CETRA2026 27-30 May 2026, Bol, Island Brač, Croatia
9th International Conference on Road and Rail Infrastructure

SUSTAINABLE BALLASTED TRACK DESIGN FOR NOISE AND VIBRATION MITIGATION

Stanislav Lenart[1], Siva Ram Karumanchi[1], David Garcia Sanchez[2]
[1]Slovenian National Building and Civil Engineering Institute (ZAG), Slovenia
[2]TECNALIA, Spain

Abstract

Noise and vibration mitigation is an increasingly important aspect of sustainable railway infrastructure, particularly in environments where community impact must be balanced with long-term track performance. At the same time, there is growing interest in reducing the environmental footprint of ballasted tracks using recycled and alternative materials. This paper investigates how sustainable modifications of ballast, including the incorporation of recycled aggregates and rubber-based components, influence the mechanical behavior of the track and its potential for noise and vibration mitigation. The study is based on laboratory testing of modified ballast materials, focusing on changes in stiffness, damping characteristics, and ballast grain breakage. These results are interpreted in terms of vibration transmission and the dynamic response of the ballasted track structure. The results indicate that selected rubber-modified ballast mixtures provide increased damping and energy dissipation while maintaining adequate load-bearing capacity and deformation resistance. Although direct acoustic measurements were not performed, the observed mechanical response is consistent with previously reported reductions in track vibration levels for systems incorporating rubber elements. The findings support the potential of sustainable ballast modifications as part of low-noise and low-vibration ballasted track solutions.

Keywords: sustainable railway design, ballasted track, noise and vibration mitigation, recycled ballast, rubber aggregate

1 Introduction

Ballasted track systems remain the most common form of railway infrastructure, providing load transfer, geometric stability, and drainage. However, ballast layers are prone to progressive degradation caused by particle breakage, settlement, and loss of confinement, which leads to excessive deformations and frequent maintenance interventions [1]. To mitigate these issues, railway infrastructure researchers increasingly study stabilization measures such as geosynthetic reinforcement and ballast material modification, including the incorporation of rubber derived from recycled tires [1]. In several European countries, including Slovenia and Croatia, the limited availability of high-quality igneous ballast necessitates the use of sedimentary rocks with lower abrasion resistance, further accelerating ballast degradation [2]. This context has intensified the need for sustainable solutions that enhance track performance while reducing maintenance demands. The reuse of waste materials in railway applications has therefore gained attention, particularly rubber-based inclusions such as tire-derived aggregates (TDA). Previous laboratory studies have shown that rubber-modified ballast can reduce particle breakage and increase energy dissipation under cyclic loading [3–6].

DOI: https://doi.org/10.5592/CO/CETRA.2026.1956

These improvements, however, are often accompanied by reduced frictional resistance and dilative behavior, which may adversely affect ballast confinement and lateral stability [4, 6]. Adequate confinement thus remains essential for ensuring the long-term performance of both conventional and modified ballast systems. Planar geosynthetics have been shown to effectively limit settlement and lateral spreading of granular layers in railway tracks and are commonly adopted for this purpose [7–10]. In addition to mechanical degradation, railway traffic generates noise and vibration, with wheel–rail rolling noise dominating in conventional ballasted tracks. Near-rail low-height noise barriers (LHNBs) have emerged as an effective source-control measure, offering comparable insertion losses to conventional barriers while reducing visual and environmental impact. Reported field and numerical studies indicate noise reductions in the range of approximately 6–10 dB(A), depending on barrier geometry and receiver position [11–13]. Further improvements have been achieved through optimized geometries and porous or absorptive materials, while life-cycle assessments suggest that low-height barrier concepts can offer environmental advantages over conventional 3-4 m high noise barriers [14–15]. This paper presents a low-noise and low-vibration ballasted track concept developed within the EU Horizon project LIAISON, integrating low-height ballast shoulder walls with planar geogrids. The shoulder elements provide lateral confinement to the ballast layer while simultaneously serving as foundations for near-rail noise barriers. Reused ballast is combined with rubber chips derived from waste tires to enhance stress redistribution and vibration damping. The paper focuses on the cyclic mechanical behavior of the modified ballast materials – namely shear modulus, damping ratio, internal friction angle, and grain breakage resistance – and discusses their implications for vibration mitigation and sustainable track design.

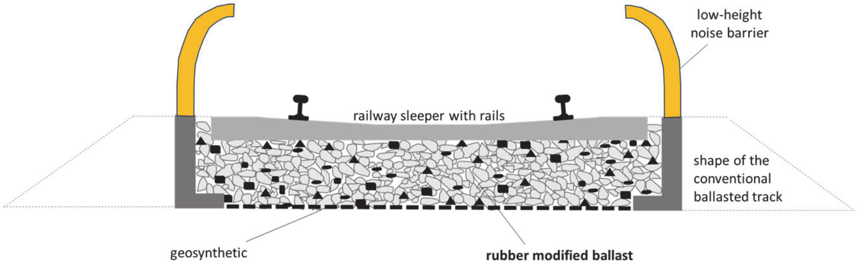

Figure 1 Illustration of proposed novel low-noise and low-vibration ballasted track concept

2 Materials and experimental background

2.1 Ballast materials

The experimental program is based on a characterization of reused ballast (RB) originating from limestone, which is commonly used in regions with limited access to high-quality igneous ballast. It was collected from existing railway tracks and exhibited rounded particle shapes and smoother surfaces due to previous operational loading and abrasion. To improve the mechanical and dynamic performance of the reused ballast, tire-derived aggregates (TDA) produced from waste truck tires were incorporated into the ballast mixture. Prior to mixing, steel wires and textile fibers were removed from the tire material. A key feature of the present study is the use of large TDA particle sizes, ranging from 22.4 to 50 mm, which closely match the size range of conventional ballast particles. This particle size selection was intended to minimize segregation effects and allow the rubber inclusions to actively participate in load transfer and energy dissipation, rather than acting solely as void fillers.

Ballast–TDA mixtures were prepared by mass replacement of reused ballast with TDA at contents ranging from 0 to 10%. Based on both previous studies and preliminary observations, TDA contents above 10% by mass were not considered, as higher rubber volumes can significantly reduce ballast stiffness and lead to excessive deformation under cyclic loading.

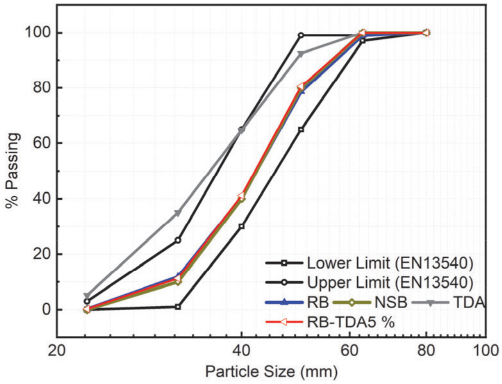

Figure 2 Particle size distribution curves of reused ballast (RB), newly sourced ballast (NSB), tire-derived aggregates (TDA), and RB–TD5% mixture

Figure 2 presents the particle size distribution curves of the RB, NSB, TDA, and the corresponding ballast–TDA mixtures. The gradation of the ballast materials was selected to comply with the requirements of EN 13450 for railway ballast. The incorporation of TDA did not significantly alter the overall grading envelope of the ballast mixtures, ensuring compatibility with standard track design requirements. The similarity between the TDA particle sizes and those of the ballast material represents a fundamental difference from many earlier studies that employed smaller rubber particles. This approach reduces the risk of downward migration and segregation of rubber particles under cyclic loading and promotes more uniform mechanical behavior throughout the ballast layer. A central objective of the experimental program was to identify an optimal TDA content that enhances damping and reduces ballast degradation while maintaining adequate load-bearing capacity and deformation resistance. Results from monotonic and cyclic laboratory testing showed that the incorporation of 5% TDA by mass provides a favorable balance between stiffness, energy dissipation, and mechanical stability. At this TDA content, the rubber particles contribute to improved stress redistribution and increased damping without causing a pronounced reduction in internal friction angle or excessive contractive behavior. In contrast, higher TDA contents (e.g. 10%) resulted in a noticeable decrease in shear modulus and frictional resistance, indicating a transition toward a more compliant composite behavior that may compromise track performance under high traffic loads. Accordingly, the 5% TDA mixture is identified as the most promising configuration for sustainable ballasted track applications aimed at noise and vibration mitigation, and it is used as the primary reference mixture for evaluating cyclic mechanical behavior in this study.

2.2 Experimental approach

The mechanical behavior of the ballast materials was evaluated using large-scale cyclic simple shear tests to capture cyclic deformation behavior relevant to railway loading conditions. The experimental program focused on key response parameters, including shear modulus, damping ratio, and grain breakage resistance, which govern ballast performance under repeated train loading and influence vibration transmission.

The multi-functional large-scale testing equipment presented in figure 3 has been designed and developed in the geotechnical laboratory at the Slovenian National Building and Civil Engineering Institute (ZAG), Slovenia, to evaluate the cyclic shear behavior of ballast materials. Details about the equipment and testing program are available elsewhere [16, 17].

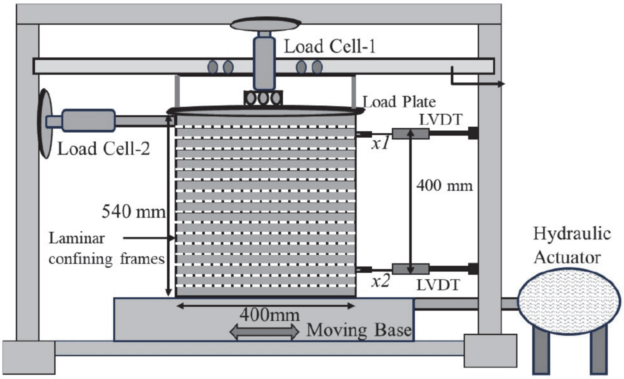

Figure 3 Schematic illustration of large-scale simple shear test setup

3 Results and discussion

3.1 Shear modulus and stiffness evolution

The shear stiffness of ballast materials governs the dynamic response of ballasted track systems and strongly influences vibration transmission from the wheel–rail interface to the substructure. Figure 4 (left) presents typical variation of shear modulus with shear strain amplitude for the reused ballast (RB) and various ballast–TDA mixtures under cyclic loading in relation to shear strain. The results indicate that the incorporation of tire-derived aggregates significantly affects the stiffness behavior of the ballast. While the addition of TDA generally leads to a reduction in shear modulus compared to unmodified ballast, the mixture containing 5% TDA maintains a stiffness level higher to that of RB over a wide strain range. This behavior suggests that an appropriate amount of rubber inclusions can enhance stress redistribution within the granular skeleton without excessively compromising load-bearing capacity.

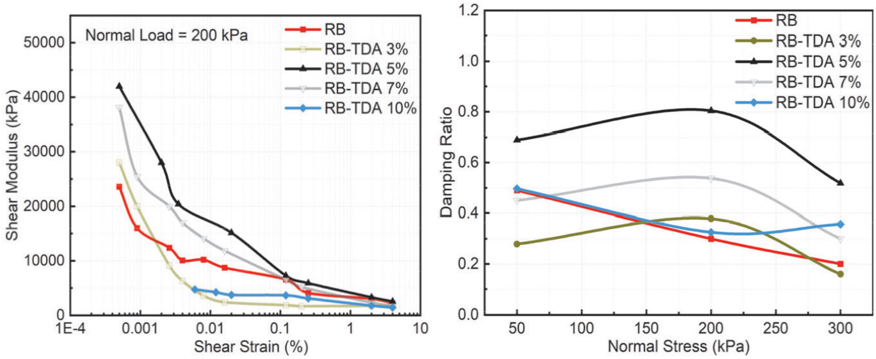

Figure 4 Shear modulus vs. shear strain at vertical stress 200 kPa (left) and damping ratio vs. vertical stress (right) for different rubber contents

3.2 Damping characteristics and energy dissipation

Damping plays a key role in controlling vibration amplitudes and mitigating the propagation of structure-borne noise in railway tracks. Figure 4 (right) shows the variation of damping ratio with shear strain for the tested rubber-modified ballast materials. The 5% TDA mixture demonstrates the most favorable performance, with damping ratios significantly higher than those of RB and also of other mixtures. The enhanced damping response is attributed to frictional sliding at rubber–aggregate interfaces and the viscoelastic behavior of the rubber inclusions, which promote energy dissipation during cyclic loading. The combination of moderate stiffness retention and increased damping observed for the 5% TDA mixture is particularly advantageous for vibration mitigation, as it enables effective attenuation of vibration energy without compromising structural performance.

3.3 Grain breakage and long-term performance

Ballast degradation through particle breakage leads to fouling, stiffness loss, and increased vibration levels over time. Figure 5 shows the grain breakage indices (BBI) of the tested ballast materials with various TDA content after cyclic loading. The results demonstrate that the inclusion of rubber particles significantly reduces ballast degradation. The 5% TDA mixture exhibits a notably lower breakage index than pure RB, indicating improved resistance to particle fragmentation. This behavior is attributed to the cushioning effect of rubber inclusions, which reduce stress concentrations at particle contacts.

Reduced grain breakage is particularly relevant for noise and vibration mitigation, as degradation-induced changes in ballast stiffness and geometry can lead to increased dynamic excitation and long-term deterioration of acoustic performance. The observed reduction in ballast breakage therefore supports the potential of rubber-modified ballast to maintain stable vibration characteristics over the service life of the track.

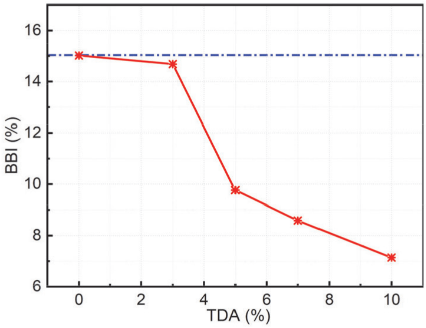

Figure 5 Ballast Breakage Index (BBI) variation with TDA (%) addition

4 Conclusion

The combined mechanical response of the rubber-modified ballast provides a clear basis for its application in low-noise and low-vibration track concepts. The 5% TDA mixture demonstrates sufficient stiffness to maintain track geometry and load-bearing capacity, significantly enhanced damping and energy dissipation as well as reduced ballast degradation under cyclic loading. These characteristics suggest that rubber-modified ballast can effectively attenuate vibration transmission from the wheel–rail interface into the track structure, thereby contributing to reduced structure-borne noise.

Although direct acoustic measurements were not performed, the experimentally observed increase in damping ratio and energy dissipation is consistent with previously reported reductions in track vibration levels for systems incorporating rubber elements and enhanced confinement. When combined with lateral confinement provided by geosynthetics and ballast shoulder walls, as proposed in the present low-height noise barrier concept, the modified ballast is expected to further improve dynamic stability and long-term performance. The results presented herein therefore support the feasibility of integrating sustainable ballast modifications into practical railway track designs aimed at simultaneous mechanical, environmental, and acoustic benefits.

Acknowledgements

This research was supported by the EU's Horizon Europe program (grant No. 101103698, project LIAISON) and by the Ministry of Higher Education, Science and Technology of the Republic of Slovenia and The Slovenian Research Agency (ARIS) Program group P2-0273.

References

[1] Prasad, K.V.S., Hussaini, S.K.K.: Review of different stabilization techniques adapted in ballasted tracks, Construction and Building Materials, 340 (2022), 127747, DOI: https://doi.org/10.1016/j.conbuildmat.2022.127747

[2] Guo, Y., Xie, J., Fan, Z., Markine, V., Connolly, D.P., Jing, G.: Railway ballast material selection and evaluation: A review, Construction and Building Materials, 344 (2022), 128218, DOI: https://doi.org/10.1016/j.conbuildmat.2022.128218

[3] Indraratna, B., Sun, Q., Grant, J.: Behaviour of subballast reinforced with used tyre and potential application in rail tracks, Transportation Geotechnics, 12 (2017), pp. 26–36, DOI: https://doi.org/10.1016/j.trgeo.2017.08.006

[4] Indraratna, B., Mehmood, F., Mishra, S., Ngo, T., Rujikiatkamjorn, C.: The role of recycled rubber inclusions on increased confinement in track substructure, Transportation Geotechnics, 36 (2022), 100829, DOI: https://doi.org/10.1016/j.trgeo.2022.100829

[5] Sol-Sánchez, M., Moreno-Navarro, F., Rubio-Gámez, M.C.: Viability of using end-of-life tire pads as under sleeper pads in railway, Construction and Building Materials, 64 (2014), pp. 150–156, DOI: https://doi.org/10.1016/j.conbuildmat.2014.04.013

[6] Gong, H., Song, W., Huang, B., Shu, X., Han, B., Wu, H., et al.: Direct shear properties of railway ballast mixed with tire-derived aggregates: Experimental and numerical investigations, Construction and Building Materials, 200 (2019), pp. 465–473, DOI: https://doi.org/10.1016/j.conbuildmat.2018.11.284

[7] Leshchinsky, B., Ling, H.I.: Numerical modeling of behavior of railway ballasted structure with geocell confinement, Geotextiles and Geomembranes, 36 (2013), pp. 33–43, DOI: https://doi.org/10.1016/j.geotexmem.2012.10.006

[8] Indraratna, B., Biabani, M.M., Nimbalkar, S.: Behavior of geocell-reinforced subballast subjected to cyclic loading in plane-strain condition, Journal of Geotechnical and Geoenvironmental Engineering, 141 (2015), DOI: https://doi.org/10.1061/(ASCE)GT.1943-5606.0001199

[9] Biabani, M.M., Ngo, N.T., Indraratna, B.: Performance evaluation of railway subballast stabilised with geocell based on pull-out testing, Geotextiles and Geomembranes, 44 (2016), pp. 579–591, DOI: https://doi.org/10.1016/j.geotexmem.2016.03.006

[10] Indraratna, B., Ngo, N.T., Rujikiatkamjorn, C.: Deformation of coal-fouled ballast stabilized with geogrid under cyclic load, Journal of Geotechnical and Geoenvironmental Engineering, 139 (2013), pp. 1275–1289, DOI: https://doi.org/10.1061/(ASCE)GT.1943-5606.0000864

[11] Lázaro, J., Pereira, M., Costa, P.A., Godinho, L.: Performance of Low-Height Railway Noise Barriers with Porous Materials, Applied Sciences, 12 (2022), 2960, DOI: https://doi.org/10.3390/app12062960

[12] Nieuwenhuizen, E., Yntema, N.: The effect of close proximity, low height barriers on railway noise, Euronoise 2018, pp. 1375–1380, Heraklion, Greece, 27–31 May 2018.

[13] Song, L., Gao, K., Liu, Q., Zhang, L., Feng, Q., Guo, W.: Acoustic performance of near-rail low-height noise barriers installed on suburban railway bridges, Environmental Science and Pollution Research, 29 (2022), pp. 62330–62346, DOI: https://doi.org/10.1007/s11356-022-20074-8

[14] Abdulkareem, M., Havukainen, J., Nuortila-Jokinen, J., Horttanainen, M.: Life cycle assessment of a low-height noise barrier for railway traffic noise, Journal of Cleaner Production, 323 (2021), 129169, DOI: https://doi.org/10.1016/j.jclepro.2021.129169

[15] European Commission DG Environment News Alert (Science for Environment Policy): Reducing railway noise and vibration: life-cycle assessments can help decide the best measures, issue 493, 27 July 2017.

[16] European Commission: GEOLAB project (H2020, GA 101006512), CORDIS, 2021., DOI: https://doi.org/10.3030/101006512

[17] Lenart, S., Karumanchi, S.R.: Deformation properties and performance evaluation of reused ballast with waste tire-derived aggregates, Transportation Geotechnics, 52 (2025), 101586, DOI: https://doi.org/10.1016/j.trgeo.2025.101586