxial Tests

Testing Facility and Sample Preparation. Large-scale cubic triaxial tests were conducted using the prototype track process simulation testing apparatus (TPSTA) as shown in Fig. 1a. It has a machine chamber that is 600 mm deep by 800 mm long by 600 mm wide; these dimensions duplicate a unit cell of the Australian standard track. The four sidewalls are allowable to move to simulate the lateral deformation in the longitudinal and transverse direction of the track. In this study, longitudinal deformation of the track is assumed to be negligible (i.e. plain strain condition), so during the test the sidewalls parallel to the sleeper were locked in position by the hydraulic systems.

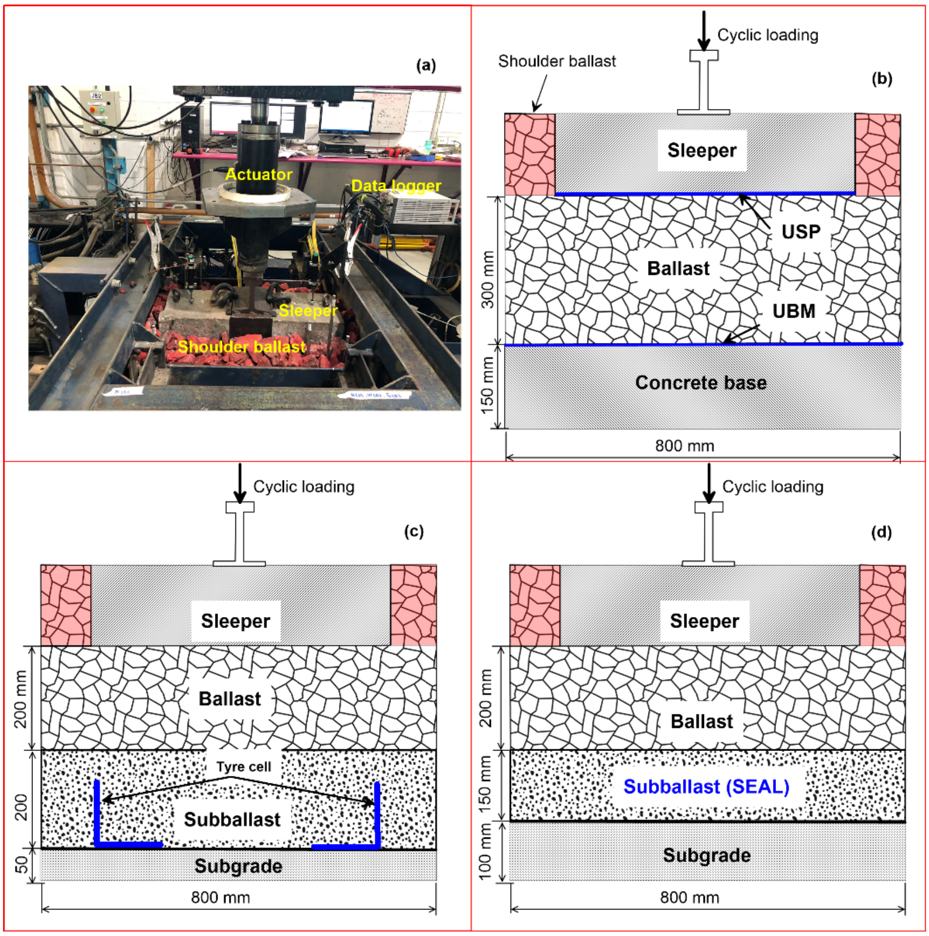

Fig. 1. (a) Cubical cyclic triaxial apparatus; schematic illustrations of (b) test specimens with USP or UBM, (c) tyre-cell reinforced track specimen and (d) test specimen incorporated SEAL (modified after [7]).

The test specimens with either rubber mats (UBM) or rubber pads (USP) were tested with stiff subgrade condition to simulate tracks built in a tunnel or on a bridge deck. Therefore, the test specimen was prepared with a ballast layer (depth: 300 mm) sitting on a 150 mm thick concrete base (Fig. 1b). The USP ($790 \times 200 \times 10\ mm$) and UBM ($790 \times 590 \times 10\ mm$) were made from recycled tyres by removing the steel cords and fibre, and Fig. 1b shows their positions in the test specimen. The test sample reinforced with a tyre cell was prepared with three layers, a 200 mm thick layer of ballast, a 200 mm thick layer of subballast filling in a tyre cell, and a 50 mm thick layer of subgrade (Fig. 1c). The tyre cell was made from the recycled tyres by removing one sidewall. The test specimen incorporating SEAL has also been compacted in three layers as shown in Fig. 1d. The novel subballast i.e. SEAL was a mixture of recycled rubber crumbs (RC) and mining rejects, i.e. coal wash (CW) and steel furnace slag (SFS). The

SEAL matrix was prepared with different amounts of RC and SFS:CW=7:3 mixed by mass suggested by Indraratna et al. [8] and Qi et al. [19] to avoid unacceptable particle degradation of CW and volumetric expansion of SFS while maintaining sufficient strength of the waste SEAL matrix.
All cyclic triaxial tests were running with a loading frequency of f=15 Hz to simulate the train speed of 115 km/h [11]. The specimen reinforced with a tyre cell was tested under the maximum vertical stress of 385 kPa to simulate a heavy haul freight train having a 40-tonne axle load, while the remaining tests had a lower vertical pressure of 230 kPa for a normal 25-tonne axle load train. All the cyclic loading tests were completed when 500,000 cycles were achieved. Details of how the specimen was prepared and tested can be found elsewhere [4, 11, 20, 21].

Vertical and Lateral Displacement. Test results for vertical and lateral deformation changing with loading cycles of the test specimen are shown in Fig. 2. All the test specimens settled quickly within the first several thousand cycles caused by particle densification and ballast breakage, and then gradually stabilised after 100,000 cycles. Note that with stiff subgrade the addition of rubber mats/pads (i.e. UBM, USP) reduces the settlement and lateral displacement of ballast, but the addition of USP is more efficient than UBM (Fig. 2a-b). Having a tyre cell in the subballast layer reduces settlement by 10-12 mm under a heavy track loading condition compared to the unconfined test specimen (Fig. 2c). The lateral deformation of the test specimen reinforced with a tyre element shows contraction, whereas the test specimen without a tyre cell is dilative (Fig. 2d). This is mainly because tyre cells included in the subballast layer increase the confining pressure on the specimen and prevent the particles from moving outward [11]. Fig. 2 (e&f) shows the settlement and lateral movement of a specimen with SEAL. It can be seen that increasing the amount of RC inside SEAL the settlement increases, but lateral dilation decreases when RC<20% and there was a large lateral fluctuation when the RC $\geq$ 20%. The specimen with 40% RC in SEAL failed within 1500 cycles due to excessive vibration and settlement [21]. This test result indicates that a certain amount of RC (10%) in SEAL will help to reduce the lateral dilation and vertical displacement of a traditional track specimen, whereas too much RC included may induce track instability (e.g. extensive vibration and settlement).

Ballast Degradation. After each test, the ballast compacted directly under the sleeper was separated collected to check the particle size distribution (PSD) curve to evaluate ballast degradation using the ballast breakage index (BBI) which is initially developed by Indraratna et al. [22]. The BBI is defined in Fig. 3a, and Fig. 3 (b-d) shows BBI for the specimen with different rubber inclusions under different test conditions. It is obvious that BBI decreases as the damping rubber products (i.e. UBM, USP, tyre cell or rubber crumbs) are incorporated in the track specimen regardless of the test conditions. As with the response of vertical deformation, the inclusion of USP is more effective than UMB, as USP reduces the BBI of the track specimen by 60%, while the UBM reduces the BBI by 24%. Ballast breakage under heavy haul loading conditions is more severe with BBI=0.2, but when confined by a tyre cell the BBI decreases significantly to 0.063. The BBI of the track specimen that incorporates SEAL without RC is similar to the traditional track specimen, but it decreases by more than half when 10% of RC is included in the SEAL matrix. However, when more RC (>10%) is added to SEAL, the BBI does not reduce more, which suggests that 10% RC in SEAL is enough to mitigate ballast degradation.

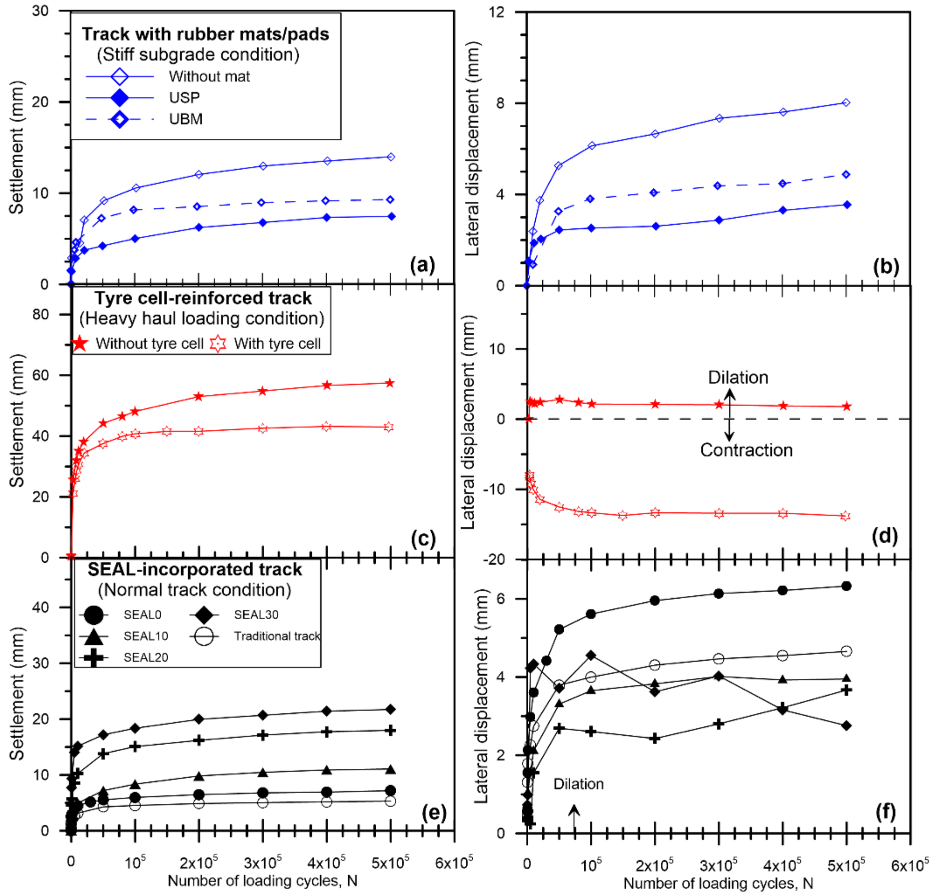

Fig. 2. Cubical cyclic test results of the vertical and lateral displacement for (a-b) test specimen with and without rubber mats/pads, (c-d) tyre cell reinforced track specimen and (e-f) test specimen incorporated SEAL [data sourced from 4, 11, 20, 21].

2.2 Drop Hammer Impact Tests

Test Facility and Sample Preparation. The dynamic impact force at the transition zones (between soft and stiff subgrade conditions) of the ballasted track is one of the key factors that induce the track instability and ballast degradation. Ngo et al. [23] proposed a solution that using a rubber energy absorbing drainage sheet (READS) placing underneath the ballast layer to attenuate the impact force and reduce ballast degradation. They then examined its efficiency through a series of large-scale impact loading tests using the drop hammer impact apparatus shown in Fig. 4a. The test sample was prepared within a rubber membrane and the schematic illustration of the test specimen is shown in Fig. 4b where a 10 mm-thick READS made from recycled rubber was installed between the ballast layer (depth: 350 mm) and the sub-ballast layer (depth: 100 mm). The 50 mm thick layer of subgrade was either soft or stiff (concrete base). Each test took 15 drops from 100-250 mm high to simulate an impact force between 250 and 550 kPa. Details of the test procedures and materials can be found elsewhere [23].

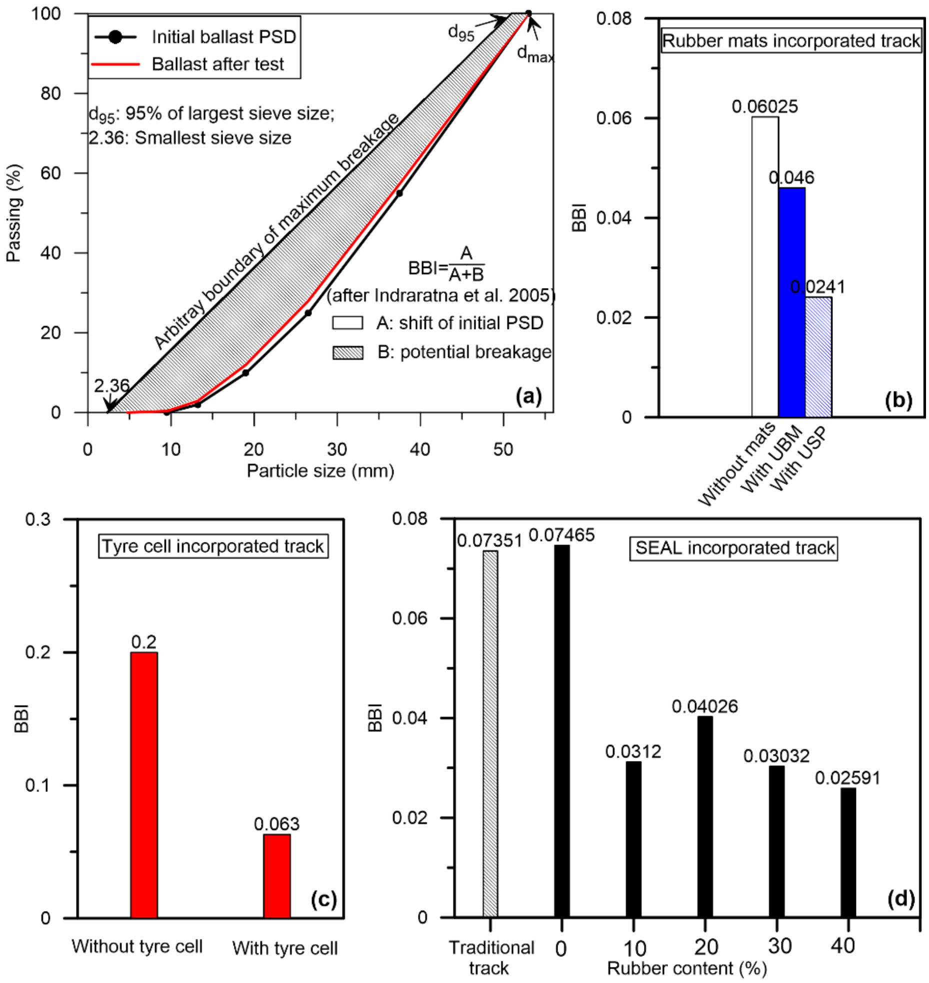

Fig. 3. (a) Definition of the ballast breakage index (BBI); BBI of (b) track specimens with USP/UBM, (c) tyre cell confined track specimens and (d) SEAL incorporated track specimen [data sourced from 4, 11, 20, 21]

Test Results. The final vertical and lateral ballast deformation of test specimens subjected to impact force with and without READS is shown in Fig. 5 (a-d). Note that the vertical and lateral movement increase with the drop height (h_d, mm) regardless of the subgrade conditions and they decrease when READS are placed under the ballast. Without READS the vertical and lateral deformation of the test specimen with a stiff subgrade is similar to those with a soft subgrade. To better evaluate the efficiency of using READS under different subgrade conditions, the percentage reduction in vertical and lateral deformation and breakage is shown in Fig. 5 (e-f).

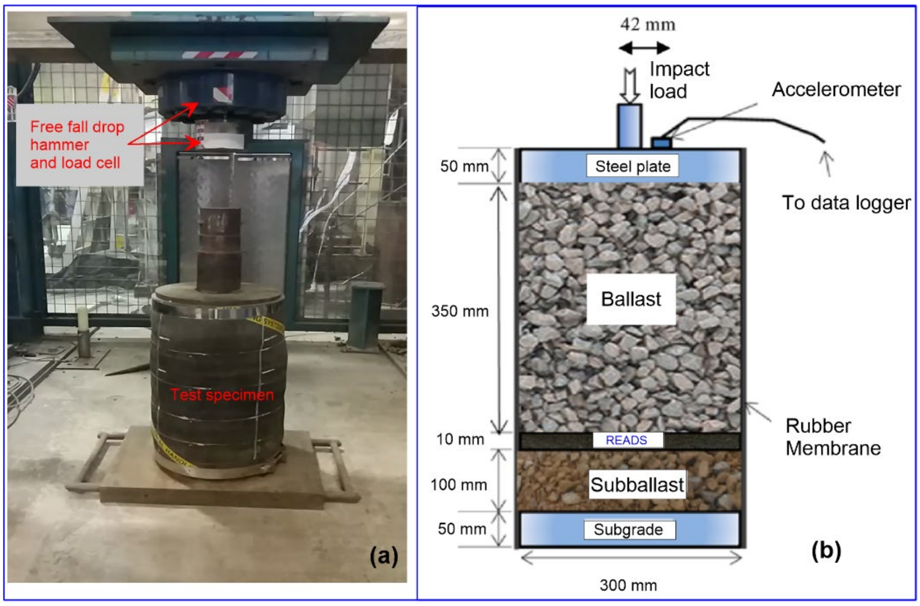

Fig. 4. (a) Drop weight impact apparatus with a prepared test specimen; (b) Schematic illustration of the test specimen for the impact test [modified after 23].

The percentage reduction factor (%) in vertical displacement (R_v), in lateral deformation (R_h), and in ballast breakage index (R_b) can be calculated as:

$$R_v = (1 - \frac{S_{v(WithREADS)}}{S_{v(NoREADS)}}) \times 100) \tag{1}$$

$$R_h = (1 - \frac{S_{h(WithREADS)}}{S_{h(NoREADS)}}) \times 100 \tag{2}$$

$$R_b = (1 - \frac{S_{b(WithREADS)}}{S_{b(NoREADS)}}) \times 100 \tag{3}$$

where S_v, S_h, and S_b are the vertical displacement, horizontal (lateral) deformation and BBI of the test specimen. It is obvious that the reduction in BBI and lateral deformation by adding READS is more pronounced with a stiff subgrade, whereas the reduction in vertical deformation is comparable for both types of subgrade. Note also that READS can help to reduce the vertical deformation by approximately 7-15% and BBI by up to 28% on the stiff subgrade. These results corroborate the energy absorbing concept for using rubber inclusions that when more energy is absorbed in the resilient rubber layer, the energy exerted onto the ballast and other track substructure layers will be attenuated and thus reduce ballast breakage and track deformation [10, 21].

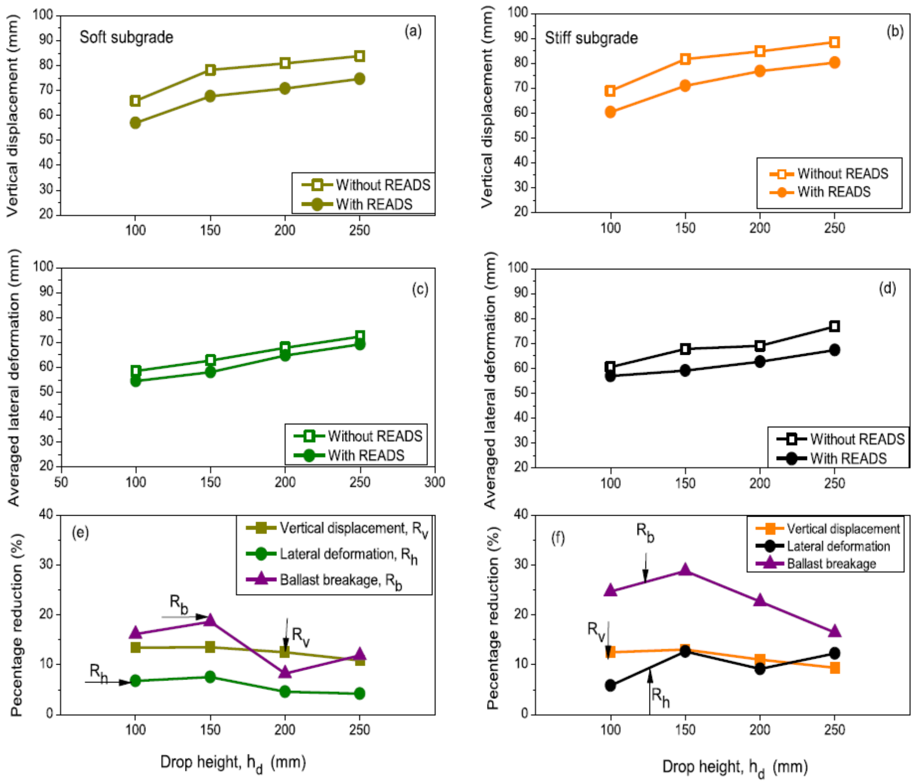

Fig. 5. Large-scale impact loading test results of the test specimen with and without READS: (a-b) vertical deformation, (c-d) average lateral deformation and (e-f) percentage reduction for deformation and ballast degradation [23]

3 Finite Element Modelling of using Waste Tyres in Tracks

Scrap tires are a major environmental concern because every year Australia produces more than 50 million waste tires, and since only 13% are recycled the remainder goes into landfill or illegal dumping. Recent research at the University of Wollongong Australia (UOW) indicates that waste tires installed under track foundations (Fig. 6a) will increase track bearing capacity and reduce lateral displacement. A three dimensional finite element analysis (3D-FEM) using ABAQUS is implemented (Fig. 6b) to examine the induced stress-displacement response of a sub-ballast layer that consists of infilled rubber tyres. For the sake of brevity, further details about the model setup, and the loading and boundary conditions can be found in [24].

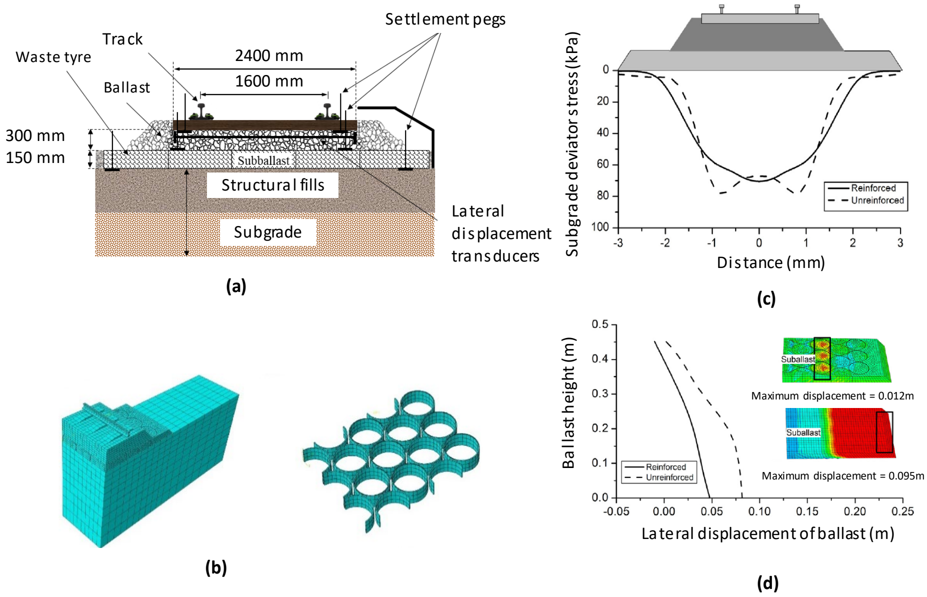

Fig. 6. (a) Typical track dimensions with rubber tyres reinforced capping layer; (b) FEM mesh for tracks and the tyre assembly; (c) stress distributions below reinforced and unreinforced track; (d) simulated lateral displacements [modified after 24].

Fig. 6c shows how rubber tyres reduce the deviator stress on the subgrade. It is predicted that the maximum deviator stress happens at the ends of sleepers and decrease towards the middle of the track. The FEM simulations show that a tyre reinforcement assembly has reduced stress by almost 12% compared to an unreinforced track section (for a 25-tonne axle load, speed: 90 km/h). Essentially, the additional confinement supplied by the tyres stiffens the gravel-infilled composite aggregates and allows more uniform stress to be transmitted to the underlying layers. Fig. 6d shows the typical contours of horizontal displacement predicted for the sub-ballast; here the highest lateral deformation of the unreinforced track is higher than the reinforced case because the additional lateral confinement provided by the tyre stiffens the infill-aggregate assembly enables a more uniform load to be transferred to the underlying subgrade; as a consequence, there is reduced lateral displacement. The results from large-scale laboratory tests and numerical modelling indicate that placing recycled tyres under the ballast layer will greatly improve overall track stability.

4 Field Test

To investigate how different geo-inclusions and shock mats affect track performance, a field case study was carried out on fully instrumented tracks at Singleton, NSW Australia (Fig. 7a). This track belongs to the Australian Rail Track Corporation (ARTC).

Construction of Tracks. Eight sections of instrumented track were built on different types of subgrades, (i) relatively soft soils mixed with alluvial-silty clay deposits, (ii) stiff reinforced concrete bridge decks (Mudies Creek), and (iii) siltstone based subgrade. A typical track substructure was built on a 300 mm thick ballast followed by a 150 mm thick sub-ballast (capping). A 500 mm thick structural fill layer was laid above the subgrade. Three types of geogrids and geo-composite (geogrid + non-woven geotextiles) were installed below the ballast layer. The biaxial geogrids include: (1) geogrid_G1 (aperture: 44×44 mm, tensile strength: 36 kN/m); (2) geogrid_G2 (aperture: 65×65 mm, tensile strength: 31 kN/m); and (3) geogrid_G3 (aperture: 40×40 mm, tensile strength: 30 kN/m). A geo-composite layer (aperture size: 31×31mm, tensile strength: 40 kN/m) attached to a non-woven polypropylene geotextile (weight: = 150 g/m^2, thickness=2.9 mm). A rubber mat (shock absorbing mat) was placed under the ballast at the bridge-deck to eliminate ballast breakage (Fig. 7b). More details on the engineering properties of these materials are contained in Indraratna et al. [25].

Track Instrumentation and Measurement. Different sensors and instrumentations were used to record data, as shown in Fig. 7c. Strain gauges installed on the grid were used to measure mobilized strains. Dynamic stresses induced by train passage were recorded by 200mm diameter pressure plates, and the vertical deformation of ballast was measured by electronic potentiometers(Fig. 7d). Settlement pegs were also used to capture the vertical displacement of the ballasted tracks. Electrical analogue signals from instrumentation and sensors were imparted using a mobile data logging system at a frequency of 2000Hz (Fig. 7e). More details of the instrumentation, the data acquisition process, and the layout of sections have been described earlier by Indraratna et al.[25, 26].

Measured settlements. Fig. 8 shows the vertical settlement S_v of ballast measured with increased load cycles, N recorded for soft subgrades and concrete bridge (hard rock). These results indicate that the increasing rate of S_v decreases as the number of load cycles N increases. The S_v for the reinforced tracks is almost 10-30% less than unreinforced tracks, proving how geogrid has reduced track settlement. A similar pattern is also observed in the laboratory [27], mainly due to the particle-geogrid interlock that reduces ballast settlement. Moreover, it is also clear that the geogrid is much more effective to eliminate the settlement of tracks built on the soft subgrade.

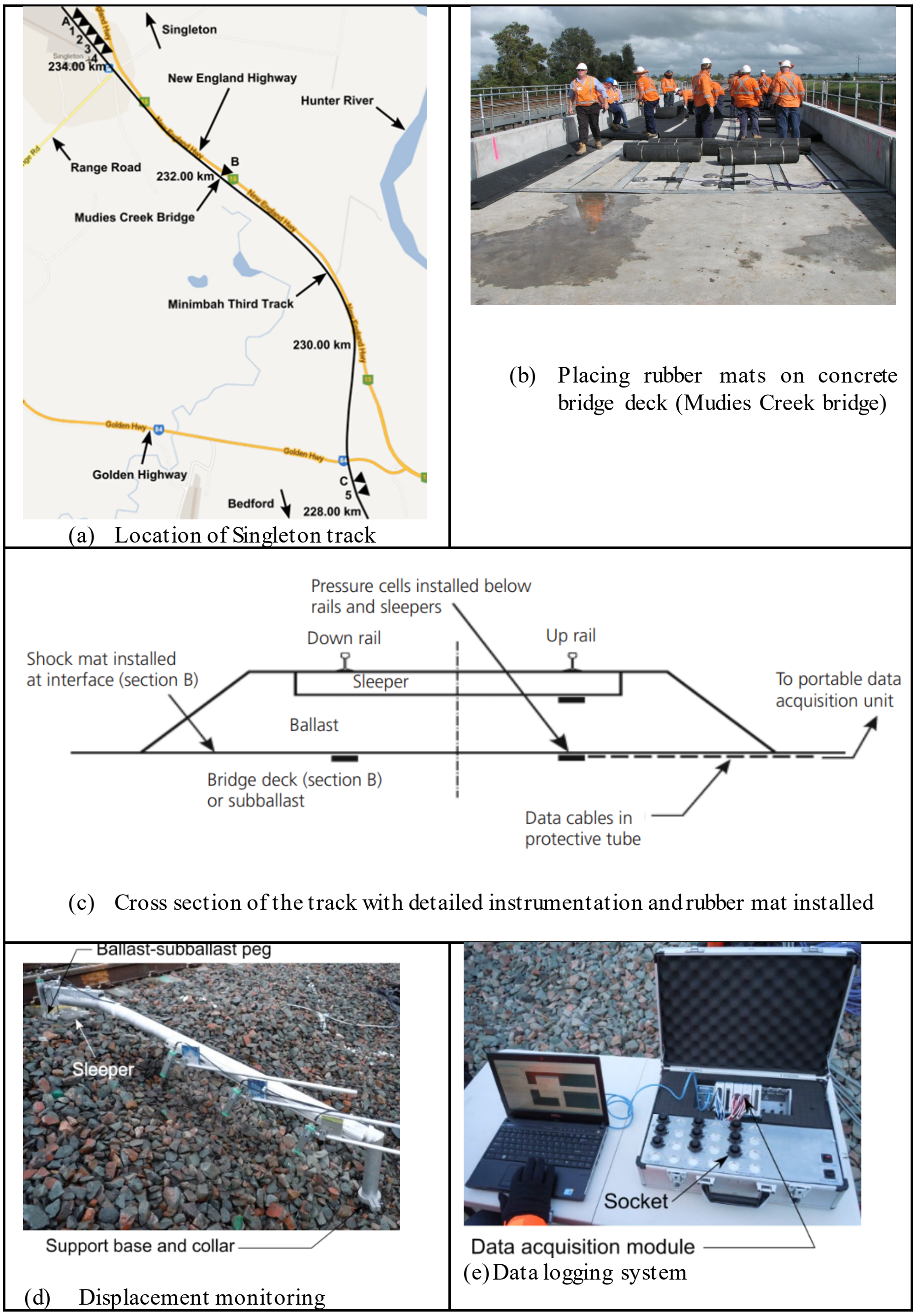

Fig. 7. Details of instrumentation of experimental sections of track at Singleton (modified after Indraratna et al. [25])

Ballast Breakage. Selected ballast aggregates were collected from beneath the sleepers as these locations appeared to be more prone to crushing due to higher load distribution. The ballast breakage index (BBI) was used to measure the breakage and the results are presented in Table 1. The BBI is largest at the top of the ballast layer, and then reduced with depth. The BBI is less than 0.05 (BBI=5%) which shows that minimal breakage occurs when obtaining these measurements. The higher stresses also cause more ballast breakage due to increased inter-particle contact forces. For the alluvial-deposit subgrade, there is a larger settlement due to more breakage occurs in these track sections. The smallest breakage occurs at the concrete-bridge decks, which shows that the shock mat has mitigated particle degradation. The measured data clearly reveals how rubber shock mats installed on concrete bridge decks reduces ballast breakage. This is mainly because the rubber mat (shock mat) absorbs the kinetic energy caused by the moving train and as a result, less impact energy is being transmitted to ballast aggregates causing reduced breakage [23].

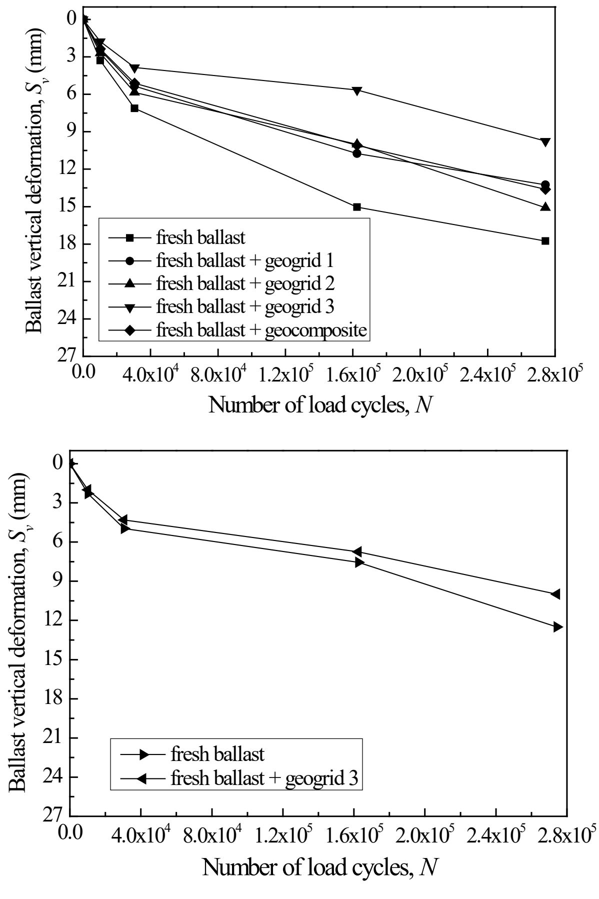

Fig. 8. Measured settlements of ballast for (a) soft subgrade; (b) hard rock (data source: Indraratna et al., [25]).

Table 1. Measured ballast breakage (data source: Indraratna et al. [24])

No.	Subgrade conditions	Ballast breakage index (BBI) for		
		Top layer	Middle layer	Bottom layer
1	Alluvial-silty clay (track section A)	0.17	0.08	0.06
2	Concrete-bridge (track section B)	0.06	0.03	0.02
3	Siltstones (track section C)	0.21	0.11	0.09

5 Conclusions

This paper has introduced several innovative methods of using recycled rubber products such as under ballast mats (USM), under sleeper pats (USP), a synthetic energy absorbing layer for subballast (SEAL- a mixture of mining waste and rubber crumbs), rubber energy absorbing drainage sheets (READS), and a tyre cell confined capping layer. Large-scale cubical cyclic triaxial tests and drop hammer impact tests, and finite element modelling and field tests were carried out to investigate how efficiently these recycled rubber products could reduce ballast breakage and deformation, the salient findings are summarised as follows:

- Cubical cyclic triaxial tests revealed that the inclusion of USPs and UBMs and the use of the tyre cells to enhance the capping layer, efficiently reduced ballast degradation and track deformation (settlement and lateral dilation). Also, adding 10% rubber crumbs in SEAL significantly reduced ballast breakage and lateral displacement, and also ensured the settlement of the track specimen was comparable to a traditional track specimen.
- The drop hammer impact loading test showed that READS reduced ballast breakage and deformation (vertical and lateral) under impact loading regardless of the subgrade conditions (stiff or soft), albeit there was more reduction in settlement and BBI with a stiff subgrade.
- The FEM simulation of track reinforced with tyre cells further validated their ability to provide greater uniform lateral confining pressure to the track and thus reduce lateral movement.
- The field tests carried out on the sections of track with geogrids and shock mats showed enhanced deformation and reduced ballast degradation due to the geogrid-particle interlock and the energy absorbing property of the rubber mats. The geogrid reinforcement was also found to be more efficient on softer subgrades.

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