The Fifth International Conference on Railway Technology
RAILWAYS 2022
22–25 August 2022
Montpellier, France

Proceedings of the Fifth International Conference on
Railway Technology:
Research, Development and Maintenance
Edited by J. Pombo
Civil-Comp Conferences, Volume 1, Paper 8.10
Civil-Comp Press, Edinburgh, United Kingdom, 2022, doi: 10.4203/ccc.1.8.10

Ballast reinforcement for improved structural performance at track problem areas

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Abstract

Problem areas on ballasted track are known for non-homogeneous track support, excessive settlement, poor track geometry and track component fatigue and failure. Ballast reinforcement using rigid polyurethane foam (RPF) was utilised in this study to strengthen the ballast, thereby reducing settlement and improving the long-term performance of the ballast. Full ballast layer as well as ballast shoulder reinforcement were investigated by carrying out cyclic loading tests in a laboratory using both a single sleeper and a half sleeper in a large ballast box. Unreinforced, reinforced, 50% reinforced and shoulder reinforced ballast with a thickness of 300 mm depth were tested at accelerated frequencies to a total of nearly 5 million load cycles. The results indicated that RPF reinforced ballast settled 60% less than an unreinforced layer and in the test where only the lower half of the ballast layer was reinforced, 42% less settlement was recorded compared to the unreinforced ballast layer. In tests where only the shoulder of the ballast was reinforced, a 30% reduction in settlement was obtained when compared to that of unreinforced ballast. By implementing ballast shoulder reinforcement, the resilient modulus of the ballast layer was not altered significantly. The use of RPF to reinforce ballast is beneficial to track performance and could result in improved track geometry and reduced maintenance, resulting in lower life cycle costs at specifically track problem areas.

Keywords: ballast reinforcement, polyurethane foam, ballast settlement, lateral confinement.

1 Introduction

Studies and field trials have been carried out across the world to investigate the reinforcement of the ballast layer with different products such as polyurethane polymers and rigid polyurethane foams [1,2,3,4,5]. The purpose of ballast reinforcement is to reduce settlement and to increase ballast track stiffness to match the higher stiffness of more rigid track structures such as bridges, viaducts and tunnel slabs – also known as track transitions [6].

Urethane cross-linked polymers (polyurethane) form a 3-dimensional ballast polymer matrix (geocomposite). The unfoamed polyurethane material forms a stiff bond between ballast particles, while foamed polyurethane is more elastic [7]. The RPF is injected into the ballast where it expands and flows through the voids of the ballast. The bond formed between the RPF and the ballast is critical to the formation of a geocomposite ballast layer [8].

Indraratna, Lackenby & Christie [9] investigated the effect of confining pressure on the degradation of ballast by carrying out isotopically consolidated, drained cyclic triaxial tests. This research confirmed the notion that increased confining stress in the ballast, through reinforcement of the ballast shoulder or layer, would lead to reduced settlement and degradation. Lateral confinement can be improved by either increasing the ballast friction angle, curtailing lateral flow of the ballast using geosynthetics, preventing lateral flow of ballast using modified sleepers, or by increasing the shoulder height and compaction [10].

A major disadvantage of rigid polyurethane foam reinforced ballast, is that the foam renders the ballast unmaintainable for a period of time. To lessen this effect, partial reinforcement of the ballast was proposed for the testing described in this paper.

Figure 1 shows the four models/laboratory setups that were created for the testing. Model (a) represents the base case with no reinforcement of the structural ballast layer or the shoulder. In Model (b), only the ballast shoulder is reinforced, allowing tamping of the full depth of the ballast layer. In Model (c), 50% of the ballast layer is reinforced, allowing tamping of the top ballast only, while Model (d) has a fully reinforced ballast layer that would not be maintainable through tamping.

The focus of this research was to investigate the potential structural advantage that could be achieved through rigid foam reinforcement of the ballast at problem areas with limited length, assuming that other aspects such as drainage and ballast maintenance (eg. tamping and screening) would be addressed as practically solvable problems in future studies.

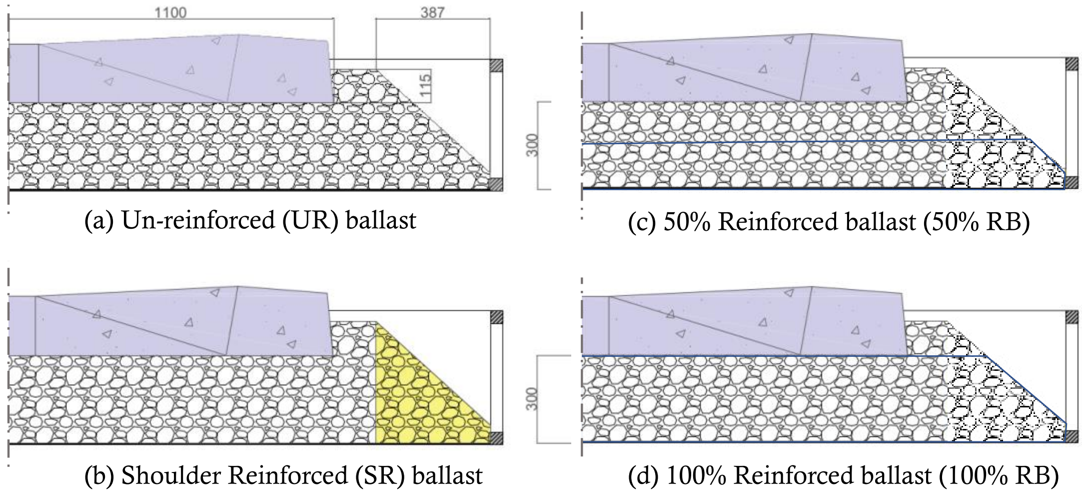

Figure 1: Four laboratory models with varying degrees and locations of ballast reinforcement

2 Methods

Elastopor ®H 1311/1 Rigid Polyurethane Foam was used to reinforce the ballast. The foam was supplied in two separate components namely a Polyol-component (A-component) and an Iso-component (B-component). The polyol component is a mixture of polyether polyols, stabiliser, catalyst, flame retardant and water. The iso-component is Polymeric Diphenylmethane Diisocyanate (IsoPMDI 92140).

A hydraulic MTS load frame with a maximum actuator capacity of 500 kN and loading frequency of 100 Hz was used to apply the cyclic loading to the ballast and foamed ballast placed in a steel box. The tests that involved foaming of the entire sleeper width (Fig. 1a, 1c and 1d) were conducted with a full sleeper in a box with internal dimensions of 2400 mm long, 600 mm wide and 400 mm high. The shoulder reinforced tests (Fig. 1a and 1b) were carried out with a half sleeper in a smaller box with a length of 1200 mm and similar width and height as before. Each sample consisted of a 300 mm ballast layer with a PY-sleeper on top of the ballast. Linear variable differential transducers (LVDTs) with a full scale of 20 mm were mounted onto the test frame at the sleeper end for local sleeper displacement measurement in addition to the displacement obtained from the internal actuator. The experimental test setup with the MTS actuator, a full sleeper and the accompanying ballast box is shown in Figure 2.

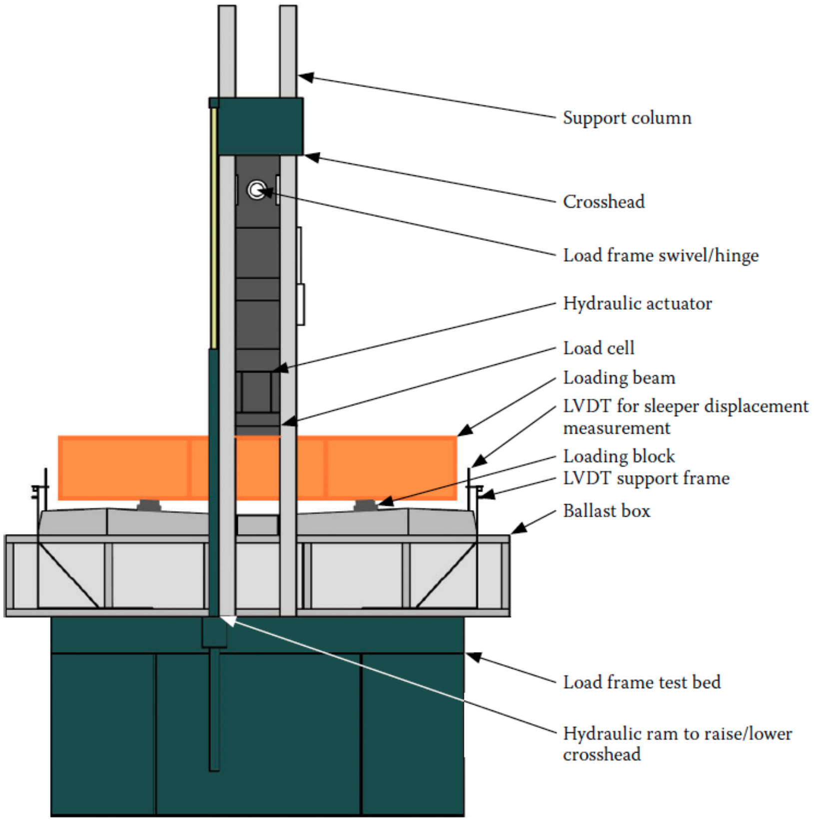

Figure 2: Hydraulic actuator with ballast and sleeper box for cyclic loading

A compaction procedure was performed for each box test to ensure an optimum density and to reduce consolidation settlement during the initial stage of loading. A compaction plate and frame were placed on top of the ballast layer to ensure adequate compaction of the entire ballast layer. The compaction procedure consisted of approximately 57,000 cycles for the full sleeper tests and 25,000 cycles for the half sleeper tests, all performed at a frequency of 10 Hz with a maximum amplitude of between 100 kN and 225 kN, depending on the required maximum load for the specific setup.

Once the compaction phase was completed, the main cyclic loading phases commenced. All ballast models were loaded cyclically at 10 Hz for up to 5,000,000 cycles with a maximum amplitude of 260 kN for the full sleeper tests and 90 kN for the half sleeper tests. Full details of the compaction and cyclic loading procedures are given in [3], [11] and [12].

3 Results

Four ballast box tests were carried out with the full sleeper setup. Firstly, a test with unreinforced ballast was performed (Fig. 1a). This was followed by the a fully reinforced ballast layer test (Fig 1d). In this test, foaming was carried out without placing any restriction on the expansion of the ballast and foam. The settlement during the initial or compaction phase was in the order of 50 mm for both the unreinforced and reinforced tests. It was realised that the foaming with free expansion pushed the ballast stones apart, descreasing the ballast density and resulting in little to no improvement of the settlement (see Fig. 3).

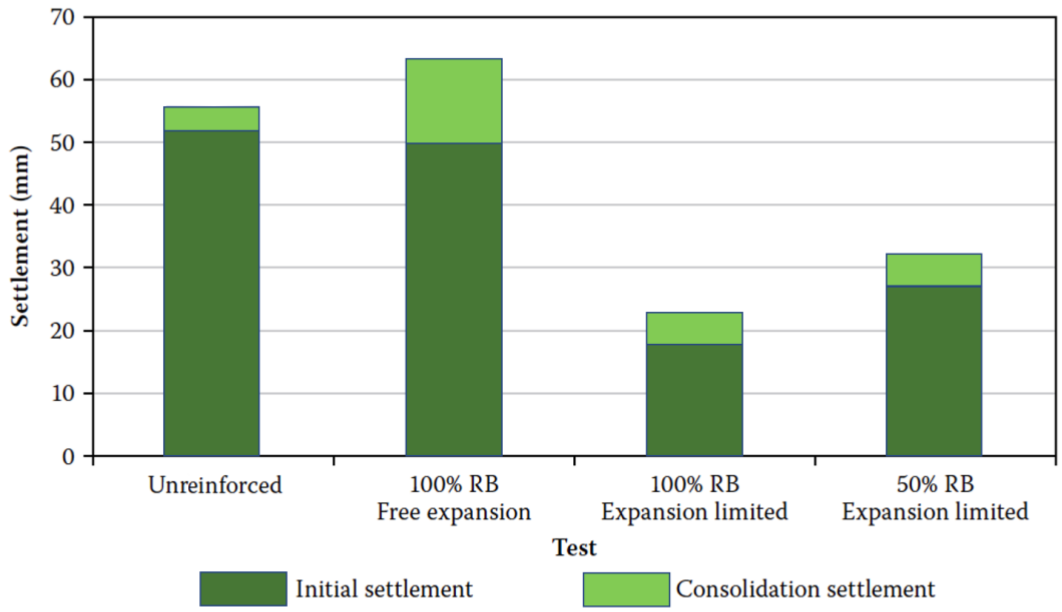

Figure 3: Settlement results of the polyurethane stabilised ballast models [3]

It was subsequently decided to limit the expansion during foaming and the results of the following two tests with 50% and 100% reinforcement of the ballast showed significant reduction of the initial ballast settlement. The consolidation settlement of all samples was similar and in the order of 5 – 12 mm after 5,000,000 cycles. The reduction in settlement as a result of RPF reinforcement equates to 60% and 42% for the fully and half reinforced ballast layers respectively.

The secant method was used to calculate the resilient modulus (E_r) of the ballast during cyclic loading. Fig. 4 shows how the resilient modulus of unreinforced ballast was reduced from 185 MPa to a value of between 75 MPa and 120 MPa. During the course of the 5,000,000 loading cycles, the resilient modulus steadily increased to the point where E_r of the 50% RB model was equal to that of the unreinforced ballast. Despite the initial restriction in expansion of the 100% RB model, the E_r of both this model and the 100% RB free expansion model converged to a value of approximately half the E_r of the unreinforced ballast.

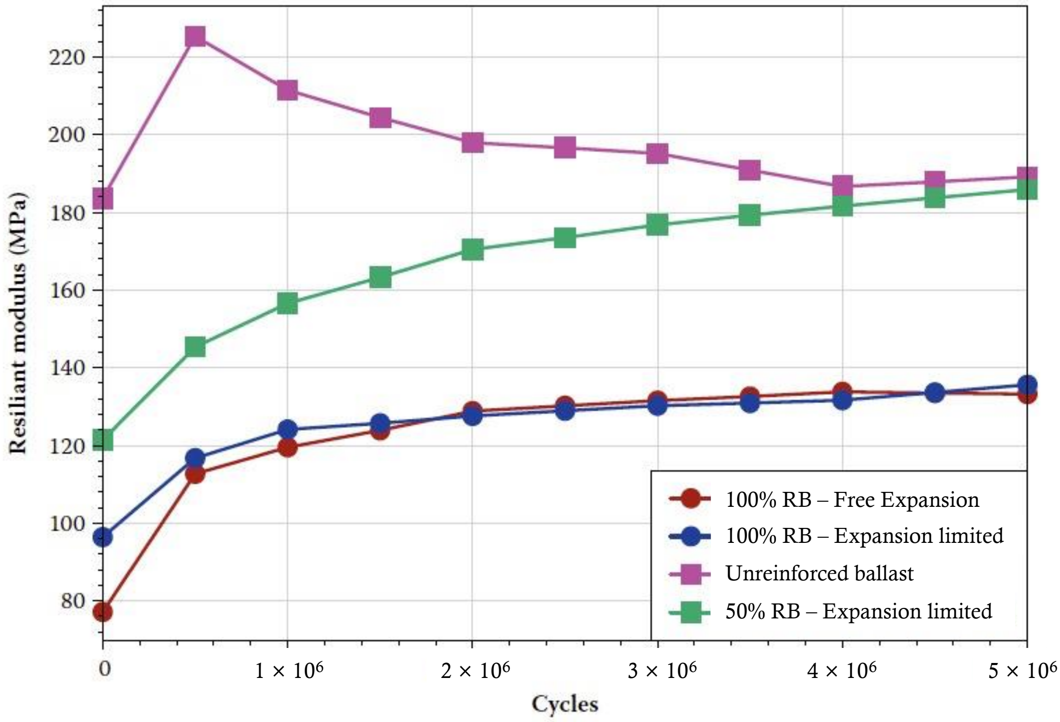

Figure 4: Stiffness results of the polyurethane stabilised ballast models [3]

The second set of tests comprised a total of 6 tests on unreinforced and shoulder reinforced ballast in a half sleeper box (Fig 1a and 1b). Three pairs of tests were carried out with a total of 5, 4 and 3 million loading cycles respectively. The settlement of each ballast model following the compaction phase, is shown in Fig. 5. It is clear that the shoulder reinforcement significantly reduced the ballast settlement in all tests. Although the E_r results were not consistent throughout, a general trend of resilient modulus reduction following foaming can be observed, similar to the first set of tests.

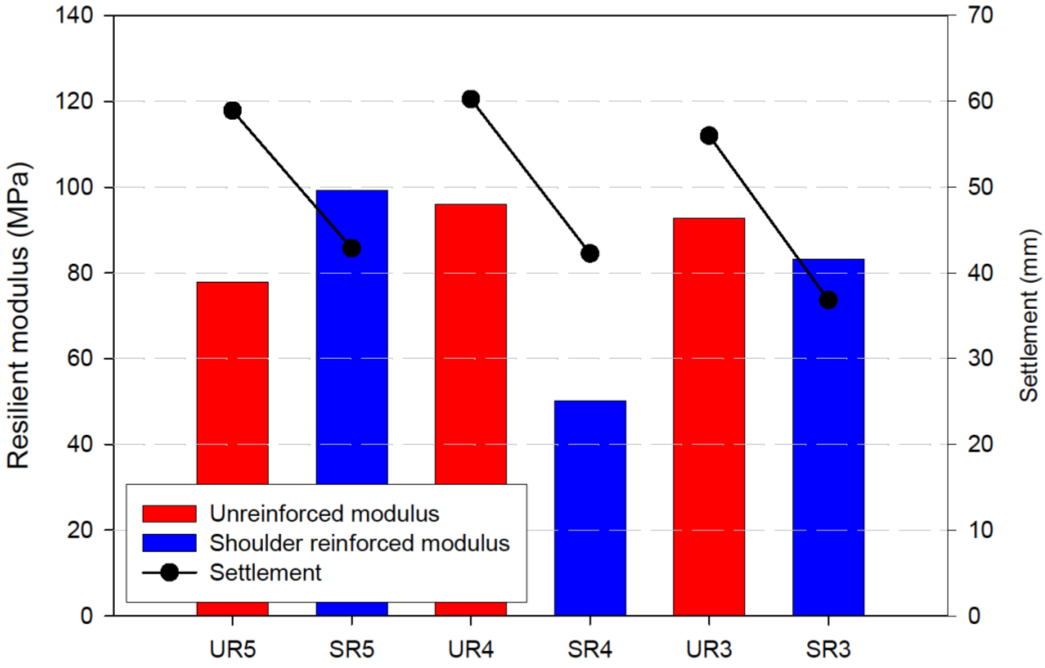

Figure 5: Resilient modulus and settlement results of the unreinforced (URx) and shoulder reinforced (SRx) ballast models (x indicates the loading cycles in millions) [12]

4 Conclusions and Contributions

The results of the ballast box tests described in this paper have demonstrated that rigid polyurethane foam (RPF) is useful for ballast reinforcement at problem areas. The main conclusions can be summarised as follows:

- Rigid polyurethane foam reinforced ballast settled 60% less than conventional unreinforced ballast when the entire depth of the ballast is reinforced .
- Reinforcing only 50% of a ballast layer resulted in a 42% reduction in settlement compared to that of the unreinforced ballast model.
- In the case of RPF reinforced ballast, the resilient modulus increased as the number of cycles increased. This increase in layer modulus with time could be used advantageously in the design of track transitions or other problem areas.
- Shoulder reinforced ballast settlement was on average 30% lower than that of the unreinforced ballast models.
- Shoulder reinforcement did not influence the resilient modulus of the ballast layer significantly.

The main advantage of RPF is that it reduces the settlement of track structures. The significant reduction in total settlement (including compaction and consolidation settlement) of RPF reinforced ballast layers could result in better long term track geometry and a reduction in impact loading at track transitions. As a result, improved track performance and a longer track lifecycle can be expected when reinforcing the ballast layer with RPF. This research confirms the notion that ballast reinforcement results in increased lateral confinement and reduced ballast settlement. These benefits have been quantified and are useful for design and maintenance purposes.

Ballast breaking, loading frequency effects and ballast settlement prediction functions were also studied and details of these can be found in [11] and [12].

Practical solutions exist for addressing the aspects of drainage and ballast maintenance that are affected by the introduction of RPF into the ballast layer.

Acknowledgements

Transnet Freight Rail is gratefully acknowledged for financial support to the Chair in Railway Engineering at the University of Pretoria. The authors would like to acknowledge and thank the laboratory staff at the University of Pretoria for assistance during the experimental work of this study.

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