The use of recycled rubber in ballasted railway tracks: a review

Weile Qiang [a], Guoqing Jing [b], David P. Connolly [c], Peyman Aela [d]

[a] Railway specialist, Institute of Infrastructure Inspection, China Academy of Railway Science Corporation Limited (CARS), Beijing 100081, China. Email: qiangweile@rails.cn

[b] Professor, School of Civil Engineering, Beijing Jiaotong University, Beijing 100044, China. Email: gqjing@bjtu.edu.cn

[c] Professor, Institute for High Speed Rail and System Integration, School of Civil Engineering, University of Leeds, Leeds, LS2 9JT, UK, Email: d.connolly@leeds.ac.uk

[d] Postdoctoral fellow, Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong, China. Email: peyman.aela@polyu.edu.hk

Abstract

The disposal of waste tyre rubber (WTR) is an environmental challenge, and a significant amount of waste is sent to landfills. However, modern railway tracks depend on rubber materials for their resilient elements. Therefore, extensive research is being conducted to investigate the reuse of WTR to form track components. To better understand this body of research, this paper presents a state-of-the-art review of the application of WTR in railways. First, the use of WTR for components close to the rail is explored with a focus on railroads, rail dampers, and level-crossing applications. Next, rubber–concrete sleepers and under-sleeper pads are discussed before exploring ballast-related solutions such as under-ballast mats and ballast mixed with rubber crumbs/chips. Finally, numerical simulation methods are discussed, including finite element constitutive models and the discrete element method. The paper concludes with suggestions for future research.

Keywords:

Waste tire rubber; Ballast rubber crumbs-chips; Under sleeper pads; Railway sustainability; Recycled rubber; Under ballast mat

1 Introduction

The accumulation and burning of waste tire rubber (WTR) cause severe environmental problems, such as the release of toxic fumes and water and air pollution. Discarded tires can be used as energy sources, such as gasoline, but they should be separated from other rubber products. As shown in Fig. 1, WTR can be used as an alternative fuel in cement kilns and for power generation. However, its combustion pollutes the environment. The standard practice for using WTR in civil engineering is established according to ASTM D6270-20 (2020). In 2017, only 8% of scrap tires were employed in civil engineering-related projects (USTMA, 2019). WTR is a recyclable material, and its recycling and reuse in various geotechnical engineering fields such as landfills, pavements, and embankments have increased considerably (Mohajerani et al., 2020). Because rubber has a relatively low specific gravity (1–1.36) and a suitable damping ratio, it has been extensively used in embankment fills, retaining wall backfills, drainage layers for roads, landfills, thermal insulators, vibration dampers in highway and railway infrastructure, sound barriers, and in mixtures of rubber/soil or rock materials, as reported by Humphrey (2007).

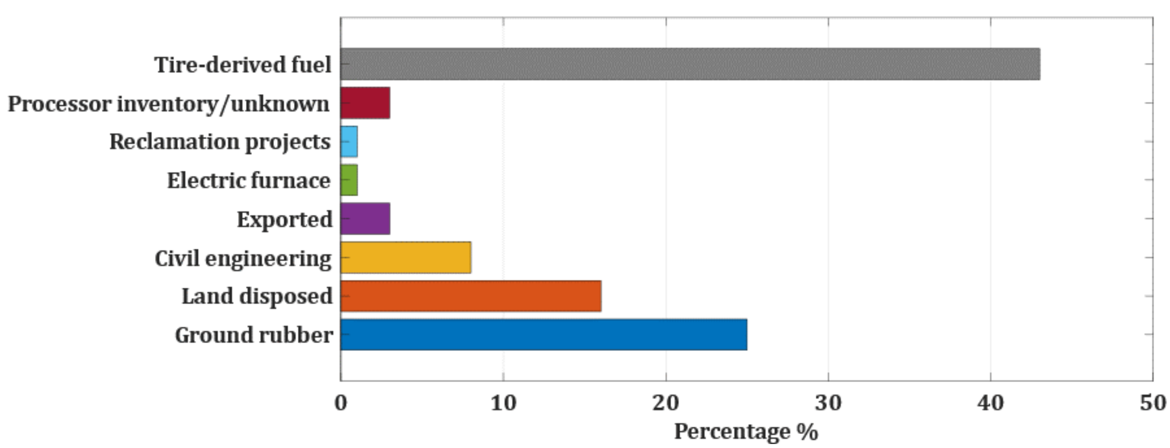


Fig. 1 Scrap tire disposition in the U.S. modified from (USTMA, 2019)

Recently, there has been a tendency to apply WTRs in railway infrastructure as granular mixtures, layered pads, or composite materials to address existing track problems (Fig. 2). Owing to the elastic characteristics of WTRs, the early goal of rubber superstructures was to implement vibration-damping measures in railway embankments. Subsequently, WTRs were used as granular and layered shapes on railway tracks. The long-term performance and cost efficiency of reinforced ballasted tracks are concerns for the further use of WTRs in the railway industry.

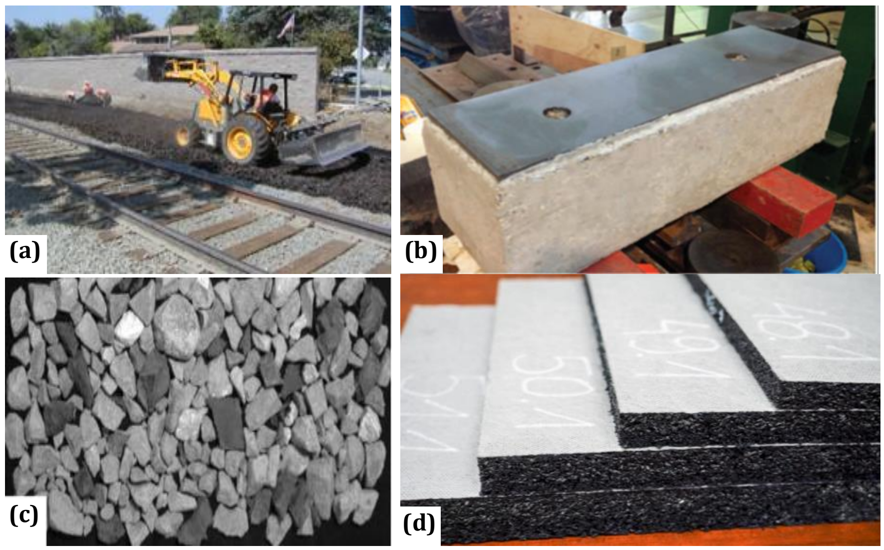


Fig. 2 The application of WTR: (a) railway embankment (CalRecycle, 2001), (b) under sleeper base (Navaratnarajah et al., 2018), (c) within the ballast layer (Fathali et al., 2019), and (d) under the ballast layer (Kraśkiewicz et al., 2023)

The specific gravity and bulk density of WTR range from 0.51 to 1.2 and 524 to 1273 kg/m3, respectively ((Fakhri and Saberi. K, 2016)). Further details on the physical and chemical characteristics of tire rubber can be found in (Siddika et al., 2019). WTRs are used in various forms and sizes in railway superstructures, such as crumbs, powders, and layered pads. The selection of a suitable rubber size and form is vital for producing highly efficient products. Layered WTRs have been used as a rail pad (RP), under sleeper pad (USP), and under ballast mat (UBM), as illustrated in Fig. 3e. From a size perspective, WTRs are categorised into tire shreds (50–305 mm), tire chips (12–50 mm), and crumb rubber (0.425–12 mm), as shown in Fig. 3a-d (ASTM D6270-20, 2020). The CEN Workshop Agreement reported a precise classification of rubber products based on particle size (Table 1).

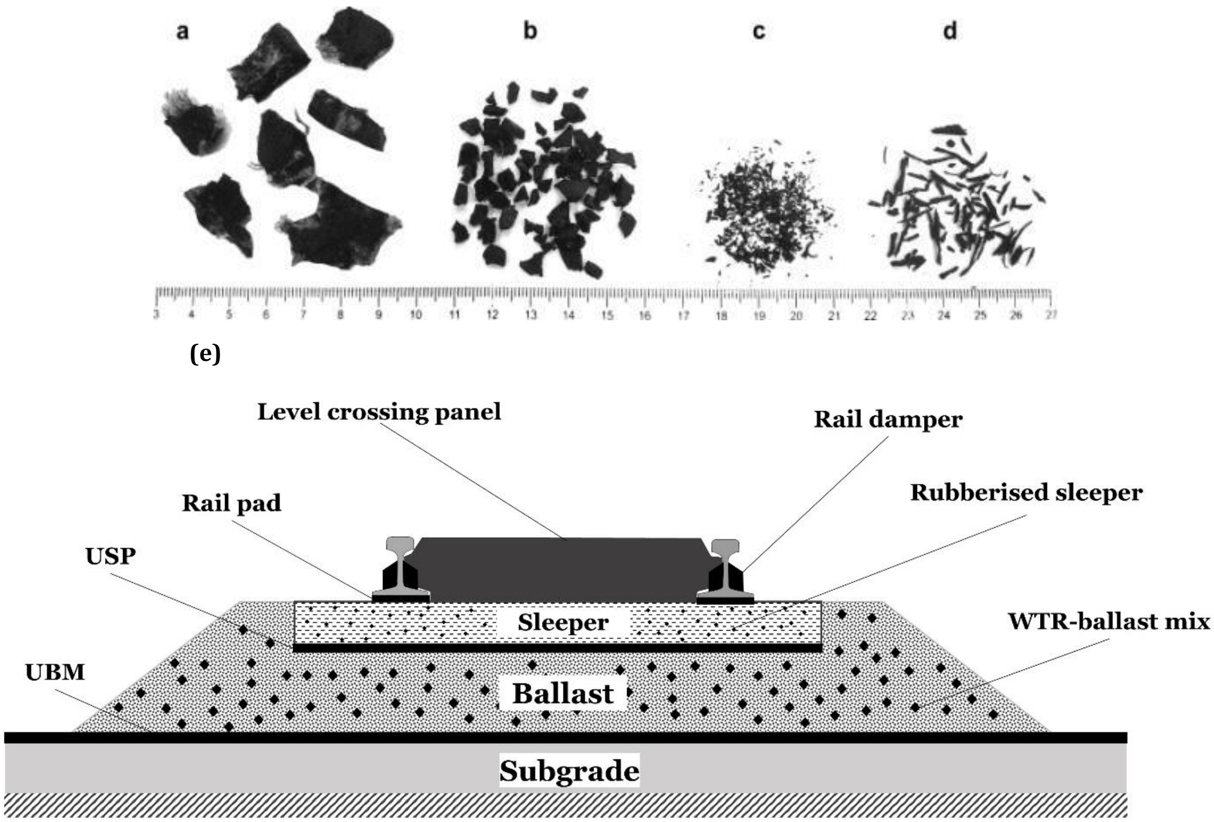


Fig. 3 Rubber aggregates: (a) shredded, (b) crumb, (c) granular, (d) fibre, and (e) rubber layers, modified from (Najim and Hall, 2010)

Table 1 Material Sizes of Tyre Derived Products (TDPs) (Oikonomou and Mavridou, 2009)

Material	Size
Cuts	> 300 mm
Shred	50 – 300 mm
Chips	10 – 50 mm
Crumb	1 – 10 mm
Powder	< 1 mm
Fine powder	< 500 µm
Buffings	0 – 40 mm
Pyrolytic char	< 10 mm

In addition to rubber size, the percentage of mixed rubber particles is another important parameter that should be considered. The increase in rubber content leads to changes in the mixture behaviour from rigid (plastic) to rubber-like (elastic) owing to the higher probability of contact between the rubber particles.

While existing review papers on rubber inclusion in railway infrastructure have mainly focused on the performance of layered WTR at the interface between railway components (Sol-Sánchez, Miguel et al., 2015), recent findings by Mayuranga et al. (2023) explored the use of granular/layered WTR elements in ballasted tracks. Despite this progress, several research gaps must be addressed. Specifically, previous studies have not investigated the application of WTR in the rail zone, which is a primary source of noise and vibration propagation owing to its direct interaction with the train wheels, in components such as rail dampers and level-crossing panels. Additionally, there is a need for a quantitative-based investigation of the effect of WTR-based products on the performance of railway components, as well as guidelines for simulating WTR in railway superstructures, to provide a suitable method for analysing the interaction between WTRs and railway elements. This review aims to address these issues by focusing on three main areas: (I) experimental investigations of the performance of WTR-reinforced track superstructures, (II) numerical methods for simulating rubber-like materials, and (III) potential challenges for future studies using WTR.

2 Use of WTR in ballast track components

Using WTR in ballast track components is an area of active research and development; however, several challenges need to be addressed, including the potential for rubber particles to migrate into the ballast and interfere with the track's structural/dynamic performance. One experimental approach that has been explored is the use of rubber pads placed on the rail seat, at the top or bottom of the ballast layer, which are named under sleeper pad (USP) and under ballast mat (UBM), respectively. The rubber layer may exhibit various mechanical properties depending on the application zone. Because rubber-made layers are widely used in railways, the typical ranges of properties for different rubber layers are presented in Table 2.

Table 2 WTR layer stiffness (Kraśkiewicz et al., 2018) and physical properties (Sol-Sánchez, Miguel et al., 2015)

Product	Thickness (mm)	Density (kg/m^3)	Stiffness (kN/mm)	C_{stat} (N/mm^3)	C_{dyn} (N/mm^3)
RP	4.5-15	950 - 980	>150 (hard) 80-150 (medium) <80 (soft)	_	_
USP	5.5-20	710 - 1100	~50 (soft) ~400 (medium) ~3000 (hard)	0.25–0.45 (hard) 0.15–0.25 (medium) 0.08–0.15 (soft) <0.08 (very soft)	≥0.25 (hard) 0.09-0.25 (soft) <0.09 (very soft)
UBM	10-52	310 - 1000	_	0.018 – 0.267	>0.22 (hard) 0.9-0.22 (medium) 0.05-0.09 (soft) 0.01-0.05 (very soft)

Another approach involves the use of granular WTRs as additives in railway concrete sleepers or ballast layers. In this case, the performance of the reinforced components is governed by the rubber size distribution and percentage. Depending on the type and location of the WTR (including rail–sleeper, sleeper–ballast, and ballast–subgrade interfaces), specific laboratory tests are required to evaluate the mechanical performance of the WTR-reinforced track. Fig. 4 shows the publications on WTR inclusion in ballasted railway superstructures. Most studies have focused on rubber stiffness and its influence on track components.

However, little is known about the effects of moisture on the performance of WTR-reinforced ballast. The following sections describe the experiments conducted on each product. Moreover, climate change and its impacts have not been well investigated. Regarding rubberised concrete sleepers, although comprehensive analyses of concrete samples have been carried out, little research has considered the performance of rubberised concrete sleepers, which requires a specific mix design and sleeper-related tests.

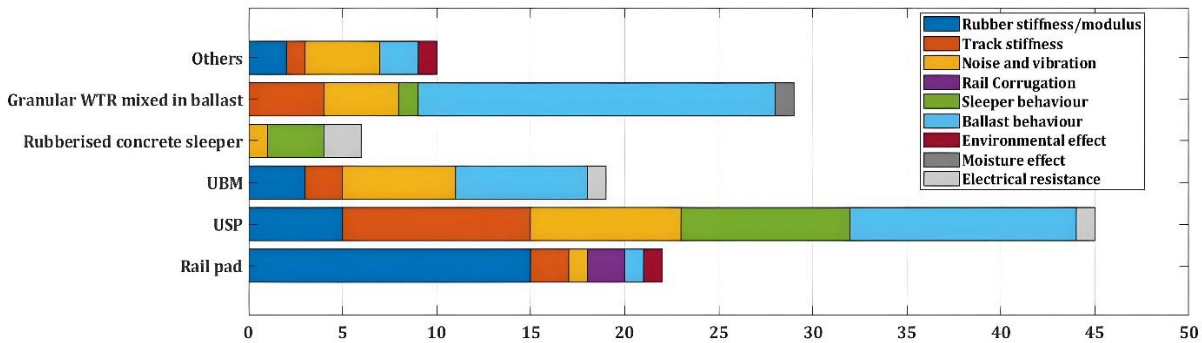


Fig. 4 Previous studies on WTR-reinforced track superstructure

*More studies on rubberised concrete were provided by Mohammed et al. (2017) and Siddika et al. (2019)

2.1 Rail

According to the literature, WTRs can be applied as rubber pads between rails and sleepers or as rail dampers to improve track performance in terms of noise, vibration, and stress transmission characteristics. The stiffness of the layered rubber is an important factor that should be examined when designing efficient elements. Grassie (1989) proposed Eq. (1) to determine the RP stiffness of rail track (k_T) based on the stiffness value obtained from laboratory tests (k_L).

$$k_T = 16.87 + 0.463k_L \quad (1)$$

In the following, the specifications of each type of element are described.

2.1.1 Rail pad

Rail pads (RPs) are typically composed of rubber, high-density polyethylene (HDPE), thermoplastic polyester elastomer (TPE), and ethylene vinyl acetate (EVA). Recycled rubber RPs isolate the rail from the concrete sleepers and reduce noise and vibration. They are typically made from recycled rubber with a thickness of 4.5 to 15 mm and are used in conjunction with springs or elastomeric fastenings to allow for the movement and expansion of the rail (Sol-Sánchez, Miguel et al., 2015). Several factors must be considered when selecting and installing recycled rubber RPs, including the type of rail, track, load, and train speed. The principal characteristic parameter of

RPs is stiffness. British Standard No. 13481-2 and AREMA No. 1-30 provide the test conditions for measuring the dynamic stiffness of RPs as part of fastening systems. A comparison of these two standards can be found in (Qi et al., 2022).

Studies on the relationship between the stiffness of RPs and the mechanical properties of ballasted tracks are presented in Table 3. The results show the importance of the RP stiffness in transmitting stresses into the ballast bed. They also indicate that stiffer RPs are suitable for reducing the rail vibration and displacement and prolonging the service life of the fastening system, whereas softer RPs are appropriate for reducing the imposed vertical stress on the ballast and the consequent track stiffness, sleeper deterioration, rail corrugation, and vibration between the sleeper and ballast bed.

Table 3 Laboratory tests on RPs stiffness

Author	**Variable**	**Findings**
Giannakos (2010)	Static loading	An increase in pad stiffness from 40 to 250 kN/mm led to a 20% increase in stress on the ballast bed.
Teixeira (2004)	Track stiffness	The decrease in RP stiffness below 100 kN/mm reduces the changes in track stiffness.
Carrascal Vaquero (2010)	Dynamic loading	Applying repeated loads led to an 18% increase in stiffness and a 40% decrease in dissipated energy.
Maes et al. (2006)	Load frequency Preload	A steady trend of dynamic stiffness when the frequency is between 20 and 2000 Hz and a rapid rise of stiffness when the frequency rises up to 2500 Hz
Egana et al. (2006)	Rail wave	Reduction in RP stiffness from 90 to 60 kN/mm resulted in a 55% reduction in rail wave.
Thompson and Jones (2006)	Noise	Variations when RP stiffness increased from 25 to 8000 kN/mm: Sleeper: +16%; Rail (vertical): -20%; Rail (lateral): -10%; track (total): -11%.
Carrascal et al. (2010)	Temperature Severe environmental conditions	30 % stiffness increment with a 30° C increase in temperature. 33-41% increase in RP stiffness after a life service of 1-3 years.
Leykauf and Stahl (2004)	Ballast acceleration	90% variation of recorded vibration when loading frequency is between 16 and 250 Hz.
Ilias (1999)	Rail corrugation	The stiffer pads, the faster the corrugation growth, so an increase in RP stiffness from 280 to 500 kN/mm led to a 72% and 51% increase in wear rate for 100 mm and 300 mm wavelength, respectively.

As shown in Fig. 5, an application of deconstructed tyres as RPs was proposed by Sol-Sánchez et al. (2014a). A thickness of 7.5–9 mm was proposed as the most efficient tire RPs under static and dynamic loading conditions. The research findings indicated that using a tire pad in the system caused a slight reduction in vertical stiffness, likely because of its lower dynamic stiffness compared to that of a rubber pad. The dynamic test results showed that the tire pad had a vertical stiffness of approximately 52.5 kN/mm, which is similar to that of the commercial pad (approximately 61.5 kN/mm). This suggests that tire pads could be a viable replacement for traditional RPs. Moreover, the dissipated energy levels for both types were fairly similar (mean value near 4.94 J for tire pads and 4.75 J for commercial pads).

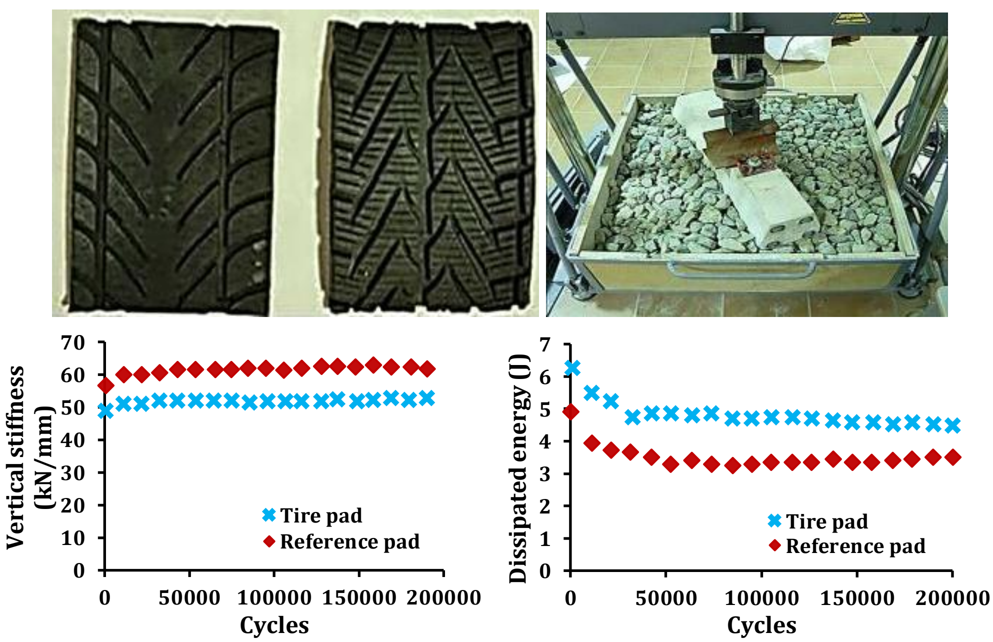


Fig. 5 Ballast box test on deconstructed tire-made RPs (Sol-Sánchez et al., 2014b)

2.1.2 Rail damper

Rubber-made rail dampers are another railway application for WTRs (Fig. 6). Rail dampers are manufactured using either rubber or rubber–steel plate assemblies. Rail dampers are passive components attached to either side of a rail web to decrease rail noise and vibration. Given the results of compression and tension under severe freezing conditions, Kraśkiewicz et al. (2021) stated that the density of manufactured rail dampers should be greater than 1000 kg/m^3, corresponding to a static bedding modulus of 0.426 N/mm^3 when the range of the applied stress is 0.02–0.07 N/mm^2. In addition, dynamic tests showed the frequency dependence of the rail damper on the performance; therefore, an increase in the loading frequency from 1 to 20 Hz led to an increase in the dynamic bedding modulus from 0.219 to 0.448 N/mm^3.

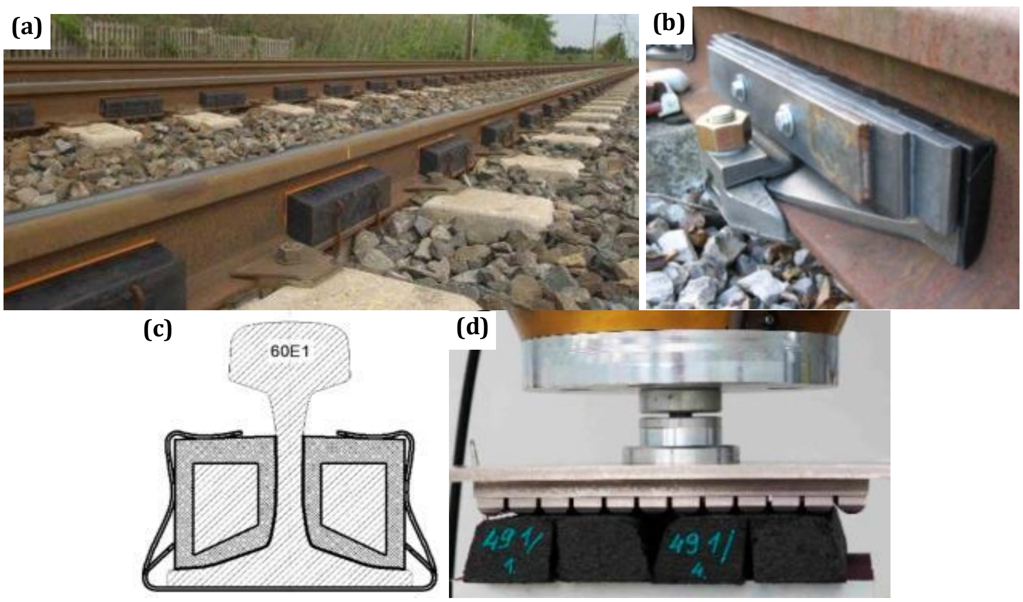


Fig. 6 (a) Rail damper in a ballasted track (Zvolenský et al., 2017), (b) rubber-steel plate damper (Toward and Thompson, 2012) (c) Cross-section of dynamic rail damper with a steel insert and a rubber cover, (d) compression test on representative ballast plate and rail damper (Kraśkiewicz et al., 2021)

2.1.3 Rubber level crossing panel

WTRs can be used as materials for level crossings in railway systems (Fig. 7). Rubber provides a durable and flexible surface that can withstand heavy axle loads and constant train movements. The advantages of using WTR at railway-level crossings include noise reduction, improved track safety and durability, reduced track maintenance costs, and the prevention of rail deterioration owing to snow residue and road salt. Further, (Hans Bendtsen, 2007) reported a 1-2 dB noise level reduction when using rubber level crossings.

Fig. 7 Installation of rubber level crossing (a) in the UK (RosehillRail, 2022), (b) in Germany (STRAIL, 2022)

2.2 Sleeper

Railway sleepers are superstructural components that transmit loads from the rail to the ballast bed. They can be formed from various materials such as concrete, timber, steel, and composites. WTRs can be used either as a powder/crumb mixed with concrete or as a pad underneath the sleeper base (USP). In the first group, concrete-related tests were performed to evaluate the applicability of rubberised concrete samples, whereas the performance of rubber pads was assessed according to the standards for elastomers and railway sleepers, in which rubber stiffness is the primary concern.

2.2.1 Powder/crumb rubber concrete

Railway sleepers are superstructural components that transmit loads from the rail to the ballast bed. They can be formed from various materials such as concrete, timber, steel, and composites. WTRs can be used either as a powder/crumb mixed with concrete or as a pad underneath the sleeper base (USP). In the first group, concrete-related tests were performed to evaluate the applicability of rubberised concrete samples, whereas the performance of rubber pads was assessed according to the standards for elastomers and railway sleepers, in which rubber stiffness is the

primary concern (Li et al., 2014). Powder and crumb rubber can be used as a replacement for fine aggregates in concrete sleeper construction. Previous studies have highlighted the importance of rubber size on concrete behaviour; however, the nanoscale mixture of rubber concrete samples has not yet been assessed (Mohammed et al., 2017). Kaewunruen et al. (2018) stated that finer crumb rubber sizes decrease the damping and increase the compressive strength of concrete by filling the spaces in the concrete. However, replacing fine aggregates with microscale crumb rubber can enhance the electrical resistance of concrete.

Table 4 presents the laboratory tests performed on the RC samples. Generally, the compressive, tensile, and flexural strengths and elastic modulus decrease after adding WTR to concrete samples (Fig. 8), whereas higher impact and fatigue resistances are achieved compared with conventional concrete sleepers. In addition to its mechanical properties, rubberised concrete is vulnerable to changes in temperature; therefore, adding more rubber reduces the resistance of concrete (Siddika et al., 2019).

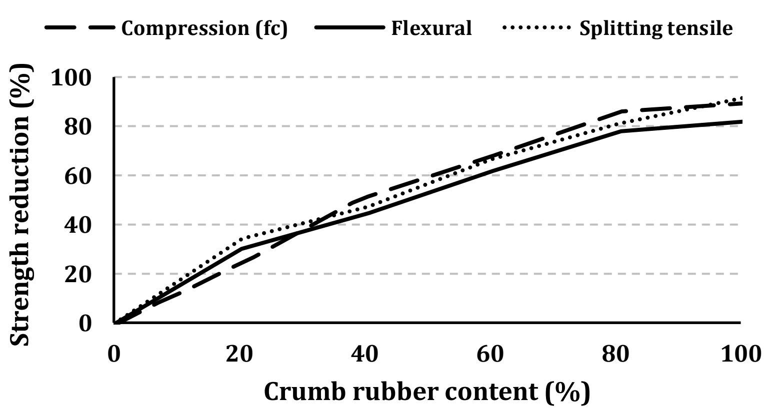


Fig. 8 The effect of rubber content on concrete strength parameters (Batayneh et al., 2008)

Table 4 Changes in the mechanical behaviour of rubberised sleepers compared to the conventional type

Author	Rubber size and content	Measured parameters	Findings

Hameed and Shashikala (2016)	d_{max}: 12.5 mm RC_v: 15%	Impact resistance Fatigue strength	80-110% increase in resistance to crack initiation 40-60% increase in impact strength
Siahkouhi et al. (2022)	d: 0.28 mm RC_v: 5, 10, 15%	Compressive, flexural and tensile strength	28-34% reduction of compressive strength 6-10% reduction of flexural strength About 10% reduction in tensile strength
Jing et al. (2022)	d: 0.28 mm RC_v:	Load for Crack initiation Load for crack branching	20% higher load for crack initiation 20 kN lower load for crack branching
Meesit and Kaewunruen (2017)	d: 425, 75 µm RC_w: 5, 10%	Damping ratio	42% increase in damping ratio for 425 µm rubberised concrete samples
Noaman et al. (2016)	d: 1.18-2.36 mm RC_v: 5 – 15%	Compressive strength Elastic modulus	12.7-26% reduction in compressive strength 9.4-18.5% reduction of elastic modulus
Akinyele et al. (2015)	RC_v: 4 – 16%	Tensile strength Crack initiation Chemical properties	41% and 58% decrease in tensile strength when 4% and 16% rubber were added, respectively Reduction in the bond between cement paste and aggregates in the presence of water
Bompa et al. (2017)	d: 0 – 20 mm RC_v: 0, 5, 10, 15, 20%	Uniaxial compression strength Modulus of elasticity	Compression $f_{cr} = \frac{1}{1+2\left(\frac{3\lambda\rho_{vr}}{2}\right)^{3/2}} f_{c_0}$ Elastic modulus $E_{cr} = 12\left(\frac{f_{cr}}{10}\right)^{2/3}$ Tensile strength $f_{ctr,sp} = 0.24 f_{cr}^{2/3}$
Feng et al. (2022)	d: 1-3; 3-5 mm RC_v: 5, 10, 15, 20, 30%	Compressive strength Bonding splitting tensile strength Rubber size	The decrease of the bond splitting tensile strength for rubberised concrete. 10% RC reaches the maximum tensile strength. Compressive and tensile strengths of 3-5 mm-made rubber concrete are greater than that of mixed with 1–3 mm rubber.

λ: A function of the replaced mineral aggregate size ($2< \lambda<3$); ρ_{vr}: Volumetric replacement factors

In addition to testing the rubber concrete mixture, the mechanical behaviour of the rubber concrete sleeper should be considered. As stated by Zeng et al. (2020), the application of rubberised sleepers can result in vibration reduction in the ballast (2.32 dB) and ground (1.69 dB). Jing et al. (2022) reported the initiation of crack propagation at a lower vertical force for rubberised concrete sleepers compared to conventional ones, which could be associated with the nonuniform mixture of rubber cement or the size of the crumb rubber (Fig. 9).

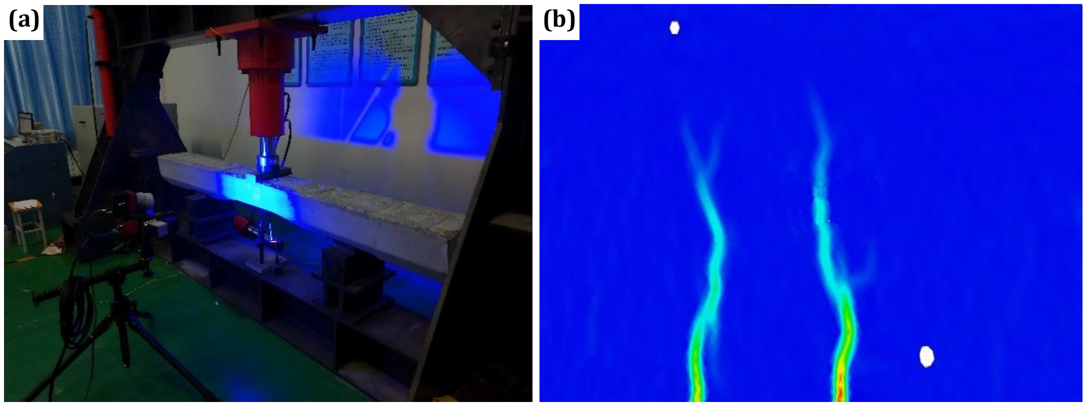


Fig. 9 (a) Measurement of crack propagation on rubberised concrete using DIC, (b) crack growth throughout the sleeper height (Jing et al., 2022)

Given some of the challenges associated with rubberised concrete sleepers, manufacturing concrete sleepers with an outer shell made of WTR is an alternative approach for maintaining the structural performance of the sleeper while providing environmental advantages in terms of railway maintenance and sleeper replacement (Dolci et al., 2020).

Ferdous et al. (2021) investigated the performance of waste rubber concrete-filled FRP tubes with external flanges as railway sleepers and indicated the low efficiency of rubber concrete in a tube structure (Fig. 10). Owing to the lower strength (9 MPa) and elastic modulus (17 GPa) of rubberised concrete compared with those of ordinary Portland cement (OPC) concrete (30 MPa strength and 25 GPa elastic modulus) as infill material, adding 25% crumb rubber to OPC concrete reduced the moment capacity by 17%, bending stiffness by 1%, horizontal plane shear by 9%, and vertical plane shear by 10%. However, the specimen filled with rubberised concrete was 9% lighter and more durable than that filled with normal concrete.

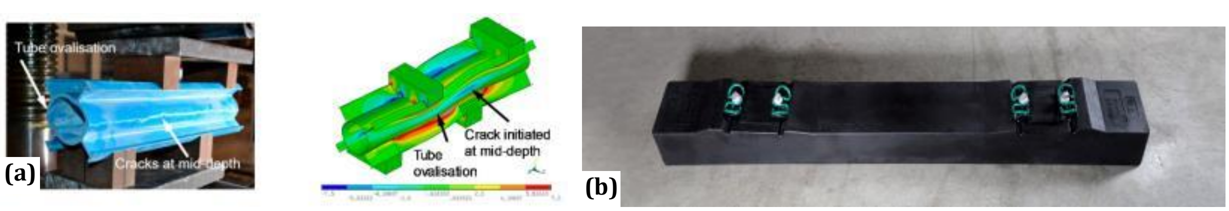


Fig. 10 (a) Experiments and numerical analysis of FRP tube performance (Ferdous et al., 2021), (b) Concrete sleeper covered with a shell of WTR (Jing et al., 2021)

2.2.2 Under Sleeper Pad (USP)

The use of WTR as a USP is effective in reducing vibrations, ballast degradation (Johansson et al., 2008), and delaying rail corrugation (Mayuranga et al., 2020). BS_EN16730 (2016) outlines mandatory and optional tests for the mechanical behaviour of USPs, which include static and low-frequency dynamic bedding modulus tests and fatigue tests. The medium stiff USP ($0.15 < C_{stat} \leqslant 0.25$) has been identified as an appropriate type for different locations (Ngamkhanong and Kaewunruen, 2020). Previous studies evaluated the performance of USPs in terms of vibration, track settlement, lateral track resistance, and stress distribution at the sleeper/ballast interface (Table 5). The results show that USPs increase the sleeper/ballast contact area and reduce the ballast vibration and degradation caused by trains. Hard USPs positively increase the ballast lateral and vertical resistance and reduce rail corrugation (Fig. 11), whereas soft USPs are beneficial for improving the ballast layer performance .

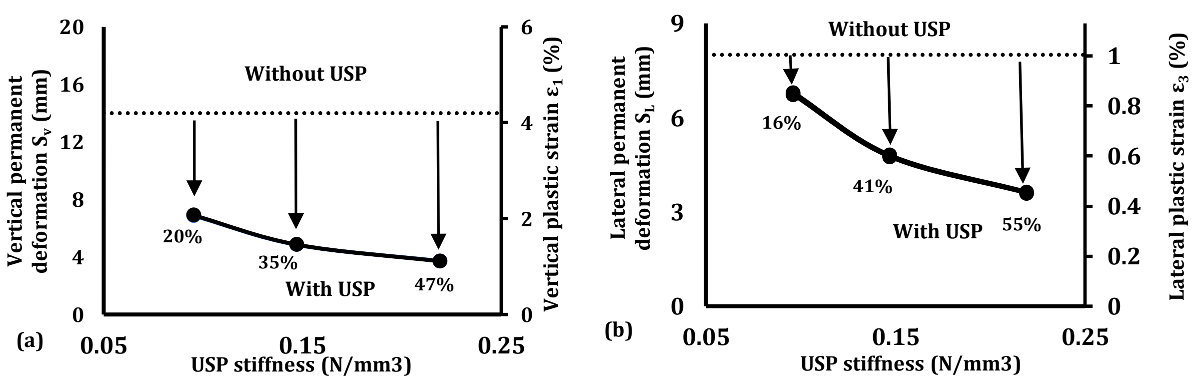


Fig. 11 (a) Vertical and (b) lateral deformation of the ballast sample at the end of the cyclic loading test with and without USP (Indraratna et al., 2021)

Table 5 Studies on ballast performance using USP-reinforced sleepers

Author	Test type (Standard)	Parameters	Findings
Navaratnarajah et al. (2018)	Ballast box test	USP depth: 10 mm Subballast dry density: 2115 kg/m^3 Subballast moisture: 10% Load frequency: 15, 20 Hz	19-29% decrease in ballast settlement 9-14% decrease in ballast lateral displacement

		Load amplitude: 250, 350 kN Load cycles: 5e+05	37-43% and 53-60% increase in ballast vertical and lateral displacement when axle load increase from 250 to 350 kN 51-57% and 27-33% increase in vertical and lateral displacement when loading frequency increased from 15 to 20 Hz. 50% reduction in ballast breakage
Jing et al. (2018)	STPT (UIC)	USP depth: 10 mm USP bump height: 6, 10 mm Ballast depth: 350 mm	25% increase in the lateral resistance of steel sleepers
Esmaeili et al. (2022)	Cyclic box test (ASTM-CEN)	Ballast depth: 450 mm USP depth: 12, 13 mm USP modulus: 0.13, 0.3 N/mm^3 Load frequency: 3 Hz Load amplitude: 43 kN	16.6 % reduction in ballast settlement 7.9 % reduction in ballast breakage 34.6 % reduction in ballast stiffness 114.6 % increase in ballast damping
Müller and Brechbühl (2013)	Field test (CEN)	C_{stat}: 0.11-0.13 N/mm^3 C_{dyn}: 0.14-0.16 N/mm^3	33% reduction in ballast settlement using soft USP. 40% reduction in lateral track resistance.
Sol-Sánchez et al. (2017)	Ballast box test	The USP-like layer of stone rubber blowing under the sleeper Rubber size: 8 – 25 mm Rubber thickness: 2.5 mm (hard), 4.5 mm (soft) RC_v: 10, 25, 50%	Injecting 50% rubber particles over a layer of small stones is recommended, resulting: 14-20 mm is recommended rubber size 91% reduction in ballast settlement compared to pure stoneblowing 50% reduction in ballast stiffness 90% reduction in ballast breakage (BBI) 33% higher density of dissipated energy 34% reduction of pressure on subgrade 1500-2000 cm^3 WTR is recommended value for lateral resistance increment
Guo et al. (2020b)	Ballast box test	USP depth: 6 mm USP bedding modulus: 0.212 N/mm^3 Ballast bulk density: 2050 kg/m^3 Load amplitude: 125 kN Load frequency: 8 Hz	35% reduction in ballast settlement 4-5% reduction in ballast breakage 13.3% increase in ballast-sleeper contact
Omodaka et al. (2017)	Single-tie push test	USP stiffness: 6.5, 8 kN/mm	18-20% increase in lateral resistance 20-40% reduction in ballast settlement

ASTM: American Society for Testing and Materials; CEN: European Committee for Standardization;
UIC: International Union of Railways

More recently, contradictory findings have been reported regarding the vibration characteristics of track components with and without USPs. According to tests conducted by Loy (2008) and Indraratna et al. (2021), the rate of sleeper–ballast contact increased by up to 30%–35% for sleepers reinforced with USP (Fig. 12), resulting in a 10%–25% reduction in ballast stresses and a 40%–60% reduction in ballast breakage, as reported by Mayuranga et al. (2020). From a vibration perspective, using USPs leads to lower vibration velocities than conventional sleepers for frequencies greater than 16 Hz (Stahl, 2005). Field test findings by Marschnig et al. (2022) indicate that USPs operate better on 20 cm ballast beds than normal concrete sleepers, which makes USPs appropriate solutions when external boundary constraints, such as those in bridges or tunnels, require a low ballast depth. By contrast, Schneider et al. (2011) stated that using USPs with C_{stat} = 0.3 N/mm^3 led to a 2-3 times increase in sleeper vibration, although the displacement decreased by 10-15%. Therefore, the USP stiffness and track conditions are essential parameters influencing the track vibration behaviour, causing different impacts of USPs on ballasted tracks.

The static and dynamic stiffnesses of USPs are in the range of 0.12–0.19 N/mm^3 and 0.17–0.23 N/mm^3, respectively (PANDROL, 2021). Stiffer pads are advantageous when the field requirement for USPs is to reduce the rail and sleeper vibrations, sleeper acceleration, rail deflections, rail-bending moments, and corrugation. Alternatively, soft USPs are useful for minimising settlement and ballast vibration, as recommended by Mayuranga et al. (2020).

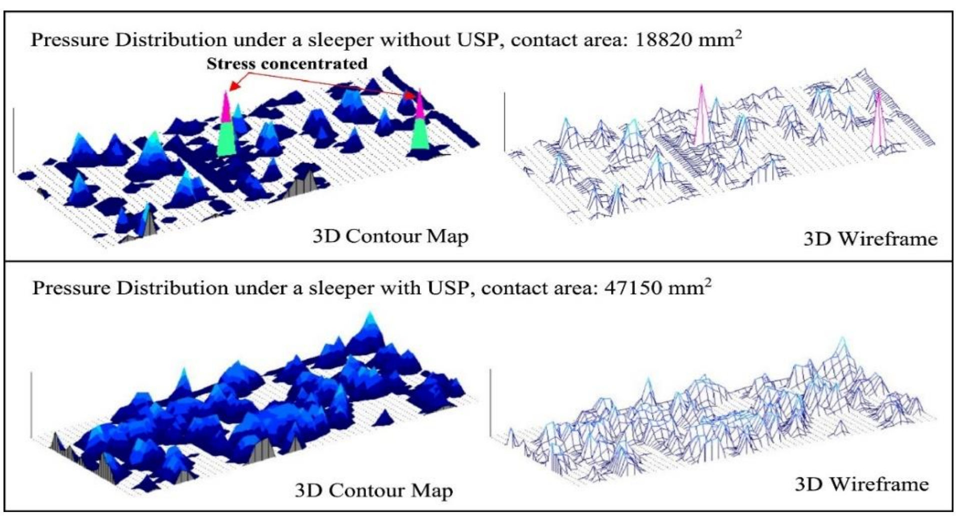


Fig. 12 Stress distribution under a sleeper with and without USP under cyclic loading (Indraratna et al., 2021)

Temperature also affects rubber behaviour, and a 3.5 MPa decrease in Young's modulus was found when the temperature rose from −60° to 0°. The corresponding formulation for calculating the nonlinear stiffness of rubber pads at different temperatures and pressures can be found in (Xu et al., 2020). Fig. 13a-b depict the effect of pressure and temperature on the rubber stiffness at a temperature of 25 °C and a pressure of 57 kN, respectively. The graphs indicate that the rubber stiffness decreased as the temperature increased, whereas it increased at higher pressures. The stiffness increased by 38% when the temperature dropped from 0 to –60 °C. However, the impact of temperature on the stiffness was less significant when the temperature was above 0 °C. Conversely, maintaining a constant temperature while increasing the pressure from 45 to 85 kN resulted in a 100% increase in USP stiffness. The findings from these experiments suggest that both temperature and pressure have a significant impact on the stiffness of rubber materials such as USP. Temperature has a more pronounced effect on stiffness at lower temperatures. These results highlight the importance of considering both temperature and pressure in the design and performance evaluation of USPs.

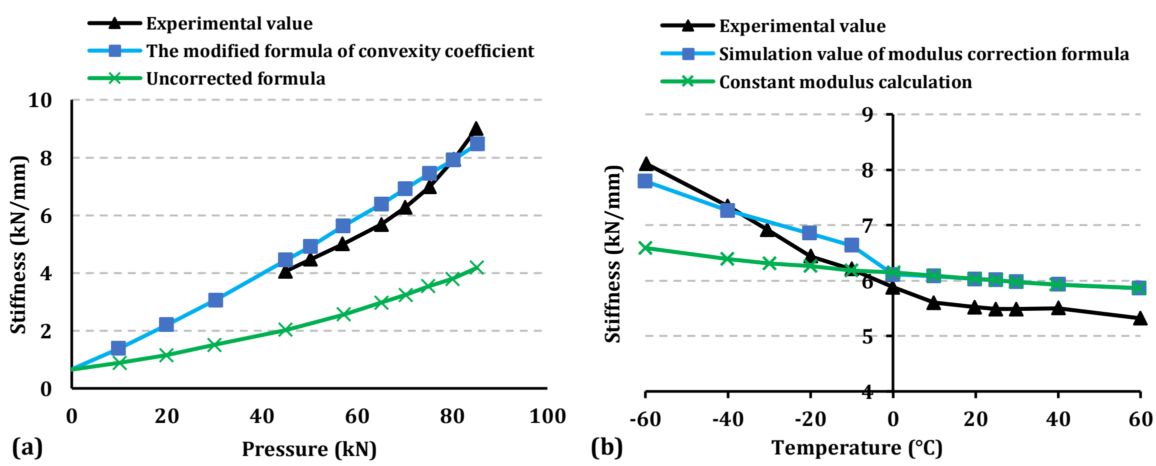
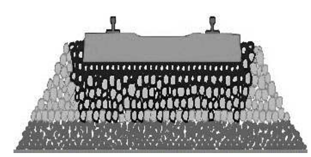


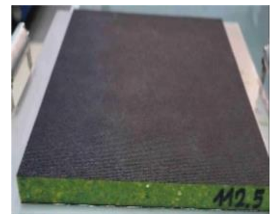
Fig. 13 Relationship between (a) temperature, (b) pressure and stiffness of rubber pads (Xu et al., 2020)

2.3 Ballast

Granular WTR is a typical type of WTR used as a mixture with ballast (Sol-Sánchez, M. et al., 2015), whereas layered WTR (Ballast Mat (BM)) is placed beneath the ballast layer. Different parameters are measured depending on the type of WTR used within or beneath the ballast layer, as described in the following subsections. As presented in Table 6, several methods have been proposed for the application of WTRs to ballast layers, including resiliently bound ballast, rubber-coated ballast, dry granular WTR–ballast mixtures, ballast mats, and tire-infilled granular waste materials (Indraratna et al., 2022b). The use of granular and layered WTR is a common approach for rubber inclusions in railway superstructures. Generally, the proposed methods significantly reduce ballast layer vibration and particle degradation; however, the construction cost and impact on ballast layer stiffness differ depending on the preparation process and additive materials (e.g., resin and epoxy binder).

Table 6 Granular WTR reinforced ballast layer methods

Ballast-granular WTR- types	**Description**	**Pros and Cons**	**View**
Resiliently Bound Ballast (Ho et al., 2013)	A stable mixture of ballast and WTR bound together with a resilient epoxy binder	• Increase in sleeper/ ballast interaction • High vertical stiffness • Less ballast breakage but higher ballast abrasion	
Rubber-Coated Ballast Esmaeili and Namaei (2022); Fontserè et al. (2016)	Coating ballast with powder or crumb rubber using binder/resin	• Less maintenance • Less ballast height • Higher construction cost • Less ballast breakage • The stiffness independency upon the mother rock type	

Dry granular WTR-Ballast mixture (Sol-Sánchez, M. et al., 2015)	The volumetric or gravimetric mixture of granular WTR and ballast	• Less construction cost • Difficulties on uniform distribution of WTR within the ballast layer • Directly exposed to the solar thermal effects • Filling ballast gaps and disturbance of ballast drainage	 
UBM (Kraśkiewicz et al., 2022)	Placement of a rubber pad under the ballast layer	• Easy installation • Reduction of imposed stress on subgrade • Ballast fouling prevention from subgrade • Higher construction cost	
Tire-infilled granular waste materials (Indraratna et al., 2022a)	Placement of rubber tire-confined capping layer as a subballast layer	• Less maintenance • Higher lateral resistance • 40% reduction of vertical stress on subgrade	

2.3.1 Ballast mixed with granular WTRs

Researchers have investigated the suitability of dry granular WTR mixed with ballast for railway tracks. The optimum size and percentage of granular WTR have been studied in terms of settlement, degradation, and energy dissipation (Table 7). Crumb rubber and rubber chips (ballast size WTR) are the most common mixing sizes Fig. 14a-b. Arachchige et al. (2022b) proposed an optimum size for granular WTR, 9.5 to 19 mm, to reduce ballast degradation. Using WTR in the ballast layer leads to a decrease in ballast stiffness, vibration, and degradation, and an increase in ballast damping. However, a reduction in ballast stiffness may cause dynamic-related problems due to passing trains. The volumetric percentage of the mixed rubber content should be less than 10%; however, an appropriate rubber content should be selected based on the track specifications. Moisture content and temperature variations have not been studied extensively and should be considered in future studies. Additionally, Sol-Sánchez et al. (2017) proposed the innovative idea of stone-rubber blowing under a sleeper to improve lateral stability and act as a USP. The results indicated that an amount of 1500-2000 cm^3 of WTR could reduce the ballast stiffness, settlement, and breakage while improving the lateral stability (Fig. 14c).

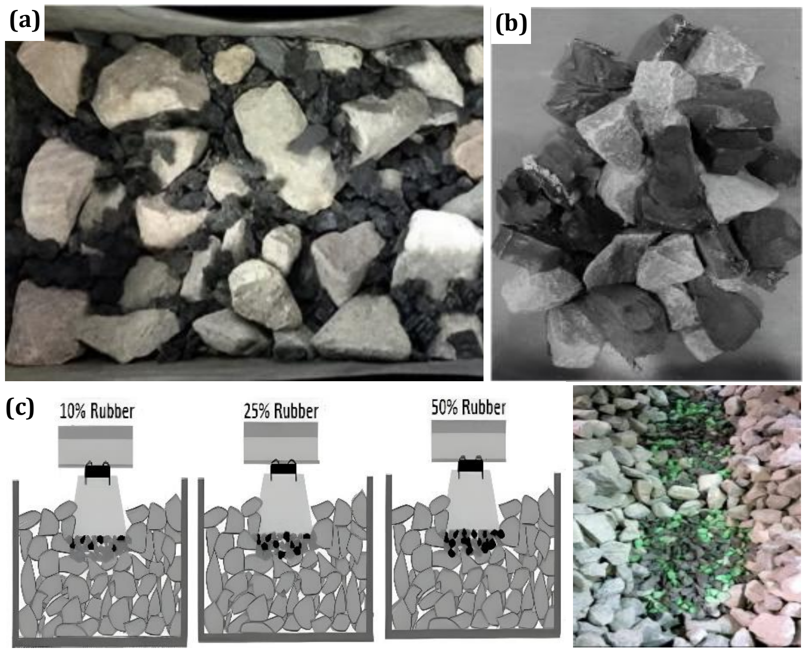


Fig. 14 (a) Crumb rubber-ballast (Sol-Sánchez, M. et al., 2015) and (b) chips rubber-ballast samples (Fathali et al., 2017), (c) WTR-stone blowing under the sleeper (Sol-Sánchez et al., 2020)

Table 7 Studies on applied granular WTR into the ballast layer

Author	**Test type**	**Characteristics**	**Findings**
Guo et al. (2019)	Los Angeles abrasion test and Image analysis	Rubber size: 3 – 25 mm RC_w: 0, 10, 20, 30% Surface texture index: STI= $(A_1 - A_2/A_1)$	• Insignificant reduction of ballast degradation using ballast-size WTRs • Less impact on ballast breakage but a considerable effect on ballast abrasion reduction • 10% is optimum RC mixed with ballast
Arachchige et al. (2022a, 2022b)	Triaxial compression test	Rubber size: 9.5 – 37.5 mm RC_w: 0, 5, 10, 15% Confining pressures: 10-60 kPa Modulus degradation: E/E_i	• 9.5–19 mm is recommended rubber size to preserve ballast strength and reduce ballast breakage • Reduction of modulus degradation up to 10% RC_w • 6% decrease in friction angle for 15% RC_w sample • 50% reduction in the dilation angle when RC_w > 10% • 15% increase in strain energy density when RC_w = 10% • 30 and 80% reduction in ballast breakage when RC_w is 10 and 15%, respectively
Sol-Sánchez et al. (2017)	Ballast box test	A USP-like layer of stone-rubber blowing under the sleeper Rubber size: 8 – 25 mm Rubber thickness: 2.5 mm (hard), 4.5 mm (soft) RC_v: 10, 25, 50%	Stone + 50% Rubber blowing is recommended mixture, resulting in the following: • 91% reduction in ballast settlement compared to pure stoneblowing • 50% reduction in ballast stiffness • 90% reduction in ballast breakage (BBI) • 33% higher density of dissipated energy

			• 34% reduction of pressure on subgrade • 1500-2000 cm^3 is the optimum amount of WTR for improving resistance
Esmaeili et al. (2017)	Ballast box test	Adding ballast-size WTRs RC_w: 5, 10, 15%	• 5% RC_w is recommended Ballast-WTR mixture • 15% reduction in ballast breakage for 5% RC_w (B_g index) • 28% increase in ballast damping ratio for 10% RC_w • 33% reduction in ballast stiffness • Ballast moisture content should be lower than 5% for the efficient act of WTR • Ballast-WTR settlement formula: $S = 0.007 \times T^2 \times (F+20)^{0.153} \times Ln\ N$
Koohmishi and Azarhoosh (2020, 2021, 2022)	Permeability test Impact loading test	Rubber size: 2 – 25 mm RC_v: 10, 20, 30 % Ballast gradations: AREMA_No. 3, 4, and 25	Reported results for AREMA No. 4: • Averagely 36% reduction of ballast hydraulic conductivity when RC increased from 10 to 30% • 18, 28, and 42% increase in hydraulic conductivity when rubber size increased from 2-4.75 mm to 12.5-25 mm, and RC is 10, 20, and 30%, respectively • Higher resistance against impact loads using rubber size of 4.75-9.5 mm • 10% RC_v is recommended regarding vertical deformation
Zhang et al. (2022)	Impact loading test	Rubber size: 8 – 16 mm RC_v: 0, 5, 10, 15%	• The effect of WTR on ballast breakage is independent of particle morphology • Increase of ballast degradation when RC raised from 0 to 5% • The greatest rubber impact on ballast with the size of 25 – 35.5 mm
Song et al. (2019)	Direct shear test	Rubber size: 10 – 50 mm RCv:0, 5, 10% Ballast gradation: AREMA 4A Normal stress: 30, 50, 70 MPa N: 300 cycles	• 5% is proposed as the optimum RC mixed with ballast • 15% increase in ballast damping ratio • 10% reduction in resilient shear stiffness and friction angle

ε_a: Axial strain; E_i: Initial tangent modulus; $E = \Delta q / \Delta \varepsilon_a$; S: Settlement;
N: Number of load cycles; T: Rubber content; F: Fouling percentage

2.3.2 Under Ballast Mat (UBM)

WTR can be employed in the form of pads under a ballast layer, which is known as a ballast mat (Fig. 2d). UBMs are typically composed of two layers of polymeric material: (I) a distribution layer to evenly distribute loads and (II) an elastic layer to attenuate stresses. To reduce costs, alternative composites made from recycled tires are being explored in addition to traditional elastic materials. Similar to the testing of a single USP, BS_EN17282 (2020) proposed specifications for UBMs in which fatigue testing is mandatory. Kraśkiewicz et al. (2022) conducted comprehensive experimental tests on the performance of UBMs composed of diverse materials under severe environmental conditions or subjected to cyclic loading conditions. They found that exposure to water, frost, and cyclical loads can permanently alter the static and dynamic properties of elastic elements in railway superstructures. This can potentially affect the effectiveness of vibration reduction throughout the lifespan of railway tracks.

UBMs are primarily used to decrease vibrations transmitted to subgrades. Research results in Germany indicated a 15 dB reduction (~30%) for frequencies higher than 31.5 Hz compared with a conventional track (Werkstoffe, 2006). The application of the UBM is promising in cases where stress reduction on the substructure is a concern (e.g., in tunnels, bridges, and switches). In this regard, the thickness and density of the mat and the size and type of the constitutive material are influential parameters. Sol-Sánchez, Miguel et al. (2015) found that soft UBMs can be beneficial as they decrease ballast pressure, degradation, and ground vibration and increase track damping. The utilisation of circular and square aperture GRIDMAT was respectively suggested in recent publications by Sol-Sánchez et al. (2022) and Siddiqui et al. (2023), who merged the properties of the geogrid and ballast mat to simultaneously enhance both track stability and damping (Fig. 15). To achieve optimal efficiency, a highly efficient GRIDMAT with an aperture size of 50−60 mm and a void area of up to 25% was recommended. The study demonstrated that this type of GRIDMAT resulted in a 10% decrease in ballast settlement compared with the UBM-reinforced ballast layer.

Fig. 15 Different shapes of rubber grid mats used as UBM (Sol-Sánchez et al., 2022)

According to previous studies, the mechanical behaviour of UBM-reinforced ballast has been investigated in terms of ballast settlement, stress distribution, ballast breakage, track noise, and vibration, as presented in Table 8.

Table 8 Studies on the performance of the UBM-reinforced ballast layer

Author	Test type	Characteristics	Findings
Navaratnarajah and Indraratna (2017)	Ballast box test	Ballast depth: 300 mm UBM depth: 10 mm Weight 9.2 kg/m^2 C_{static}: 0.2 N/mm^3 C_{dyn}: 0.46-0.59 N/mm^3 Load frequency: 10,15,20,25 Hz Load amplitude: 250, 350 kN	• 10-20% reduction in vertical strain • 5-10% reduction in lateral strain • 35-45% reduction in degradation (BBI) • 20% reduction in stress at the ballast/sleeper interface • Efficient performance of UBMs on a stiff subgrade rather than the soft one
Nimbalkar et al. (2012)	Impact loading test	Ballast depth: 300 mm UBM depth: 30 mm Weight 9.2 kg/m^2 C_{static}: 0.2 N/mm^3 C_{dyn}: 0.46-0.59 N/mm^3 (soft and hard UBM) Dynamic stress: 400–600 kPa Impact blows: 10 times	• 19% reduction of BBI on stiff subgrade • 24% reduction of BBI on weak subgrade
Lima et al. (2017)	Ballast Box test	Ballast PSD: AREMA_No. 4A Ballast depth: 300 mm UBM depth: 5, 10 mm Load frequency: 5 Hz Load amplitude: 1.8 – 26 kN	• Ignorable changes in ballast breakage under low force magnitude and frequency

Diego et al. (2017)	Fatigue test	Using ballast plate: C_{static} ~ 0.0139 N/mm^3 $C_{static,h}$ > 0.0050 N/mm^3 C_{dyn} measurement: 1000 initial loading cycles Cyclic load amplitude:1.8–9 kN Cyclic load frequency: a) 1, 5, 10, 20 Hz at room temperature b) 10 Hz at -20, -10, 0, 30 °C	• 135% increase in C_{dyn} when load frequency raised from 1 to 20 Hz • 60% drop in C_{dyn} when temperature raised from -20 to 30 °C • 13 mm settlement after 1st 5.10^5 cycles • 10 mm settlement after 2nd 5.10^5 cycles • 26.2% increase in C_{static} for frost damage test
Indraratna et al. (2021)	Impact loading test	Ballast depth 350 mm UBM depth: 10 mm UBM weight: 10.5 kg/m^2 C_{static}: 0.142 kg/m^3 C_{dyn}: 0.107 kg/m^3 Load: 5.81 kN Load speed: 10 m/s	• 7 – 15% decrease in ballast vertical and lateral deformation • 28% and 10-17% reduction in ballast breakage (BBI) for hard and soft subgrade, respectively
Esmaeili et al. (2020)	Field test	Granular WTR pillow between ballast and bridge Ballast depth: 200 mm Rubber size: 20 – 50 mm Rubber pillow depth: 0,100, 200, and 300 mm Train load: 75,100,125 kN Train speed: 40,60,80,100 km/h	• Using a 300 mm rubber pillow led to a) 52%, 66%, 73, and 50% decrease in bridge deck acceleration, b) 56%, 60%, 43%, and 40% increase in rail acceleration, c) 13%, 11%, 7% and 25% reduction in bridge vertical displacement, when train speed was 40, 60, 80 and 100 km/h, respectively.

2.4 Implementation of investigated WTR products in practical applications

Numerous projects focus on the application of WTR in railway tracks, particularly for the mitigation of noise and vibration; however, few projects are available for the application of WTR in ballast deformation and stress reduction, which can be attributed to the uncertainty of the long-term performance of WTR-made products. The following are examples of projects that use WTR products in ballasted railway superstructures:

- Application of rail dampers in Germany and France to reduce rail noise and vibration (Lakušić and Ahac, 2012).
- Installing rubber level crossing in Germany manufactured by (STRAIL, 2022).

- Application of USPs in the Tehran–Mashhad railway in Iran to reduce train-induced vibrations that adversely affect the track infrastructure and its surroundings, as reported by Zakeri et al. (2016).
- Application of rubber-coated sleeper (GREENRAIL) in the line Reggio Emilia – Sassuolo, Italy (Emilia, 2018) to reduce ballast degradation and vibration.
- Application of tire-infilled granular waste materials in Chullora Railway (Sydney, 2022), to reduce vertical stress on the subgrade and improve lateral track resistance.

Notably, the use of granular WTR mixed with ballast has not been widely implemented in practice because of the uncertainty associated with its behaviour within discrete ballast particles. The complex interaction between the WTR and ballast particles can affect the mechanical properties of the mixture, and there is limited knowledge of its long-term performance and durability under various environmental conditions. Therefore, further research is required to address the challenges and uncertainties associated with the implementation of WTR ballast mixtures in railway trackbeds.

3 Numerical simulation rubber elements

Numerical modelling of rubber-like materials allows for the analysis of their behaviour under diverse circumstances. This encompasses the simulation of deformation and stress−strain behaviour, the prediction of thermal and electrical properties, and their interaction with other components in the track system. The discrete element method (DEM) and finite element method (FEM) are two useful techniques for modelling rubber inclusions in ballasted tracks. Researchers have employed elastic linear contact models to provide a simplified model of the interaction between rubber elements and rigid railway components. Nonlinear/hyperelastic contacts have also been employed for specific scenarios. In the following sections, we describe the techniques applied and the potential challenges for future investigations.

3.1 Finite element method

Several continuum methods have been developed to model the mechanical behaviour of materials, including the boundary element method (BEM), finite element method (FEM), and finite difference method (FDM). For modelling layered WTRs (RPs, USPs, and UBMs), FEM is the most commonly used method (Ferreira and López-Pita, 2013). In general, unlike the DEM, the FEM has difficulty replicating multifracture states in solids (Oñate et al., 2018). However, the FEM allows the discretisation of the geometry (rubber products) into small elements that can be connected to form a mesh. The behaviour of each element can be approximated using the constitutive model and equations of motion, and the overall behaviour of the material can be obtained by combining the responses of all the elements. This allows for the accurate prediction of the deformation and stress distribution within a material, which is desirable for simulating large deformable rubber-like materials (Latham et al., 2020).

3.1.1 Constitutive models of rubber particles

In many studies, a linear elastic model has been used for the simulation of soft-rigid contacts, which is given by:

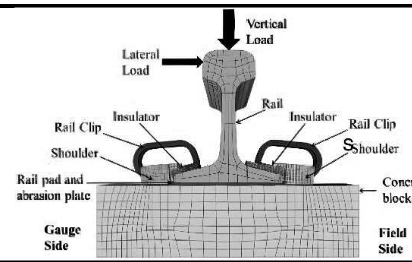
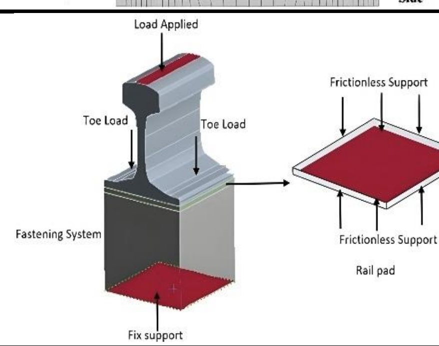
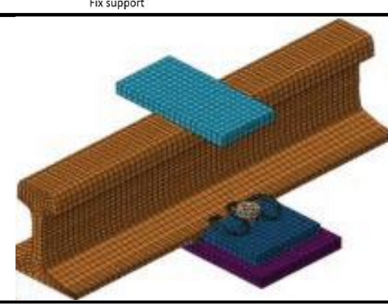
$$\sigma = E\varepsilon = E\frac{\delta}{L} \tag{2}$$

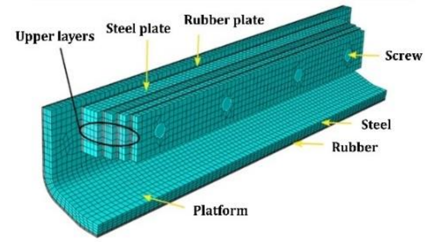
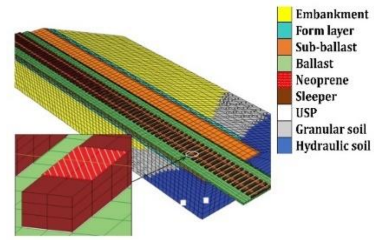
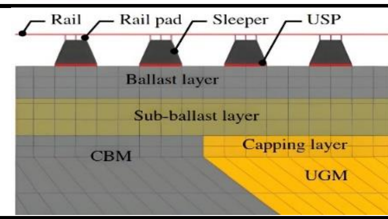
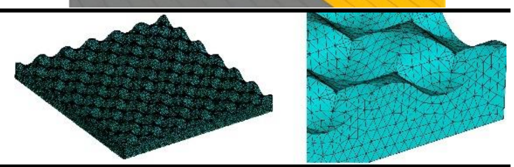
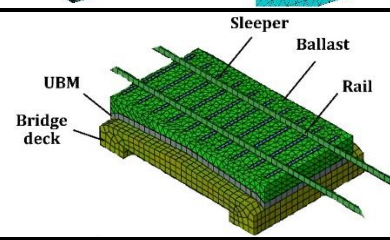
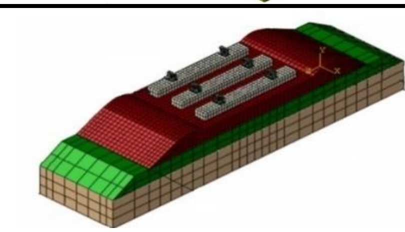
Owing to the nonlinear behaviour of rubber, a hyperelastic model may be suitable for modelling the interaction between WTRs and rigid railway components. Hyperelasticity is a constitutive model used to describe the nonlinear behaviour of materials resembling rubber that undergo significant elastic deformation. A hyperelastic material is often characterised by a strain energy density function in the finite element method (FEM), which connects the deformation of the material to its energy. The strain energy density function is generally described in terms of the invariants of the deformation tensor, such as stretches or primary strains. Several methods have been developed for the hyperelastic modelling of materials, such as the Arruda–Boyce, Marlow, Mooney–Rivlin, Neo-Hookean, Ogden, and polynomial methods (Ali et al., 2010). Marckmann and Verron (2005) categorised 19 hyperelastic models in terms of their validity domain for traction (T), pure shear (PS), equibiaxial extension (EQB), and biaxial extension (BE) for Treloar data considering the following assumptions: I) If the accuracy is good, the parameters are retained. II) If the accuracy is poor, the validity domain is modified as follows: a) If the model cannot reproduce the strain hardening at large strains, the domain of validity is reduced for the uniaxial extension mode (λ_{max}); b) otherwise, other deformation modes are eliminated from the identification procedure. The domain of validity (λ_{max}) for the various modes of deformation is observed in the response curves. Depending on the deformation domain evaluated, the neo-Hookean, Mooney, and Ogden models were proposed for small, moderate, and large strains, respectively. The constitutive behaviour of a hyperelastic material is based on the total stress–total strain relationship, where the strain energy density is only a function of the deformation gradient (F), expressed in the principal directions of the stretch. The formulation for the hyperelastic modelling of rubber materials can be found in (Farooq et al., 2021).

3.1.2 FEM-based studies on ballasted railway problems

The FEM has been widely used for modelling layered WTR-reinforced tracks, including RPs, USPs, UBMs, and rail dampers. The displacement, stiffness, and vibration (acceleration) of track components under static, cyclic, or train loading were evaluated using FEM (Indraratna et al., 2021). For instance, Shih et al. (2019) used the FEM to simulate the static response of a railway track reinforced by USPs. The results showed that the USP slightly increased the track settlement owing to the lower confining pressure in the ballast layer. In addition, Sadeghi et al. (2020) conducted nonlinear modelling of rail fastening, including the bilinear stiffness and damping coefficient (C). The effects of the RP stiffness, load frequency, and preload magnitude (as the principal influencing parameters) on the mechanical behaviour of fastening systems were explored through parametric analyses of fastening systems. Given the FEM-based analyses in Table 9, the FEM is suitable for investigating the impact of padded rubber on railway infrastructure performance, particularly track vibration, stiffness, and plane stress distribution.

Table 9 FEM-based studies on rubber-used railway superstructure

Author	Loading type	WTR type	WTR Contact model	Outputs	View
Chen et al. (2013)	Fastening system vertical/lateral loading	RP	Linear elastic	• Tensile and compressive stress of superstructure components	
Othman et al. (2022)	Fastening system vertical loading	RP	Hyperelastic (Neo-Hookean)	• RP stiffness	
Sadeghi et al. (2020)	Fastening cyclic loading test	RP	Nonlinear (mathematical model)	• Rubber stiffness	

Kuchak et al. (2021)	Rail shaking	Rail damper	Linear elastic	• Decay rate • Rail noise • Rail vibration	
Insa et al. (2014)	Train moving load	RP USP	Linear elastic	• Track stiffness • Track vibration	
Alves Ribeiro et al. (2015)	Passenger tilting train load	USP	Nonlinear	• Track vibration • Track settlement	
Diego et al. (2017)	Vertical static and cyclic loading	UBM	Non-linear-Hyperelastic (Mooney-Rivlin)	• Static/Dynamic bedding modulus	
Esmaeili and Siahkouhi (2019)	Train moving load	Impact absorber (UBM)	Linear elastic	• Bridge deflection • Bridge vibration	
Farooq et al. (2021)	Train loading	USP UBM	Hyper elastic	• Track vibration • Track settlement • Vertical stress • Horizontal stress	

3.2 Discrete element method

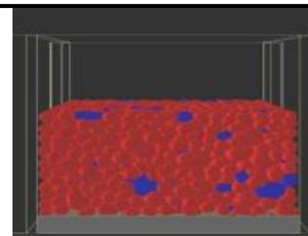
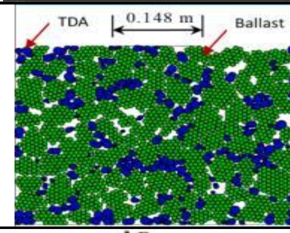
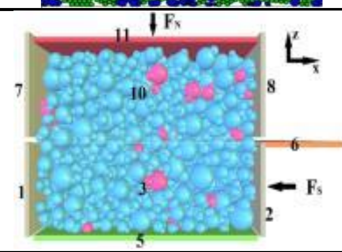
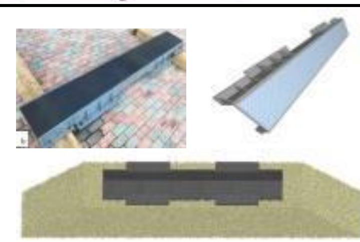
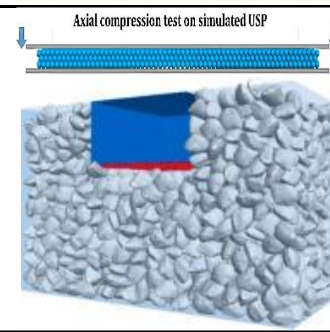
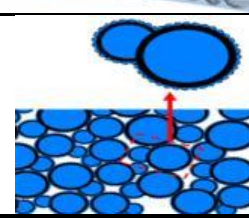
The DEM has been widely used to simulate granular materials, considering the discrete and continuum characteristics of particles (Jing and Stephansson, 2007). Although numerous investigations have been performed on sand–rubber contact using numerical methods (particularly

DEM), there are few studies on the numerical modelling of rubber elements in ballasted railway tracks. The DEM may be useful for simulating granular WTR-reinforced railways. According to previous studies, the linear spring–dashpot and Hertz–Mindlin models have been adopted for the simulation of contacts between rigid elements. Different methods have been proposed for modelling deformable materials, including bonded pebbles, elastic clumps, deformable spheres, and flexible polyhedra. Owing to the irregular shape of granular WTR, bonded pebbles, elastic clumps, and flexible polyhedrons are suitable alternatives for the accurate analysis of soft-rigid contacts in railway superstructures.

Given the nonhomogeneous behaviour of granular WTR, the DEM might be a better alternative to provide a particle-scale analysis of WTR-reinforced railway components. In this regard, the DEM has been mainly used to simulate granular WTR-reinforced ballast (e.g., rubber-coated ballast and granular WTR–ballast mixture). Interparticle contact forces significantly govern the behaviour of granular materials. While the FEM uses approximations to model the contact forces between particles, the DEM explicitly models particle-particle contact mechanics. Modelling the behaviour of granular WTR requires accurate modelling of the contact mechanics, and the DEM enables a more accurate depiction of these forces. Moreover, the DEM can be employed to model the USP/UBM as a bonded ball layer to evaluate its impact on the ballast force chain, ballast vibration, degradation, and displacement. Table 10 presents the analyses of the WTR-reinforced ballast railway components using the DEM.

Table 10 DEM-based studies on rubber-used railway superstructure

Author	**Loading type**	**WTR type**	**WTR Contact model**	**Outputs**	**View**

Wu et al. (2021)	Impact loading	Crumb	Hertz-Mindlin	• The vibration of ballast mixed with granular WTRs	
Guo et al. (2022)	Train loading	Crumb	Linear elastic	• Wheel/rail contact force • Rail displacement • Ballast stress-strain	
Gong et al. (2019)	Direct shear test	Crumb	Linear elastic	• Ballast shear strength • Coordination number • Ballast breakage	
Wang et al. (2022)	Sleeper lateral resistance	USP	Hertz-Mindlin	• Sleeper lateral resistance • Ballast force chain	
Li and McDowell (2018)	Cyclic loading	USP UBM	Linear elastic	• Ballast stress-strain • Ballast settlement • Ballast breakage • Coordination number	
Guo et al. (2020a)	-Direct shear force -Vertical Cyclic loading	Granular WTR-coated ballast	Linear elastic	• Track settlement • Track vibration • Ballast shear strength • Ballast force chain	

4 Future research directions

There are specific gaps in the literature regarding each WTR element, as listed in Table 11. For instance, although several studies have been conducted on the use of WTR in the ballast layer, there is limited research on the performance of WTR in rail and sleeper components. Additionally, the effects of environmental factors such as temperature and moisture on the performance of WTR products have not been fully explored. Given the research gaps listed in Table 11, the use of WTR in railway infrastructures poses several challenges that must be addressed to ensure optimal performance.

I. *General challenge*: WTR is a temperature-dependent material; therefore, the impact of temperature variation should be considered for the numerical modelling of WTR inclusions in railway infrastructure, particularly when WTR is directly exposed to sunlight (e.g., granular WTR mixed with ballast and USP).

II. *The challenge of granular WTR mixed with ballast*: Heavy rain significantly impacts railway track operation by disturbing the ballast drainage system. In this case, the ballast permeability is governed by the selection of a suitable rubber particle size, content, and shape, which is problematic because these parameters influence the permeability of the ballast–WTR mixture. This can be assessed through experiments and numerical methods.

III. *The challenge of rubberised concrete sleepers*: Although many types of research have been conducted on rubberised concrete samples, little is known about the suitable size and percentage of WTR mixed in a concrete sleeper with respect to the standards for railway sleepers. This problem can be evaluated using the FEM–DEM, considering concrete as a continuum and aggregates as embedded discrete elements.

IV. *The challenge of studies on WTR-reinforced rail*: As previously mentioned, rail dampers are used to reduce induced-train noise; however, it is essential to determine the optimum interval for installing rail dampers along the rails. In addition, the manufacture and analysis of WTR-made sound protection walls fastened to the rail foot, which requires the design of their size and location along the trackside, will be of great interest.

Table 11 Relationship between WTR products and influential parameters

Parameters	**Railway components**										
	Rail			**Sleeper**				**Ballast**			
	RP	Rail damper	Level crossing panel	USP	RC	Rubber-coated sleeper	FRP tube	UBM	GRIDMAT	Granular WTR-ballast mix	Rubber tyres
Rail noise	✓	✓	✓								
Rail vibration	✓	✓		✓							
Rail corrugation	✓	✓		✓							
Electrical resistance			✓		✓						
Sleeper fatigue strength					✓						
Sleeper impact resistance					✓						
Sleeper vibration					✓						
Sleeper damage					✓						
Compressive/ flexural/tensile strength					✓		✓				
Chemical properties					✓						
Ballast settlement				✓		✓		✓	✓	✓	✓
Ballast stress distribution				✓		✓		✓	✓	✓	✓
Ballast breakage				✓		✓		✓	✓	✓	
Ballast lateral resistance				✓				✓			✓
Track stiffness	✓	✓		✓		✓		✓	✓	✓	
Ballast damping	✓			✓		✓		✓	✓	✓	
Ballast acceleration	✓			✓				✓	✓	✓	

5 Conclusion

In this review, we explored the potential benefits of utilising WTR in the ballasted superstructure of railway tracks, including the rail, sleeper, and ballast layers. Rubber can be used in the form of pads or granules of varying sizes depending on its specific application. This study provides a comprehensive evaluation of the performance of WTR-reinforced ballasted tracks in terms of vibration, noise, stiffness, settlement, breakage, damping, shear strength, and lateral resistance. The results from experimental studies have highlighted the effectiveness of rubber-reinforced railways in reducing noise and vibration, altering track stiffness, and improving overall performance. Moreover, the development of numerical modelling using the DEM or FEM is discussed to analyse the performance of rubber-reinforced railway tracks. Such modelling can aid in optimising the design of railway tracks, leading to improved safety, reduced maintenance costs, and extended service life. Overall, this study indicated that the use of WTR in railway infrastructure has significant potential and warrants further investigation to fully understand their benefits and limitations.

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