Utilization of Granular Wastes in Transportation Infrastructure – A Circular Economy Perspective

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ABSTRACT

Attributed to environmental preservation in urban infrastructure development, recycling of waste materials produced in the coal and steel industry as well as reusing off-the-road tires is a high priority in Australia. In this paper, the practical applications of (i) coal wash and steel furnace slag mixtures, (ii) coal wash and fly ash mixtures, and (iii) rubber crumbs from recycled tires mixed with granular fills are discussed. In this regard, some examples of real-life applications in port reclamation, road and rail environment in the state of New South Wales, Australia (e.g., Port Kembla, Kangaroo Valley highway and Chullora Rail Precinct) are highlighted. The performance of the materials is assessed and their mixed composition optimized using large-scale laboratory testing, while confirming their suitability in transportation infrastructure. The paper outlines various aspects of site investigation, construction techniques, and the installation of instrumentation to evaluate the field performance of waste materials, in contrast to traditional (natural) quarried materials. The results from case studies demonstrate that properly engineered waste material mixtures can exhibit promising characteristics to efficiently meet the expected technical standards, as proven by experimental results and field performance monitoring in real-life projects. These research outcomes blatantly support a circular economy perspective to be embraced in the future development of transportation infrastructure, with the aim of catering for increased freight loading and track longevity with substantially reduced maintenance intensity.

Keywords

Circular Economy, Industry Waste Materials, Recycled Tires, Sustainability, Transport Infrastructure.

Introduction

In view of Australian geographic and demographic trends combined with inevitable long-distance supply chains associated with the mining and agriculture industries, the operational efficiency of transportation infrastructure in terms of safety and reliability is vital for a sustainable national economy. The use of coal mining wastes (e.g., coal wash, steel furnace slag, and fly ash) offer significant monetary benefits over conventional (quarried) aggregates in substructure construction and land reclamation projects (Indraratna et al. 1994). Despite its favorable properties, such as adequate shear strength and permeability (drainage), Heitor et al. (2015) have shown that the breakage of coal wash is significant during initial compaction and subsequent shearing under live loading.

Through extensive laboratory studies, it is proven that combinations of granular wastes including rubber tire segments, steel slag and coal wash can offer adequate load-bearing properties to replace traditional (natural) road base, ballast, capping and structural fill, while ensuring enhanced longevity of transportation corridors. The application of coal wash (e.g., Leventhal 1996; Rujikiatkamjorn et al. 2013; Heitor et al. 2015) and mixtures of coal wash, steel furnace slag and rubber crumbs (Chiaro et al. 2014; Indraratna et al. 2018; Qi et al. 2018) have demonstrated that marginal materials could be optimally engineered to attain acceptable mechanical and geotechnical characteristics, in relation to the required specifications of port reclamation fill (Indraratna et al. 2015), capping or sub-ballast layers in rail tracks (Indraratna et al. 2018). Wang et al. (2019) have proven the performance of coal wash mixture as an appropriate base or subbase material for pavements.

Several laboratory studies have demonstrated the potential use of rubber inclusions such as rubber granules, rubber geogrids, and waste tires in strengthening track substructure (Sol-Sánchez et al. 2015; Fernández et al. 2018; Koohmishi and Azarhoosh, A. 2020; Arachchige et al. 2022*b*; Indraratna et al. 2022*c*). Recently, Arachchige et al. (2022*a*) conducted large-scale triaxial tests and demonstrated the favorable mechanical and compressibility characteristics of an optimally blended mix of ballast aggregates (latite basalt) and rubber granules for heavy haul railways, namely the Rubber Intermixed Ballast System (RIBS). Recycled rubber panels derived from discarded rubber conveyor belts from minerals processing plants would offer a potential energy-absorbing inclusion within the track substructure to provide increased reinforcement against undue lateral movement of granular particles. Using waterjet cutting, Energy-Absorbing Rubber Geogrids (EARS) made of used conveyor belts were prepared as grids with predetermined aperture sizes and shapes. They were expected to serve in a similar capacity to conventional high-density polyethylene geogrids, the difference being their energy-absorbing capacity attributed to increased damping. In another study by Indraratna et al., (2022*c*), real-size prototype tests were conducted using the National Facility for Cyclic Testing of High-speed Rail to investigate the performance of Infilled Tire Cell Foundation (ITCF) where recycled tires infilled with granular waste are assembled beneath the ballast layer to replace traditional capping material. Test data indicated reduced lateral deformation within the ballast layer and reduced acceleration of the concrete sleepers, compared to a traditional track structure. The tire assembly infilled with used ballast aggregates could be placed as an energy-absorbing medium to replace a traditional rockfill capping layer apart from providing adequate confinement to control lateral movement.

This paper describes real-life trials that were conducted at (i) Chullora Rail Technology Precinct (ii) Port Kembla Reclamation, and (iii) Kangaroo Valley Highway to assess the potential benefits of granular waste materials when innovatively blended in optimal mix compositions. The technical contents elucidate the salient aspects of material preparation, construction procedures with field instrumentation, and loading processes. The ultimate goal is to promote more economical and carbon-efficient infrastructure components by adopting granular waste materials for sustainable transportation infrastructure within the framework of a circular economy as strategically fostered by the State Government, c/o Transport for NSW.

CHULLORA RAIL PRECINCT

A fully instrumented track was constructed at Chullora (New South Wales, Australia) to investigate real-life scale applications of laboratory-proven recycled rubber elements solutions. This track was constructed in collaboration with industry stakeholders such as Transport for NSW (formerly Sydney Trains), Bridgestone Corporation, and Ecoflex. Three different innovative applications were tested, namely RIBS, EARS, and ITCF. In addition, an instrumented standard track section was also built for comparison and benchmark purposes.

Site Description

The test track section constructed in Chullora Technology Precinct had a total length of 380 m, and was situated between two turnouts from 17.61 to 17.99 km (Figure 1). For construction and monitoring purposes, the track was divided into four sections, namely (i) Section F-G: ITCF section (from 17.720 to 17.740 km), (ii) Section E-F: Control track section (from 17.800 to 17.840 km), (iii) Section D-E: EARS section (from 17.840 to 17.860 km) and (iv) Section B-C: RIBS section (from 17.900 to 17.920 km). As shown in Fig. 1, three 20-m long sections were constructed with intermediate standard sections to avoid the boundary effects.

The sub-surface profile comprises a layer of compacted fill followed by a thin sandy clayey silt, residual silty clays with ironstone gravel, and stiff clay or shale bedrock. The stiff weathered shale was encountered as an inclined layer at 1.2 m and 3.8 m deep at the RIBS and ITCF sections, respectively. Although the water table was located below 5 m depth, the subgrade layer was found to be saturated due to waterlogging under heavy to medium rainfall.

Material preparation and track construction

Fresh ballast complied with the nominal 60-graded specification (AS 2758.7:2015, T HR TR 00192 ST:2018-TfNSW) *Aggregates and Rock for Engineering Purposes - Railway Ballast*) was selected for all test sections except for the RIBS section. In the RIBS section, a 150-mm thick layer having fresh ballast mixed with 10% recycled rubber granules (by weight) was placed above the capping layer (Fig 3). In this test section, the rubber particle size was in the range of 8 to 15 mm. While Arachchige et al. (2022*a*) suggested an optimum rubber particle size range of 9.5 to19 mm, a slight deviation was considered because the optimum range recommended according to the standard sieve sizes was not available commercially. As shown in Fig. 2*a*, a large-scale calibrated volumetric mixer was employed to mix fresh ballast and rubber particles to the desired mix proportion, and it ensured the particle size distribution of the mix still complied with the ballast specifications. The particle size distributions of RIBS, fresh ballast, and capping materials are shown in Fig. 2*b*. The capping material contained 15% fines (e.g. smaller than 75 μm), which slightly deviated from the standard of *Earthwork Materials* by Transport for New South Wales, Australia (T HR CI 12111 SP:2018-TfNSW). Table 1 shows the grain size characteristics of the fresh ballast, RIBS, and sub-ballast used for the field trial.

For the EARS section, rubber geogrids with square apertures were prepared by water jet cutting method using end-of-life conveyor belts rubber panels. The aperture size and thickness of the rubber panel (1 m×1 m) were 51×51 mm^2, and 10 mm, respectively. The panels were laid at the interface of the capping and ballast layers. For ballast-infilled tire assembly (ITCF), the conventional capping (subballast) layer was replaced with 200 mm thick and 600 mm diameter tires filled with compacted fresh ballast. The ITCF units were assembled in a triangular pattern. A control track section having 250 mm ballast and 200 mm capping was constructed in accordance with the standard for *Earthworks and Formation* by Transport for New South Wales, Australia (T HR CI 12110 ST:2018-TfNSW.

In all sections, the other track components, including sleepers and rails adopted were the same. Medium-duty concrete sleepers and AS60SC rails manufactured according to the Australian standards for *Railway Track Material, Part 1: Steel Rails* (AS 1085.1:2019, were used for the track. Figure 3 shows the vertical cross-sections of (*a*) standard track, (*b*) RIBS, (*c*) EARS and (*d*) ITCF. After excavating the stiff clayey subgrade (500-mm below the original ground level), 200 mm diameter cess drains were installed in the gravel layer to facilitate the drainage. A layer of nonwoven geotextile was placed between the capping layer and the ballast interface to ensure the ballast would not be contaminated with fines from the capping layer. The maximum dry densities of ballast, capping, and RIBS layers are reported in Table 1. Figure 4 presents the placement of RIBS material, the placement of energy-absorbing rubber geogrids, and the assembly of tire cells at the ITCF section.

Instrumentation scheme

In each section, pressure cells having 200 mm in diameter, were placed horizontally at three interfaces (i.e., sleeper-ballast, ballast-capping, and capping-subgrade) to measure vertical stress. In addition, pressure cells were placed vertically in each section below the sleeper edge at the mid-level of the ballast layer to measure the lateral pressure within the ballast layer. The active face of the pressure cell was against and perpendicular to the centreline of the track. Electrical cables connected to the sensors were covered with flexible conduits to avoid damage during track operation. The cables were connected to a high-speed data acquisition system (DAQ) mounted on cabinets located at the side of the track. For greater autonomy, the data acquisition system was powered by solar cells and batteries, automatically triggered, and the data were recorded at 50 Hz sample frequency.

Loading application

A locomotive (81 Class: 21.5-ton axle load and 21.15 m long) was selected as the rolling stock for all the test sections. Limited running at a speed of 10-13 km/h was due to the restriction at the site. The typical vertical pressure variations under loading conditions are shown for the control track section in Fig. 5. In this study, a loading cycle is defined by a pass of one axle, i.e., a set of three wheels. A total number of 12 loading cycles (an initial loading test) was conducted. As no considerable change was observed in the value of vertical pressure from the 1st to the 12th loading cycle, the 5th loading cycle (N=5) was considered to analyse the pressure distribution.

Pressure distributions

Figure 5*b* shows the variations in vertical pressure distributions at different levels of the substructure in the 5th loading cycle. As expected, the vertical stresses at the base of the ballast layer were significantly reduced, e.g., by more than 30%, in RIBS and EARS sections compared to the control section. Minor reductions of vertical pressure around 3% and 11% were observed at the ballast-sleeper interface of the RIBS and ITCF sections, respectively. This may be attributed to the effect of the decreased overall stiffness of the track substructure due to the rubber inclusion within the depth of influence. Since the rubber geogrid is relatively thin compared to the thickness of the entire substructure, the effect of the rubber geogrid is negligible on the stress redistribution at the ballast-sleeper interface level in the EARS section.

Furthermore, considering the stresses at the subgrade-capping interface, for the RIBS and EARS sections, there is a substantial reduction in the vertical stress transferred into the subgrade, albeit more prominent in the EARS track section. In contrast, there is a 55% increase in vertical stress at the capping-ballast interface for the ITCF track section compared to the control section (Fig. 5*b*). While this might not correspond to the intuitive behavior first expected, no considerable change was observed in the vertical stress at the subgrade-capping interface. It implies that the ITCF layer acts as a relatively stiff capping layer, thus resulting in an increase in stresses on the ballast layer.

Lateral pressure was measured using vertically installed pressure cells in the middle of the ballast layer at a point below the sleeper edge. Figure 6 compares normalized lateral pressures ($\tilde{\sigma}_L$) in all sections. The $\tilde{\sigma}_L$ is the ratio between the recorded maximum lateral pressure in a particular section and the control section. Lateral pressures were measured at the middle of the ballast layer vertically below the edge of the sleeper. Lateral pressure through lateral confinement is essential to control ballast dilation and to reduce track instability. The normalized lateral pressures in RIBS, EARS, and ITCF sections increase by 3.4, 1.4, and 10 times, respectively. This is not surprising as the RIBS facilitates a well-interlocked particle assembly, EARS provides an effective interlock between the ballast and its apertures at the interface, and ITCF enhances capping layer confinement via the tire cell assembly.

PORT KEMBLA OUTER HARBOUR RECLAMATION

Port Kembla (100 kilometers south of Sydney) opened in the late 1890s to facilitate general cargo loading and unloading and the export of steel and coal from the Illawarra region. In the past decades, to keep pace with the growth of the local industries the Port has been expanding, particularly the inner harbor. To alleviate congestion, enhance capacity and increase productivity, the port authority planned the development of the Outer Harbor (Fig. 7). The Port Kembla Outer Harbor created additional bulk cargo berths and terminal areas on 45 hectares of reclaimed land.

Site description

A volcanic sandstone bedrock can be found at the bottom of the Outer Harbour area (RL -15 to

20 m) (Stroud et al. 1995). At the site, the thickness of the estuarine clay was relatively thin and hence consolidation settlement is not a critical issue. Therefore, the type of fill selected for the reclamation scheme was critical to ensure an acceptable level of long-term settlement and sufficient load-bearing capacity. In addition, it is essential that a geotechnical characterization of fill materials and associated stabilization techniques is conducted to avoid sudden subsidence of granular media, large lateral displacements and differential movements that could, in turn, cause damage to the main structures, as well as to adjacent facilities (pipelines, retaining walls, etc.). At Port Kembla, an innovative blend of locally available granular waste by-products including coal wash (CW) and Basic Oxygen Steel furnace slag (BOS) were considered in lieu of conventional dredged fills (Rujikiatkamjorn et al. 2013; Tasalloti et al. 2015). While the blends of these two wastes are attractive from an economical and environmental standpoint, their individual adverse geotechnical properties, i.e., particle breakage for CW (Indraratna 1994, Heitor et al., 2015) and swelling for BOS slag (Chiaro et al. 2015) poses some challenges. A series of experimental investigations were conducted by Chiaro et al. (2015) and Tasalloti et al. (2015) to assess CW-BOS mixtures suitability for port application in terms of: (i) compaction effectiveness; (ii) permeability; (iii); shear strength and bearing capacity (iv) particle degradation after compaction and shearing; and (v) swelling behavior. CW-BOS mixtures of 3:1, 1:1, and 1:3 (ratio by weight of dry CW:BOS) were prepared.

Figure 8 shows the performance of the CW-BOS blends in terms of swelling and particle breakage. It can be observed that the free swelling behavior due to hydration of free lime (CaO) and free magnesium (MgO) can be up to 8% for pure BOS and decreases with an increase in CW content. Similarly, the Breakage Index (BI), used to quantify particle breakage, decreases with increased BOS content. Interestingly, Figure 8 shows that the individual adverse characteristics of CW and BOS slags can be minimized when the two waste materials are blended. To evaluate shear strength properties of the mixtures, a series of drained triaxial compression tests with a confining pressure of 120 kPa (mimicking port loading conditions) were conducted on fully saturated specimens. The friction angles of mixtures are shown in Table 2. As expected, the friction angle increases from 36.5 degrees to 38 degrees when the BOS content increases due to better particle interlock. Similarly, the soaked CBR values increase from 8% to 31% as the proportion of BOS increases. However, the permeability of the mixtures decreases from 5×10^{-7} m/s (100% BOS) to 5.0×10^{-7} m/s (100% CW) as the result of the reduction in void ratio with an increase in BOS content. When used as a fill, the content of BOS needs to be optimized to prevent excessive settlement and swelling, which can damage the infrastructure in the Por (Fig 8). The following criteria were adopted to determine the appropriate mixtures to be used as an engineering fill at the Port Kembla Reclamation Project.

(a) Friction angle greater than or equal to 30° and/or a CBR > 10% to provide sufficient bearing capacity and curtail long-term deformation

(b) Permeability coefficient in the range of 1×10^{-8} m/sec and 1×10^{-6} m/sec (similar to sandy soil) to ensure sufficient drainage and minimize accumulation of excess pore pressure

(c) Swelling should be less than 3% to maintain the stability and serviceability of the infrastructure

(d) Particle breakage should be less than 10% to maintain the original particle size distribution affecting the shear strength of the mixtures

Two mixtures with BOS content of 57% and 73% were selected for the field trial and verification in September 2012 at Port Kembla Reclamation Site before assessing swelling and particle breakage (Indraratna et al. 2015). The field trial was an essential step to assess in-situ swelling and performance of CW-BOS blends as compacted fill. The trial site (55 m long, 14 m wide, and 1.4 m deep) was divided into two equal sub-sections where approximately 1200 tons of CW and 1600 tons of BOS were used to prepare the mixtures using an excavator, grader and a twin-shaft pugmill. A 13-ton vibration smooth steel drum roller was used to compact 300 mm thick lifts. To evaluate compaction efficiency, both sand cone replacement and nuclear density techniques were adopted. It was found that four roller passes could achieve a compacted dry density over 90% standard Proctor compaction. After the compaction, a series of dynamic cone penetration tests were conducted. The number of blows to penetrate 100 mm was greater than 10, which is on par with dense sandy soils.

After six months, free swelling for sections with BOS content of 57% and 73% were found to be 4.5% and 6%, respectively. Based on the field trial and further laboratory investigations, it was concluded that although the strength of mixtures with BOS content over 50% is higher than that of conventional fill (e.g., sandy soil), a relatively high level of swelling (i.e., > 3%) should be controlled by reducing the BOS content when used as structural fill, unless the overburden pressure of at least 100 kPa is applied through live load and surcharge weight of pavement and built infrastructure.

MOSS VALE ROAD, KANGAROO VALLEY

Coal mining wastes from the Illawarra region, NSW, Australia (e.g., coal wash) have significant monetary benefits over conventional (quarried) aggregates when utilized in construction and reclamation projects in the form of pavement and fill materials (Indraratna et al. 1994, Wang et al. 2019). Despite its favorable properties, such as adequate shear strength, Heitor et al. (2015) showed that the extent of coal wash breakage during compaction and shearing is significant, which in turn can hinder its application as base/subbase material in road pavements. To address this limitation, an innovative solution incorporating fly ash (FA) fines was investigated by Wang et al. 2019. The FA fines can increase the compatibility and, therefore, the mechanical interlock and the permeability of compacted CW. In addition, the Fly Ash (FA) fines serve as a void filler, reducing the potential breakage of coal wash particles and thus enhancing the properties of the mix. In Wang et al., 2019 study, a Class F Fly ash (FA) with no pozzolanic activity was procured from Eraring Power Station (New South Wales, Australia). Fig. 9*a* shows the particle size distribution (PSD) of CW, FA and different mixes having different FA content. It can be observed that PSD of CW does not satisfy the minimum fines content specified by Transport for NSW formerly Road and Maritime Services or RMS, for base/subbase material. However, with the addition of FA content ranging from 7 to15% by weight, the particle size distribution curve of the mixes complies with the acceptable range for a base/subbase material. However, while the 7-15% FA mixes conform with the expectations in terms of PSD, it is crucial to assess their suitability as a base and/or sub-base material.

Wang et al. (2019) reported that maximum values using unconfined compressive test and California Bearing Ratio (CBR) were obtained for mixes of CW having 7% FA. This is not surprising as the minimum void ratio under modified Proctor compaction energy is also obtained for this mix (Fig. 9*b*). Furthermore, the collapse potential was well below the allowable range with a permeability of less than $5x10^{-7}$ m/sec.

To evaluate the real scale performance of the selected mix, a road pavement construction trial was conducted at Moss Vale Road (Kangaroo Valley, NSW) with the support of Transport for NSW. The site was located at the intersection of Moss Vale Road and Cavan Road, Kangaroo Valley, NSW (Figure 10). For this site, a design ESAs (Equivalent Standard Axles) of 3×10^6 was considered and hence the minimum required thickness adopted of the road base was 300 mm. The area was divided into two sections (3.5 m width and 20 m long), (a) a control section using conventional base material, i.e. densely graded base or DGB20 and (b) Coal wash Fly Ash Mixture (7% FA prepared at 6% water content). The existing road surface and the base layer (260 mm thick) were first milled. A volumetric mixer was employed to mix CW and FA. Then, the selected CWFA mix and DGB20 were compacted using a smooth steel roller in the test and control sections, respectively. The dry density of the CWFA mix recorded on site was 1.76 $t/m^{3,}$ whereas, for DGB20, the maximum dry density was 2.28 t/m^3 with a water content of 8%. (RMS, 2013). During compaction, a number of instruments were installed to monitor the CWFA mix performance under the same traffic conditions as the control section (e.g., moisture and suction sensors). The road surface was then sealed and opened for traffic.

The photo illustration of the different construction phases is shown in Figure 11. Based on the insignificant change in suction readings, the results show that the CWFA can prevent the infiltration of moisture during rainfall. As shown in Fig. 12, the rutting profile of CWFA indicates similar performance compared to the conventional section (DGB20). The long-term performance is still being monitored at the site.

Conclusion

This paper describes the practical applications of various waste materials in transport infrastructure (rail, road and port). The main types of waste considered range from those derived from coal mining (coal wash), steel manufacturing (BOF steel furnace slag), coal-fired energy plants (fly ash), and recycled rubber elements from used tires and conveyor belts. After detailed laboratory characterisation, the successful blends of these wastes were considered in three real-life projects, namely, the Port Kembla reclamation project, Kangaroo valley road construction, and the rail test track at Chullora Technology Precinct. The results of real-time monitoring of the real-life applications outlined in this paper showed that:

- The track sections having rubber intermixed ballast stratum (RIBS) and Energy Absorbing Rubber Seam (EARS) exhibited a 30% reduction of the vertical pressures at the base of the ballast layer, indicating less impact on ballast aggregates and hence degradation.

- The application of recycled ballast infilled tire cell assembly (ITCF) as the capping layer provides better lateral support by increasing the confining pressure of the ballast layer by more than ten times.
- Reduced vertical stresses in the formation of RIBA and EARS track sections could reduce the natural ballast particle degradation, and increased lateral pressures of ITCF section could reduce ballast dilation. This indicates that the proposed recycled rubber elements inclusions could have substantial long-term benefits, such as a reduction in track maintenance interventions. However, to analyze the long-term behavior, tracks should be tested for an increased number of loading cycles.
- The field tests carried out at the Port Kembla Reclamation confirmed that the compacted mixtures of CW-BOS had similar performance to conventional sandy fills. However, the mix having a higher BOF slag content showed considerable swelling and thus should be avoided in practice.
- A field study at Kangaroo Valley using a mixture of coal wash and 7% fly ash performed similarly to the conventional aggregate based on the rut depth evaluation.

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TABLE 1 Grain size characteristics of the fresh ballast, RIBS, and capping materials

Material	d_{max} (mm)	d_{min} (mm)	d_{50} (mm)	C_u	C_c	Maximum dry density (t/m^3)
Ballast	63	9.5	37.5	2.84	1.42	1.60
RIBS	63	9.5	37.5	2.84	1.42	1.45
Capping	19	0.044	2.36	75.4	1.20	2.14

TABLE 2 Friction angle, California Bearing Ratio (CBR) and permeability coefficient for CW, BOS and CW-BOS mixtures (Chiaro et al. 2015).

Material	Friction Angle (Degrees)	CBR (%) soaked	Permeability coefficient (m/s)	Swelling (%)
CW	36.5	8	5×10^{-9}	-0.6
CW-BOS 3:1	37.2	18	6×10^{-8}	0.3
CW-BOS 1:1	37.1	24	2×10^{-7}	4
CW-BOS 1:3	38.6	25	4×10^{-7}	-
BOS	38.3	31	5×10^{-7}	8

FIG. 1 Plan view of the track.

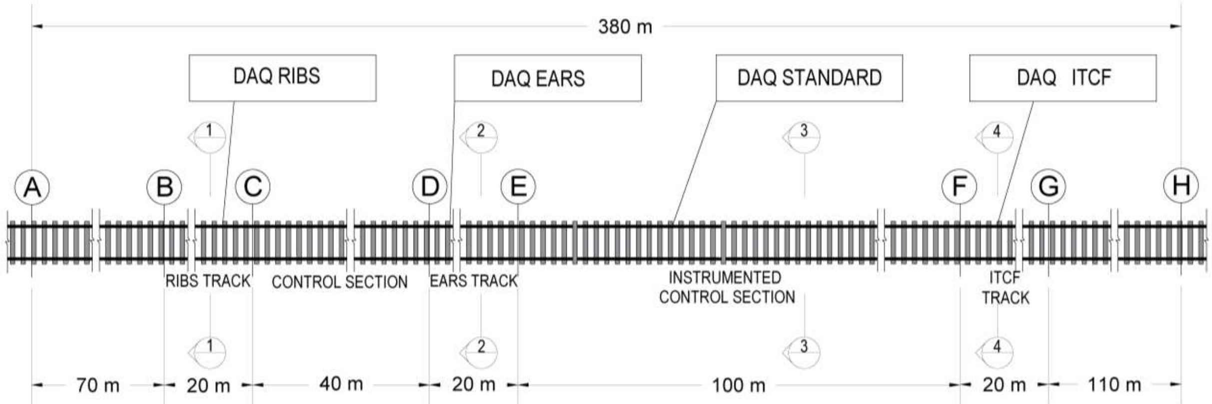
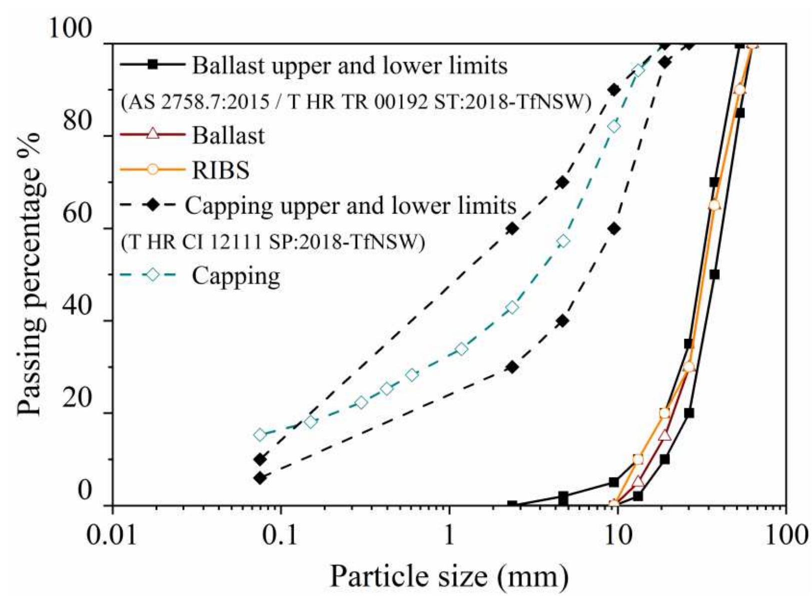


FIG. 2 Preparation of RIBS: (*a*) Volumetric mixer for mixing of ballast and rubber particles (*b*) PSD of fresh ballast, RIBS, and capping.

(*a*)



(*b*)

FIG. 3 Typical cross sections (*a*) standard section (*b*) RIBS section (*c*) EARS section and (*d*) ITCF section.

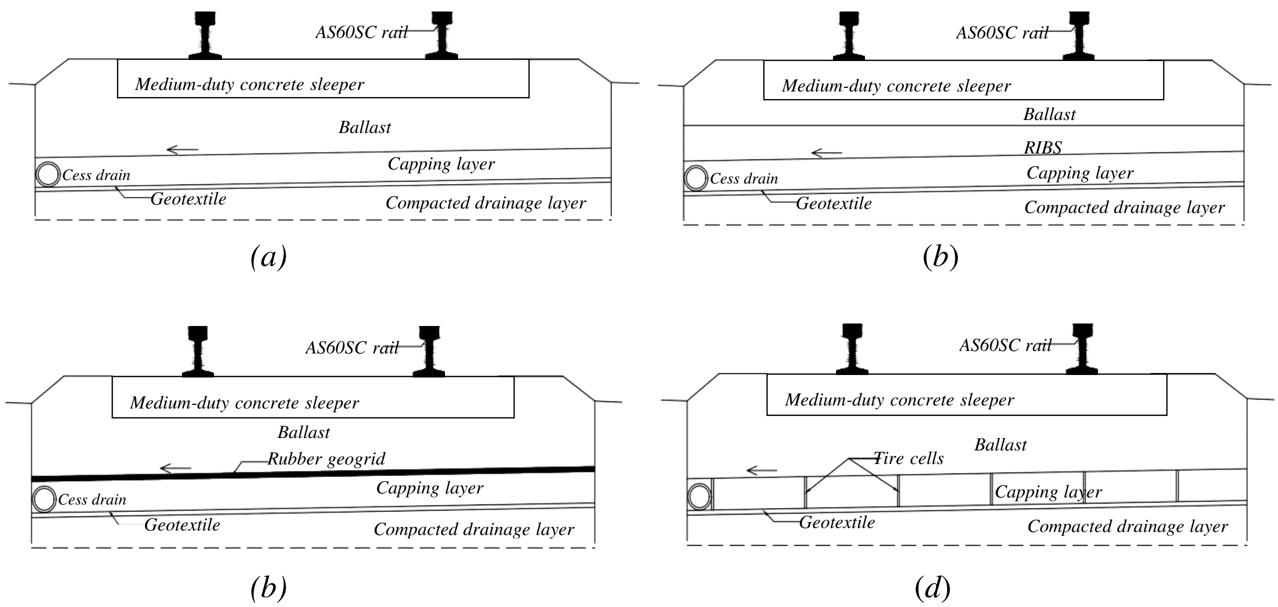
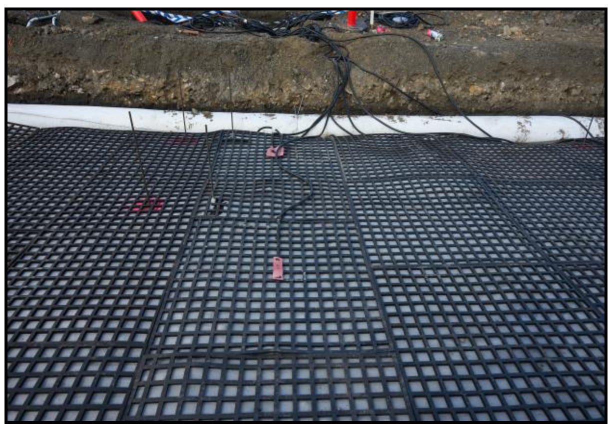


FIG. 4 Track construction (*a*) Placing RIBS in the RIBS rack (*b*) Rubber geogrids in the EARS section and (*c*) Tire cell assembly in the ITCF section.

(*a*)



(*b*)

(*c*)

FIG. 5 (*a*) Vertical pressure distributions under dynamic loading (*b*) Vertical pressure distribution of standard track, RIBS track, EARS track and ITCF track.

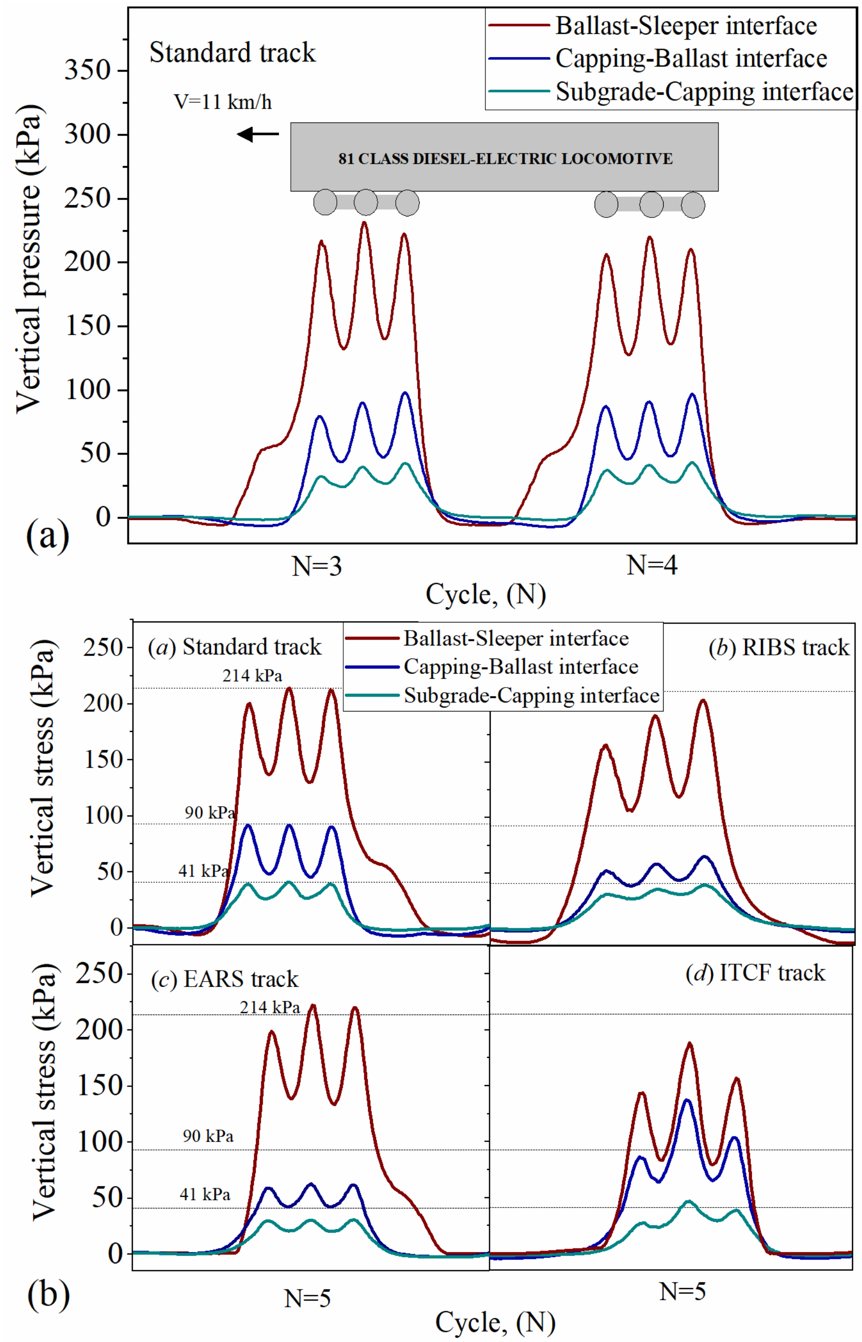


FIG 6. Normalized lateral pressures in track sections.

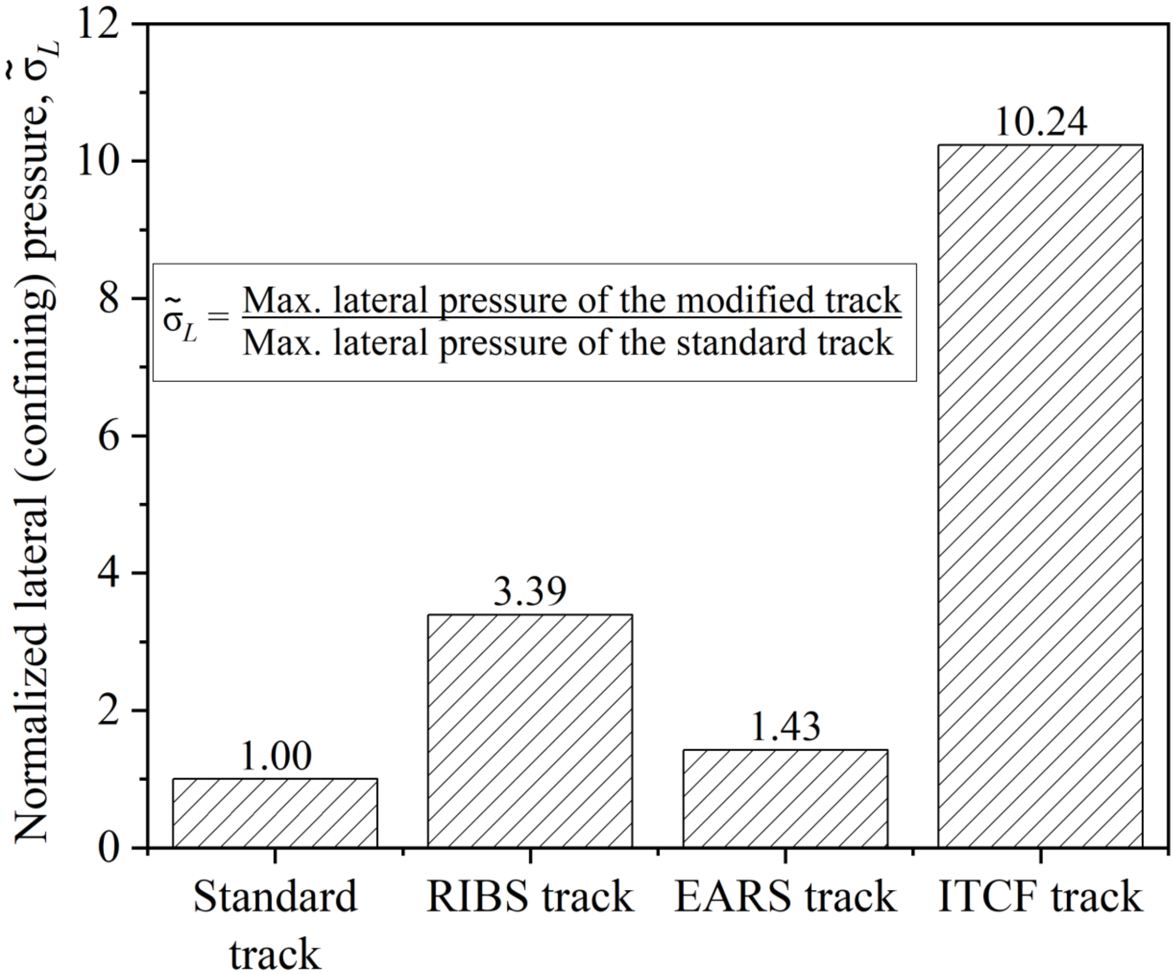


FIG 7. Location of Port Kembla reclamation project (*a*) before the reclamation in 2011 and (*b*) after the reclamation in 2017 (Google (2022) Port Kembla).

(*a*)

(*b*)

FIG 8. Optimisation of CW-BOS blend as structural fill for port reclamation (Chiaro et al. 2015).

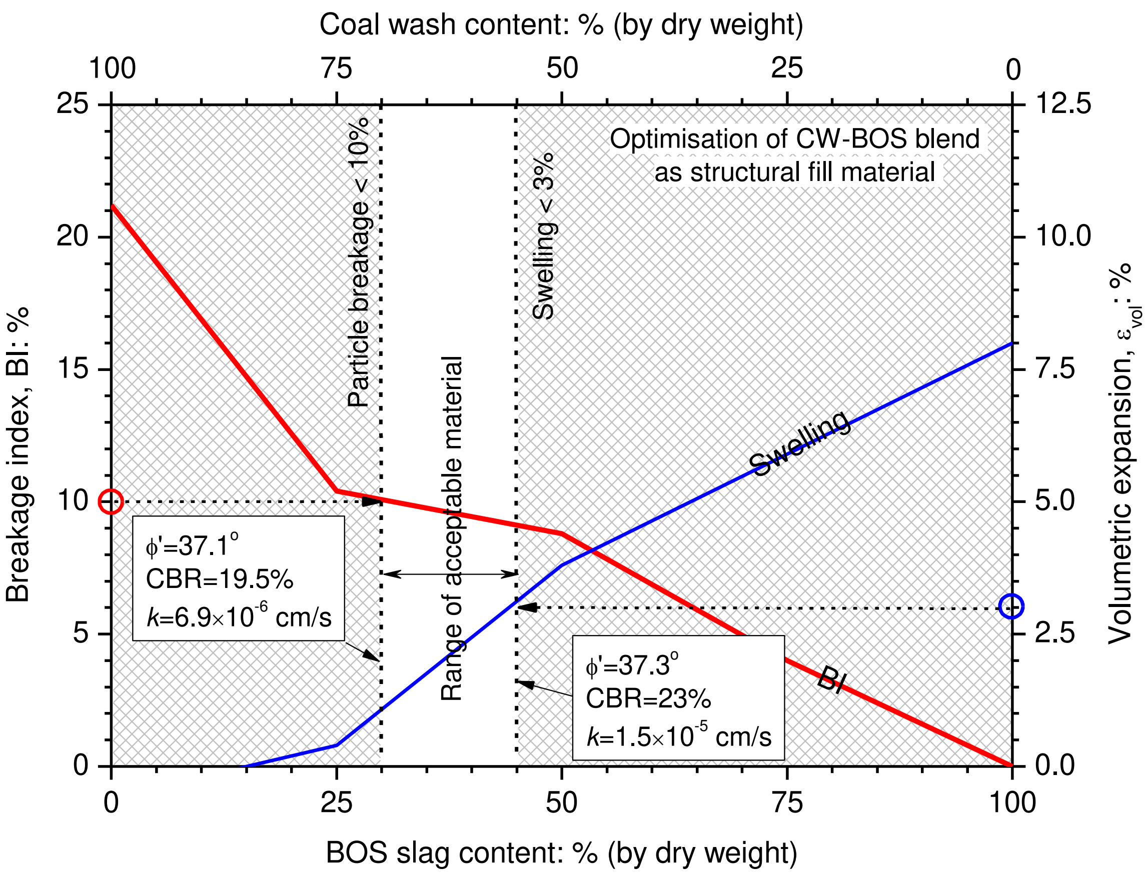
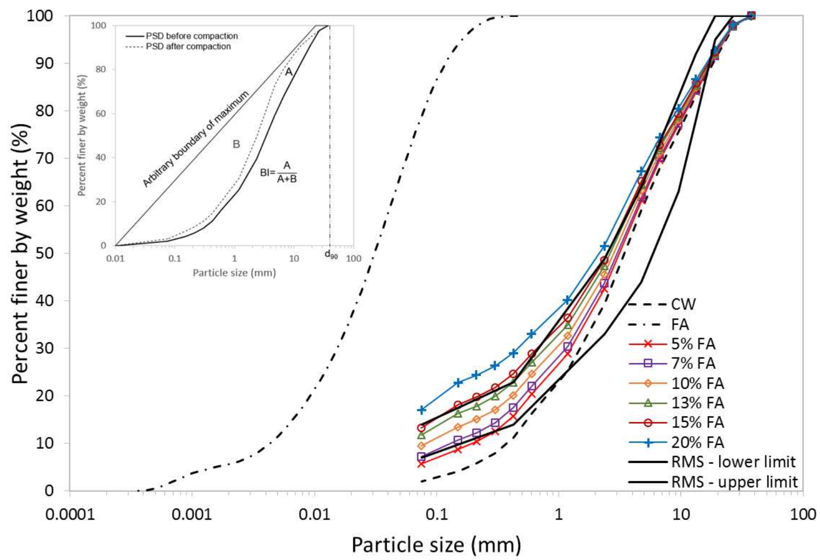
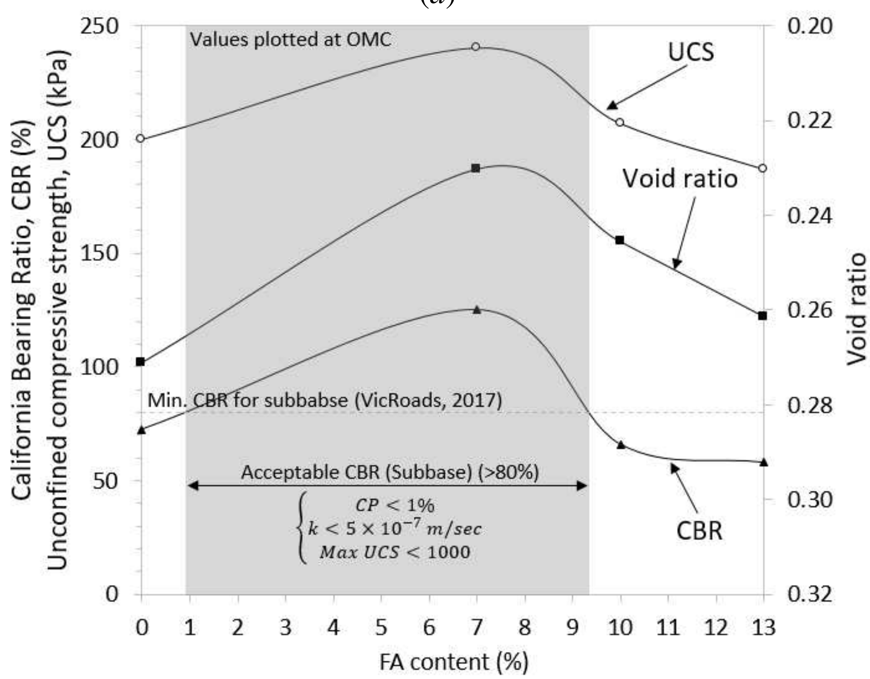


FIG 9. (*a*) PSD curves of CW, FA and CWFA mixtures and (*b*) Variations of California Bearing Ratio (CBR), Unconfined compressive Strength (UCS) and Void ratio under different FA contents (Wang et al. 2019).



(*a*)



(*b*)

FIG 10. Field trial site (Google (2022) Kangaroo Valley).

FIG 11. Construction sequences (*a*) removal of existing layer, (*b*) compaction using Roller, (*c*) complete surface.

(*a*) (*b*) (*c*)

FIG 12. Average rut depths of both sections after 2 years.