Use of Synthetic Energy Absorbing Layer (SEAL) in Rail Substructure to Minimize Track Degradation

Buddhima Indraratna, PhD., FTSE, FASCE, FIEAust, FGS [1], Yujie Qi, PhD, AMASCE[2]
Trung Ngo, PhD., MASCE[3], and Cholachat Rujikiatkamjorn, PhD, MASCE[4]

[1]Distinguished Professor, Director of Transport Research Centre (TRC), Founding Director of Australian Research Council's Industrial Transformation Training Centre for Advanced Technologies in Rail Track Infrastructure (ITTC-Rail), University of Technology Sydney (UTS), 15 Broadway, Ultimo NSW 2007, Australia; E-mail: buddhima.indraratna@uts.edu.au
[2]Lecturer, Program Co-leader, Transport Research Centre (TRC), University of Technology Sydney (UTS), 15 Broadway, Ultimo NSW 2007, Australia; E-mail: yujie.qi@uts.edu.au
[3]Senior Lecturer, Program Co-leader, Transport Research Centre (TRC), University of Technology Sydney (UTS), 15 Broadway, Ultimo NSW 2007, Australia; E-mail: trung.ngo@uts.edu.au
[4]Professor, Program Leader, Transport Research Centre (TRC), University of Technology Sydney (UTS), 15 Broadway, Ultimo NSW 2007, Australia; E-mail: cholachat.rujikiatkamjorn@uts.edu.au

ABSTRACT

This paper presents novel solutions for increasing the stability and resiliency of track structures by developing a synthetic energy-absorbing layer (SEAL) using recycled rubber products based on large-scale laboratory tests (i.e., drop-hammer impact tests and cubic triaxial tests). This includes (i) installing recycled rubber mats under ballast, and (ii) using SEAL composed of a mixture of rubber crumbs, steel furnace slag, and coal wash with changing amounts of rubber: 0%, 10%, 20%, 30% and 40% (by weight) to replace traditional rockfill as subballast. The test results confirm that the inclusion of a recycled rubber mat underneath the ballast layer actively reduces ballast deformation and the propagation of impact loading within the depth of the substructure. Also, the SEAL mixture with 10% rubber reduces the track lateral dilation, reduces ballast breakage and load distribution, and also maintains an acceptable settlement.

INTRODUCTION

In Australia, ballasted tracks play a major role in freight and passenger transport. However, these traditional track foundations deteriorate fast due to ballast degradation as they are overloaded with heavier and faster trains; this has resulted in more frequent and costly track maintenance (Indraratna et al. 2021).

Recycled rubber products such as rubber mats and granulated rubber have recently been used for ballasted tracks to reduce ballast displacement and breakage to improve track performance (Costa et al. 2012, Koohmishi and Azarhoosh 2020, Indraratna et al. 2021). When placed beneath the ballast layer, their energy absorbing nature can be exploited to reduce the energy transferred from moving trains to the ballast and other track components, hence reducing their deformation and degradation (Hanson and Singleton 2006, Montella et al. 2012). Granulated rubber or rubber crumbs (RC), are usually mixed with other materials such as ballast, sand, or some other waste materials (e.g., steel slags and coal rejects) to form a synthetic energy absorbing layer (SEAL) that helps to mitigate ballast deformation and degradation, and while being environmentally friendly and economically attractive (Tiwari et al. 2012, Sol-Sánchez et al. 2015, Arachchige et al. 2021, Indraratna et al. 2021). The inclusion of rubber mats can eliminate the hard interface between the ballast and capping layer, which allows the interfaces to bed into each other, thus increasing the contact area, minimising the force concentration, and reducing track damage. On this basis, adding rubber mats as a new energy absorbing element in track substructure increases safety and passenger comfort, as well as being a more sustainable and cost-effective track design due to the utilisation of waste materials and the consequent reduction in ballast replacement (Indraratna et al. 2011, Esveld 2014, Ross 2020, Sai Malisetty et al. 2022).

This paper aims to introduce two novel applications for using waste rubber materials in rail tracks: (i) using SEAL composite made from a mixture of rubber crumbs (RC), steel furnace slag (SFS) from steel making industry and coal wash (CW) from coal mining industry to replace traditional subballast (usually natural sandy-gravel), and (ii) installing recycled rubber mats under the ballast. Large-scale drop hammer impact tests and cubical triaxial tests have been carried out to investigate their geotechnical performance, this includes settlement and lateral displacement, ballast degradation and distributed load, along with the depth or impact load.

THE APPLICATION OF SEAL COMPOSITES

Materials and Testing Program. In this section, granular waste SFS, CW, and RC are mixed together to form the SEAL composite to replace the traditional subballast layer. Large-scale cubical triaxial tests using the Track Process Simulation Apparatus (TPSA) were carried out to compare the performance of the test specimens with traditional materials and SEAL. A cross-sectional view of the test specimen is shown in Figure 1a where SEAL has been installed in the middle of the ballast and structural fill, over which there is a concrete sleeper and shoulder ballast.

The raw materials of SFS, CW, and RC were from Australian steel manufacturing, coal mining, and a waste tyre recycling company, respectively. To prepare the SEAL composite, the SFS and CW were first mixed with a blending ratio of 7:3 (by mass) to ensure the mixture has sufficient shear strength without generating excessive swelling pressure (Qi and Indraratna 2020). After that, 0, 10%, 20%, 30%, and 40% of RC (by mass) were added to form SEAL mixtures called SEAL0, SEAL10, SEAL20, SEAL30 and SEAL40, respectively. The ballast, traditional subballast, and structural fill materials came from a local quarry at Bombo, NSW, Australia. The maximum and minimum particle size (D_{max} and D_{min}), the uniformity coefficient (C_u), the coefficient of curvature (C_c), and the maximum dry unit weight γ_{max} of the SEAL composite, ballast, traditional subballast, and structural fill are listed in Table 1.

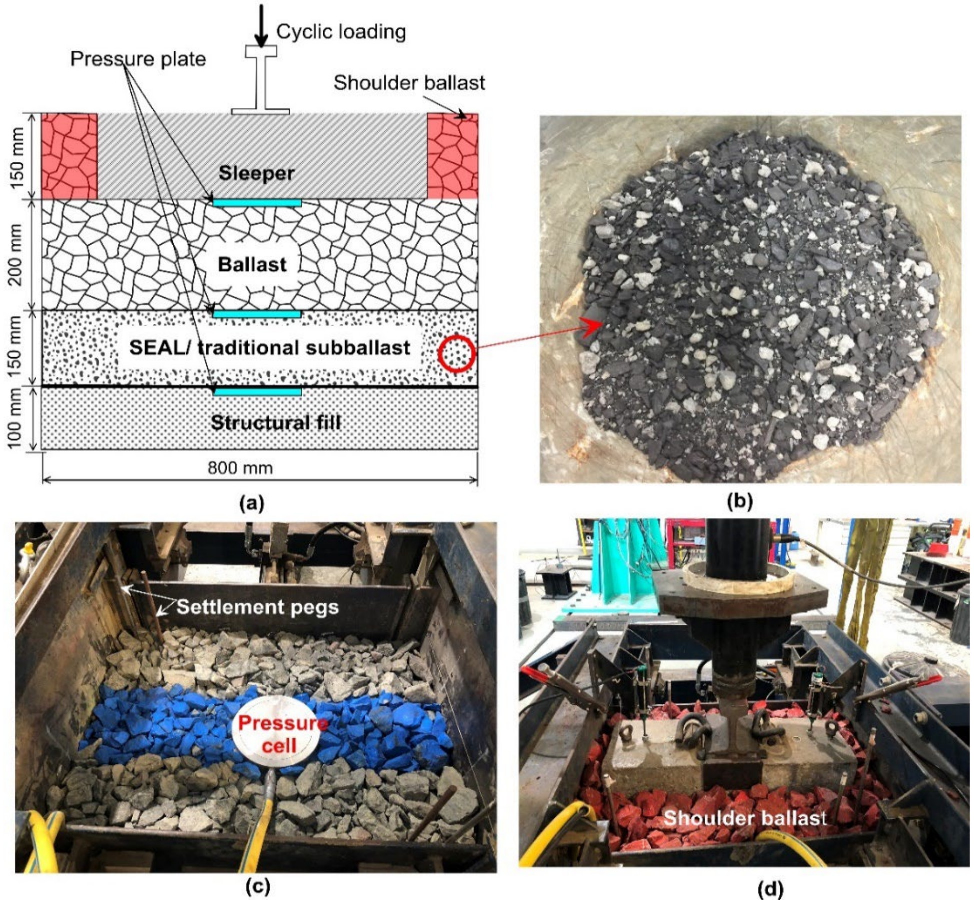


Figure 1. (a) Schematic diagram of the cubic triaxial specimen; (b) SEAL mixture with 10% rubber; (c) installing pressure on top of ballast layer; (d) a prepared specimen

Table 1. Basic properties of the materials used in this study

Materials	$D_{max}(mm)$	$D_{min}(mm)$	C_u	C_c	γ_{max}(kN/m^3)
SEAL composite	19	0.075	12	1.7	20.3-12.4
Ballast	53	9.5	2.84	1.4	15.3
Traditional subballast	19	0.075	16.3	1.3	18.5
Structural fill	26.5	0.075	2.4	1.1	21.4

The test specimen was prepared in a TPSA box with dimensions of 800 mm×600 mm in area, and 600 mm high to simulate a unit cell of rail track in Australia. The structural fill (100 mm thick) was compacted at the bottom of the sample box, then followed by subballast layer (150 mm thick) and a ballast layer (200 mm thick). Insignificant boundary effects have been verified by a track dynamic model by Qi and Indraratna (2022a). The subballast layer was either SEAL, by changing the amount of RC, or traditional subballast materials. A concrete sleeper and rail are placed on top of the ballast, and then shoulder ballast (shown as red in Figure 1ad) was place around it. To measure the pressure distributed from the cyclic loading to each layer, a pressure plate was placed at the interfaces of sleeper-ballast, ballast-subballast, and subballast-structural fill (Figure 1c). During the test, a sinusoidal cyclic load was applied from the actuator with the maximum value $q_{cyc,max} = 230\ kPa$, a minimum $q_{cyc,min} = 15\ kPa$, and a frequency of 15 Hz, to simulate a train with 25 ton axle load travelling at 110 km/h (Qi and Indraratna 2020). Also, the sidewalls of the test box, which are parallel to the sleeper, were fixed by applying an equivalent opposite stress from the hydraulic jacks, while the other two sidewalls, which are perpendicular to the sleeper were confined with a pressure of 15 kPa, but allowed to move enough to detect any lateral movement of the specimen under a plane strain condition. Each test finished after 50,000 loading cycles, unless the specimen failed earlier.

Deformation Response. Figure 2 shows the axial and lateral displacement of the test specimens changing with the loading cycles and subballast materials. It is expected that the axial and lateral movement (dilation) are increasing with the loading cycles. Note that except for the test specimen with SEAL40, which failed after 1500 cycles due to severe vibration and settlement (over 40 mm), all the other test specimens reach plastic shakedown with a minimum axial strain rate (<10^{-7} mm/mm/cycle suggested by Qi and Indraratna 2022b). Here, the plastic shakedown indicates that material settlement under cyclic loading stabilises with minimum axial strain accumulation (Indraratna et al. 2005); this is the preferred phenomenon for track foundation materials after being in service for a certain amount of time. Moreover, by increasing the amount of rubber in the SEAL composite, the axial displacement increases because the rubber-aggregate mixtures are more compressible. Lateral dilation also decreases when more rubber is used, however, when 20% or more rubber was added to the SEAL composite, the lateral movements fluctuates, indicating some lateral instability occurs. Overall, SEAL10 presents a promising deformation behaviour with reduced lateral dilation and comparable axial displacement compared to the traditional test specimen tested in this study and a previous study (Navaratnarajah et al. 2018) under similar loading conditions.

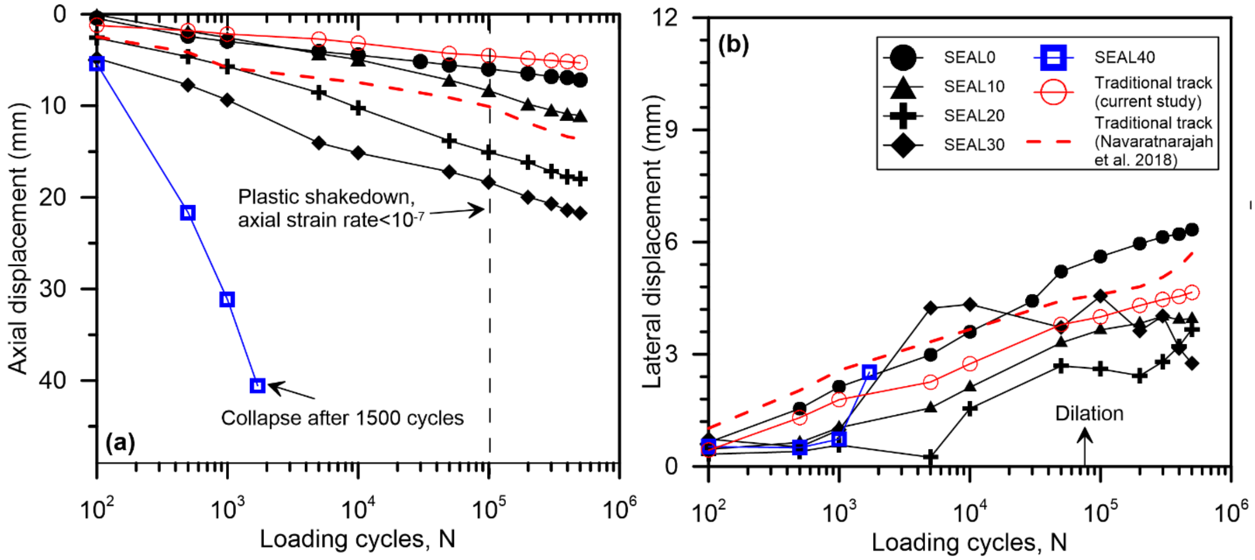


Figure 2. Deformation responses of track specimen changing with loading cycles (a) Axial displacement, (b) lateral displacement (modified after Qi and Indraratna 2020)

Ballast Breakage. When each test was completed, the ballast directly under the sleeper was separated and sieved to check for ballast particle breakage using the ballast breakage index (BBI; Indraratna et al. 2005). The BBI is calculated based on the initial and final gradation curves, as shown in Figure 3. The test specimen without rubber exhibits a similar BBI to traditional materials, but when 10% rubber was added in SEAL, a pronounced reduction in BBI (58% reduction) is achieved albeit adding more rubber (>10%) no more benefit can be seen.

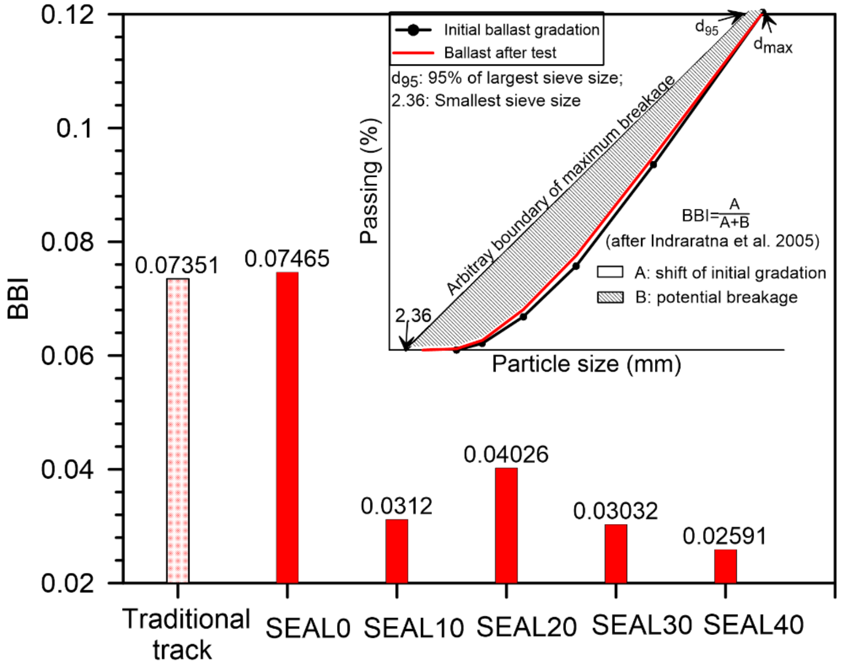


Figure 3. Ballast breakage index obtained after each test

Measured Pressure. Figure 4 shows the maximum pressure measured at the interface of the sleeper-ballast, ballast-subballast, and subballast-structural fill. Note that the distributed load decreases with depth. At the same interface, the pressure on the sample with SEAL10 was the minimum which is even less than that of the traditional track specimen. However, when increasing rubber content in SEAL, the test specimen experienced a higher distributed pressure. This may be because when more rubber is added (>10%), the skeleton of the SEAL composite is taken over by rubber materials which may generate higher elastic deformation, thus indicating more vibration which then intensifies the load amplification effect under cyclic loading (Qi and Indraratna 2020).

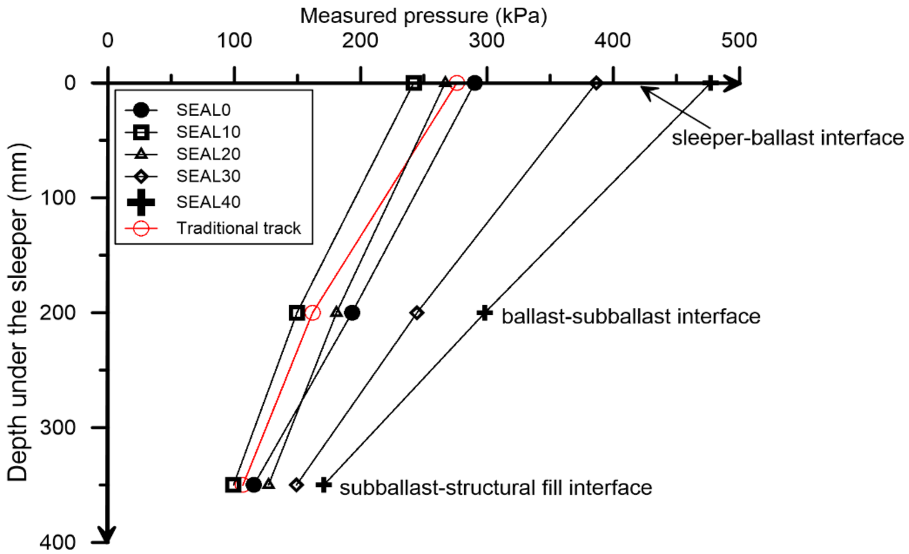


Figure 4. Measured pressure at the interface of sleeper-ballast, ballast-subballast, and subballast-structural fill (modified after Qi and Indraratna 2022b)

Overall, these test results further validate the comments from previous studies by the authors (Indraratna et al. 2021) that 10% is recommended in SEAL to help minimise ballast breakage efficiently, reduce the distributed pressure and lateral dilation, and achieve a comparable settlement compare to traditional materials.

ENHANCED TRACK PERFORMANCE WITH RECYCLED RUBBER MATS

In this study, an innovative recycled rubber mat made from recycled tyres, is placed underneath a ballast layer. The main functions of this mat are to provide: (i) energy absorption, (ii) load distribution, and (iii) a separation layer. This study is an attempt to study how effectively this recycled rubber mat can enhance the performance of ballasted tracks subjected to impact loads using high-capacity impact testing apparatus. The role of rubber mats in reducing the impact force, and the corresponding reduction in ballast deformation, is studied.

Testing Facility. A large-scale drop hammer impact testing apparatus is used in this study to investigate the role of recycled rubber mats in reducing impact loads and ballast deformation (Figure 5a). The test apparatus consists of a 5.81 kN weight hammer that can be dropped from a maximum height of 6 m to apply impact forces onto ballast specimens. A schematic diagram of a typical ballast specimen with a layer of recycled rubber mat is shown in Figure 5b. A cylindrical rubber membrane (7 mm thick, 300 mm in diameter) was used to accommodate the tested specimen. On top of the loading plate, an accelerometer was attached to measure acceleration during the impact tests. The impact forces were recorded during testing by a load cell installed on the hammer. A high speed camera was also set up and positioned in front of the ballast specimen to record the deformation of the ballast assembly during testing.

Materials and Test Program. The materials used in this current study consist of fresh ballast, capping layer (subballast), recycled rubber mats, and soft subgrade. The ballast and subballast materials are the same as shown in Table 1. The ballast and subballast were compacted in layers using a vibrating hammer to a total thickness of 350 mm and 100 mm, respectively. At the bottom of the test specimen, a 50 mm thick, soft subgrade (sandy-clay soil) was placed with a bulk unit weight of 18.5 kN/m^3. The subgrade layer can be replaced by a concrete base for tests carried out on stiff foundations (e.g. concrete bridge decks or crossings). Once the ballast sample was completed and correctly positioned in the testing facility, the initial height and circumference were measured at even spacings around the cell. The circumferences of the cell (i.e., lateral deformation) were measured at three positions: the bottom, the middle, and the top of ballast layer. A total of 16 tests were carried out on the specimen with and without recycled rubber mats under varying hammer drop heights of h_d = 100, 150, 200 and 250 mm. Each test was subjected to N=15 drops and vertical and lateral deformations of the sample were measured after each drop.

Measured Vertical Displacement. Figure 6 shows typical time histories of vertical settlement (S_v) of ballast measured at varying drops (with and without rubber mats) placed on a stiff concrete base and subjected to a hammer drop height of h_d =150 mm. The impact loads generate elastic initial settlement as well as plastic settlement. The ballast deforms from the initial position to the maximum displacement and then returns to a residual deformation within around 100 ms. Using a rubber mat below the ballast layer decreases the maximum and residual settlement, as expected. For instance, the maximum vertical displacement (i.e., after the 15th drop) of ballast specimens with and without rubber mat are S_v = 70.5 and 84.76 mm, respectively, while the corresponding residual settlements are recorded as S_v = 64.50 and 74.20 mm. Measured data shows that the ballast deformation is significant at the initial stage of impact loading (i.e., at the first 6 impact drops) which is associated with the reorientation, rearrangement, and corner breakage of ballast particles. Subsequently, the ballast deforms at a decreasing rate towards the end of testing.

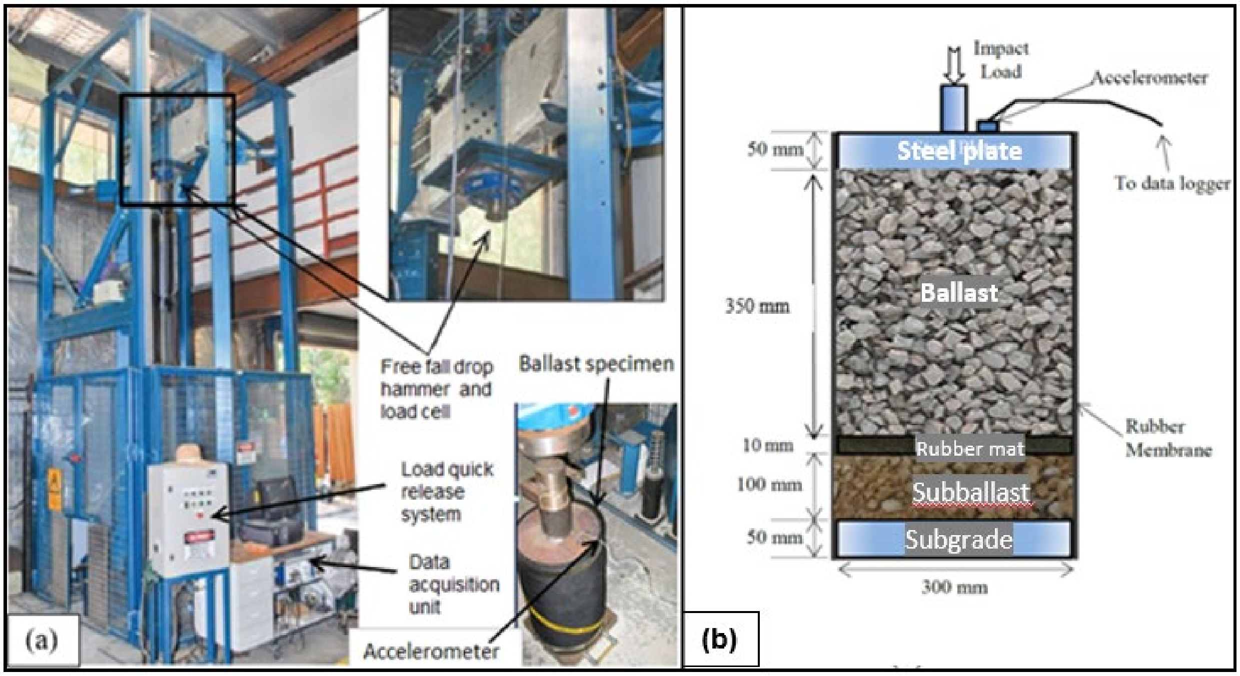


Figure 5. (a) Drop hammer impact apparatus; (b) Schematic diagram of test sample with recycled rubber mat (Source: Ngo et al. 2019 – with permission from Elsevier)

Figure 7 shows the typical lateral deformation of the test specimen before and after the 10th drop. Under impact loading the ballast aggregates were compressed and deformed in a lateral direction. The average accumulative lateral displacements (S_h) at three layers (located at points A, B, C in Figure 7a) for each test were measured after every drop (Ngo et al. 2019). It is observed that at the moment of initial contact, the hammer touches the top loading plate and the ballast assembly is compressed to its maximum vertical displacement and deforms laterally at a time duration of around $t = 15$ms (Figure 7b); the ballast assembly then rebounds upwards to its residual position (Figure 7c). The observed benefit of the recycled rubber mat in decreasing the lateral displacement of ballast fluctuated approximately 5-8% for a given drop height.

Impact Forces. The impact force measured from the test shows that all the test specimens have a similar time history pattern with multiple peaks (P_1) followed by a much longer duration of gradual peak with a smaller magnitude (P_2). Figure 8 shows the maximum impact forces P_1 and P_2 under different drop heights for both soft and stiff subgrades measured at the 15th (N=15) drop. Note that the P_1 is in the range of 154-500 kN while P_2 varies from 32 kN to 98 kN. Greater impacted forces are measured when the test specimens are over a stiff subgrade compared to the one with soft subgrade, leading to a higher vertical and lateral displacement. Adding rubber mats substantially decrease the magnitudes of P_1 and P_2; this is because that the rubber mats perform as an energy absorption layer to lessen the impact loads distributed to the ballast and other substructures.

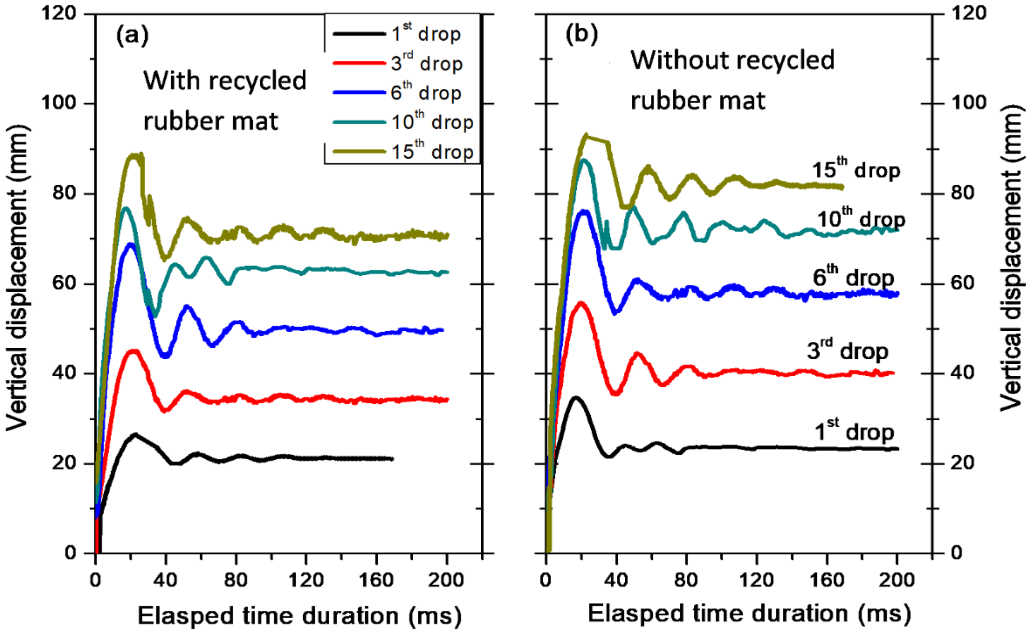
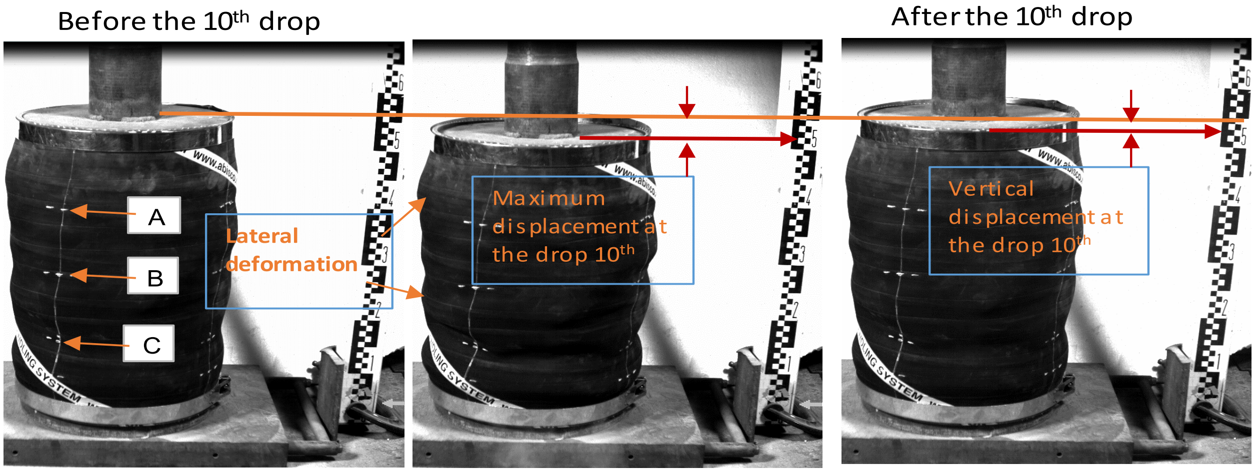


Figure 6. Vertical displacement of test specimen with stiff subgrade: (a) with and (b) without rubber mats (Source: Ngo et al. 2019 – with permission from Elsevier)



(a) t=0 (b) t=15ms (c) t=200ms

Figure 7. Lateral displacement of a test sample recorded at different time during the 10th hammer drop (Source: Ngo et al. 2019 – with permission from Elsevier)

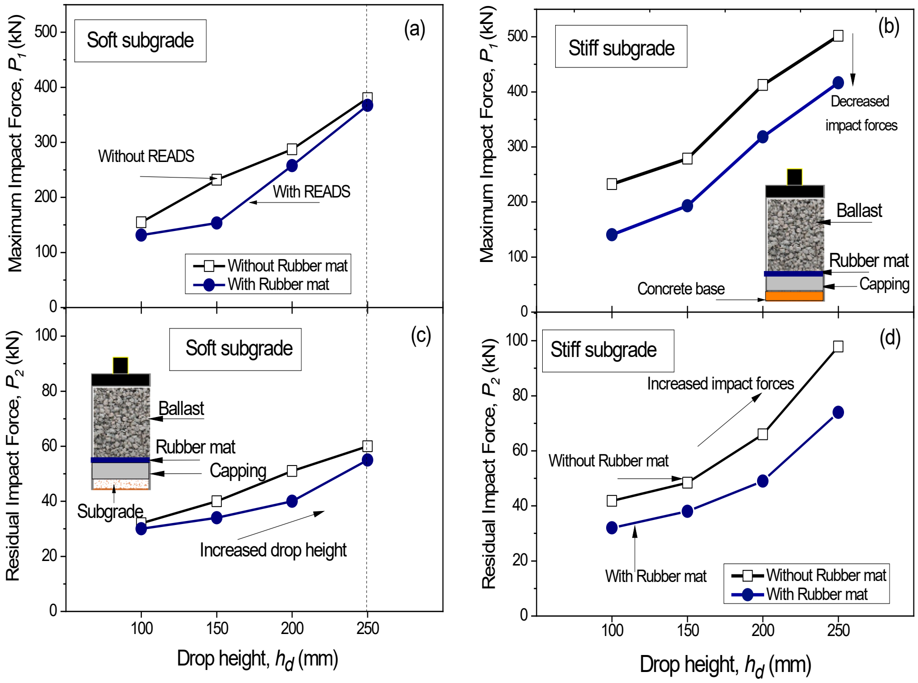


Figure 8. Impact forces of the specimen with and without rubber mat at the 15th drop: (a-b) P_1; (c-d) P_2. (Source: Ngo et al. 2019 – with permission from Elsevier)

CONCLUSION

This paper introduced two methods to improve track performance by using recycled rubber (i.e., rubber mats and rubber crumbs). Rubber mats were placed beneath the ballast layer and rubber crumbs were mixed with steel furnace slag and coal wash to form a SEAL composite for subballast.

Large-scale drop hammer impact tests and cubic triaxial tests were carried out to examine their performance. The findings are as follows:

- 10% rubber is optimal amount to add to SEAL because it reduced the lateral dilation of tracks, ballast breakage (58%), and the load transferred to the track substructure, but adding more rubber (>10%) caused more settlement and lateral instability, and intensified the load amplification effect.
- By placing recycled rubber mats under ballast, both the maximum and residual settlement of the ballast assembly were reduced, and the lateral displacement decreased by 5-8%. The impact forces were significantly reduced by adding the rubber mat, and it was more efficient for a stiff subgrade over a soft subgrade condition.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the financial assistance from the Australian Research Council (ARCLP200200915, ARC-DP220102862). The assistance provided by industry (Sydney Trains, SMEC, Bestech, Bentley Institute) is gratefully acknowledged.

REFERENCES

Arachchige, C.M., Indraratna, B., Qi, Y., Vinod, J.S. and Rujikiatkamjorn, C. (2021). "Geotechnical characteristics of a Rubber Intermixed Ballast System." *Acta Geotechnica*: 1-12.

Costa, P. A., Calçada, R. and Cardoso, A. S. (2012). "Ballast mats for the reduction of railway traffic vibrations. Numerical study." *Soil Dynamics and Earthquake Engin.* 42: 137-150.

Esveld, C. (2014). Modern railway track, MRT Press, The Netherlands.

Hanson, C. E. and Singleton, H. L. (2006). "Performance of ballast mats on passenger railroads: Measurement vs. projections." *Journal of Sound and Vibration* 293(3): 873-877.

Indraratna, B., Lackenby, J. and Christie, D. (2005). "Effect of confining pressure on the degradation of ballast under cyclic loading." *Geotechnique* 55(4): 325-328.

Indraratna, B., Qi, Y., Jayasuriya, C., Rujikiatkamjorn, C. and Arachchige, C. M. (2021). "Use of Recycled Rubber Inclusions with Granular Waste for Enhanced Track Performance." *Transportation Engineering*: 100093.

Indraratna, B., Salim, W. and Rujikiatkamjorn, C. (2011). Advanced Rail Geotechnology - Ballasted Track, CRC Press, Taylor & Francis Group, London, UK.

Koohmishi, M. and Azarhoosh, A. (2020). "Hydraulic conductivity of fresh railway ballast mixed with crumb rubber considering size and percentage of crumb rubber as well as aggregate gradation." *Construction and Building Materials* 241: 118133.

Montella, G., Mastroianni, G. and Serino, G. (2012). "Experimental and numerical investigations on innovative floating-slab track including recycled rubber elements." *Proceedings of ISMA2012-USD2012, Belgium*: 2869-2879.

Navaratnarajah, S. K., Indraratna, B. and Ngo, N. T. (2018). "Influence of under sleeper pads on ballast behavior under cyclic loading: experimental and numerical studies." *Journal of Geotechnical and Geoenvironmental Engineering* 144(9): 04018068.

Ngo, T. N., Indraratna, B. and Rujikiatkamjorn, C. (2019). "Improved performance of ballasted tracks under impact loading by recycled rubber mats." *Transport. Geotechnics* 20: 100239.

Qi, Y. and Indraratna, B. (2020). "Energy-Based Approach to Assess the Performance of a Granular Matrix Consisting of Recycled Rubber, Steel-Furnace Slag, and Coal Wash." *Journal of Materials in Civil Engineering* 32(7): 04020169.

Qi, Y. and Indraratna, B. (2022a). "Influence of Rubber Inclusion on the Dynamic Response of Rail Track." *Journal of Materials in Civil Engineering* 34(2): 04021432.

Qi, Y. and Indraratna, B. (2022b). "The Effect of Adding Rubber Crumbs on the Cyclic Permanent Deformation of Waste Mixtures Containing Coal Wash and Steel Furnace Slag." *Géotechnique*: 1-22.

Ross, D. E. (2020). Use of waste tyres in a circular economy, SAGE Publications Sage UK: London, England.

Sai Malisetty, R., Indraratna, B., Qi, Y. and Rujikiatkamjorn, C. (2022). "Shakedown response of recycled rubber-granular waste mixtures under cyclic loading." *Géotechnique*: 1-21.

Sol-Sánchez, M., Thom, N., Moreno-Navarro, F., Rubio-Gamez, M. and Airey, G. (2015). "A study into the use of crumb rubber in railway ballast." *Construction and Building Materials* 75: 19-24.

Tiwari, B., Ajmera, B., Moubayed, S., Lemmon, A. and Styler, K. (2012). Soil modification with shredded rubber tires. GeoCongress 2012: State of the Art and Practice in Geotechnical Engineering**:** 3701-3708.