Settlement Response of Fibre Reinforced Railway Ballast

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Abstract

Ballasted track is the prevalent track form worldwide and with good design and maintenance can satisfy high performance demands including those of high speed lines. However, increasingly onerous loading is being placed on existing ballasted track networks in many parts of the world by more frequent, longer, faster and heavier trains. This leads to reduced windows of time for maintenance activities while simultaneously increasing maintenance needs. Therefore there are potential advantages if ballasted track could be modified to increase durability both in terms of intervals between maintenance interventions, e.g. tamping, and overall life cycle. This paper presents an assessment of the potential for randomly reinforced ballast, a mixture of ballast and fibres of selected dimensions and properties, to increase the durability of railway track. Compared with other types of reinforcement, fibres have potential advantages of: isotropy (avoiding the formation of weak planes); the possibility of using recycled plastic material; and expected compatibility with normal maintenance procedures. A series of full size tests has been conducted in the Southampton Railway Testing Facility (SRTF) to evaluate the resilient and plastic response of reinforced ballast to vertical cyclic loading. The testing apparatus represents a slice of single track extended to the shoulders and including one sleeper. A vertical load, representing a 20 tonne train axle, was applied by a hydraulic actuator with a frequency of 3Hz to 3 million cycles. Tests carried out thus far demonstrate the importance of selecting an appropriate fibre width as a function of the average particle size of the ballast to be reinforced. Appropriately selected fibres are shown to reduce ballast vertical permanent deformations by about 25%.

1. Introduction

In response to stresses induced by train passage, ballast degrades and experiences plastic settlement. Track permanent deformations, especially when differential settlements occur, reduce track safety, and periodic maintenance, e.g. tamping, is vital. In recent years, trains have become more frequent, longer, faster and heavier. This has both increased maintenance needs and reduced the windows of time available for maintenance operations. Thus improving track performance would serve to reduce both maintenance costs and maintenance disruption. Track settlement normally occurs mainly in the ballast layer (Selig & Waters, 1994), and at least six methods to reduce ballast permanent deformation through changes to the sleeper interface or the ballast layer have been studied: e.g. (1) the use of under sleeper pads (Abadi, 2014; Abadi et al., 2015); (2) reinforcement through geogrids and geotextiles (Bathurst & Raymond, 1987; Gobel et al., 1994; Raymond, 2002; Raymond & Ismail, 2003; Brown et al., 2007; Indraratna et al., 2009; Indraratna & Nimbalkar, 2013; Hussaini et al., 2015); (3) the variation of ballast grading (Abadi, 2014; Indraratna et al., 2011; Nalsund, 2010; Tutumluer et al., 2009); (4) the use of a 3D cellular reinforcement (Kennedy, 2011; Dash & Shivadas, 2012; Leshchinsky & Ling, 2013; Indraratna et al., 2015); (5) the injection of a 3D polymeric reinforcement (Woodward et al., 2007; Woodward et al., 2011; Kennedy et al., 2013); and (6) the use of a ballast-crumb rubber mixture (Sol-Sánchez et al., 2015). A further novel technique to improve ballast durability is here introduced. This consists of the use of discrete fibres of specified material properties and dimensions to reinforce ballast. Studies have shown that the introduction of discrete fibres can improve the shear strength of sands (Michalowski & Čermák, 2003; Heineck et al., 2005; Diambra et al., 2013; Shao et al., 2014), gravels (Lirer et al., 2012) and 1/3 scaled ballast (Ajayi et al., 2014). Moreover, compared with other types of ballast reinforcement (e.g. geogrids) there are potential advantages to using discrete fibres: isotropy (avoiding the formation of weak planes), the possibility of using recycled plastic material and expected compatibility with normal railway maintenance procedures (e.g. tamping). To better understand the optimal dimensions and properties of fibres to improve ballast performance a series of cyclic tests have been conducted in the Southampton Railway Testing Facility (SRTF). In particular this paper examines the effect of fibre width to reduce track permanent vertical settlements.

2. Methods

The testing apparatus, shown in Figure 1a, represents a full size slice of a single line of track extended to the shoulders and including one sleeper. To mimic plane strain conditions, the vertical sides, 5 m long and 65 cm high, were designed to be rigid and are covered by a double layer of plastic sheet to reduce side wall friction. The 65 cm gap between the internal walls represents a typical sleeper spacing. Each test was carried out on a G44 mono-block concrete sleeper placed on top of a 30 cm ballast layer underlain by a 12 mm rubber mat. The latter mimics the subgrade and was designed to ensure realistic values of cyclic elastic deflection. The load is applied by a hydraulic actuator hanging vertically from a steel reaction frame. The vertical force is applied to two bits of rail connected to the sleeper through a steel beam placed on the top of them, as shown in Figure 1b. Further details of the test are available from Abadi (2014) and Abadi et al. (2015).

Figure 1. Test preparation (a) before placing loading beam and LVDTs and (b) ready for testing

The ballast fibre composite is a mixture of ballast and randomly oriented plastic fibres of different sizes. The sizes of the fibres are constant in any given test but vary between tests (Figure 2a). In all cases Polyethylene fibres of 0.5 mm thickness and 300 mm length were used and only their width varied (from 25 mm to 100 mm). In each test the volumetric fibre content, which will be defined in the next section, remained constant at 0.65%. The initial selection of fibre dimensions is based on triaxial monotonic tests previously carried out using a 1/3 parallel gradation of a railway ballast. These tests demonstrated the potential of the addition of fibres to increase ballast shear strength in monotonic testing (Ajayi et al., 2014). However these tests were limited to monotonic conditions and, as will be demonstrated, improved performance during cyclic loading is a compromise between having additional fibres that will increase the shear strength without increasing the propensity to settle. The ballast used is a crushed, uniformly graded, angular granite representative of the material typically used in the UK and in Western Europe. It is sourced from Cliffe Hill quarry (Leicestershire, UK). Key properties of the ballast are that the specific gravity (G_s) is 2.83 Mg/m^3, the average particle size (D_{50}) is 34 mm, the coefficient of uniformity (C_u=D_{60}/D_{10}) is 1.7 and the coefficient of gradation (C_g=$D_{30}^2/(D_{30}D_{60})$) is 1.1. The particular ballast tested was slightly finer than the standard specification but it was within the representative range of ballasts delivered to site and placed on track in the UK. In any case, fibre to particle dimensions are normalised in relation to D_{50}.

Common procedures for preparation were followed for each test: (1) the testing rig was manually filled with the appropriate ballast-fibre mixture up to the level of the sleeper soffit; (2) the ballast/fibre layer was compacted and levelled using a compactor plate; (3) sleeper, crib ballast, loading beam and

LVDTs (linear variable displacement transducers) were placed. Each test was started no longer than 24 hours after test preparation completion (to prevent significant creep from developing). A vertical cyclic compression force with a minimum of 5 kN and a maximum of 98 kN was then applied to 3 million cycles at 3Hz. This loading is representative of a 20 tonne axle, as in typical conditions about 50% of the load is transferred to the adjacent sleepers by the rails (prEN-13230-6:2014.). Further details of the test methods are described in Abadi (2014) and Abadi et al. (2015).

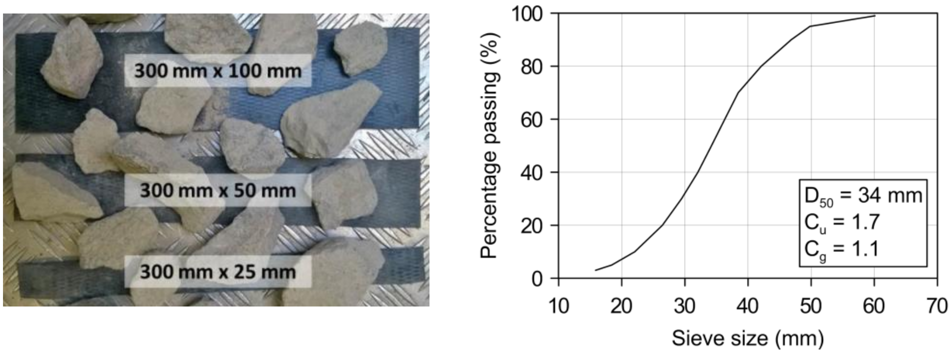

Figure 2. (a) Polyethylene fibres and (b) ballast particle size distribution

The sleeper vertical displacement was monitored by 8 LVDTs held by steel brackets clamped to the rigid sides of the apparatus, as shown in Figure 1b. The sensors were positioned at the sleeper ends, on the internal side of the rail seats and in the middle of the sleeper. Data were sampled at a frequency of 100 Hz. Results were expressed in terms of an average sleeper settlement, calculated using a weighted area method considering all 8 LVDT measurements.

3. Results

For comparison of tests the settlement data was re-zeroed after the first few cycles to remove initial bedding errors which varied between tests. Tests reported in this paper have been carried out to study the effect of fibre width (W_f) on track response for constant volumetric fibre content (V_{fr}) and fibre length (L_f). The volumetric fibre content is defined as the ratio of the volume of fibres (V_f) to the volume of ballast particles (V_p). The adopted fibre dimensions, fibre content and settlement at 3 million cycles (d_{3M}) are reported in Table 1. The fibres were chosen so that the length was held constant at 7.5 times D_{50} and the width was varied between 0.7 and 2.9 times D_{50}.

Table 1. Fibre characteristics and settlement at 3 million cycles

Test label	L_f (mm)	W_f (mm)	V_{fr} (%)	d_{3M} (mm)
T1 - Unreinforced	-	-	0.00	6.34
T1' - Unreinforced	-	-	0.00	6.42
T2 - 300x100 (0.65)	300	100	0.63	6.79
T2' - 300x100 (0.65)	300	100	0.64	6.78
T3 - 300x50 (0.65)	300	50	0.67	4.84
T4 - 300x25 (0.65)	300	25	0.69	4.85

Density box tests on fibre reinforced ballast were carried out (Figure 3). The density was measured by filling up a cubic box with internal edges of 300 mm. The loose sample was obtained by gently filling the box with the ballast-fibres mixture while the dense condition was achieved by vibrating the sample with a sieve shaker. These tests show that, while narrow fibres have a very small influence on ballast void ratio, wide fibres lead to an initially much looser particle configuration in relation to the unreinforced material.

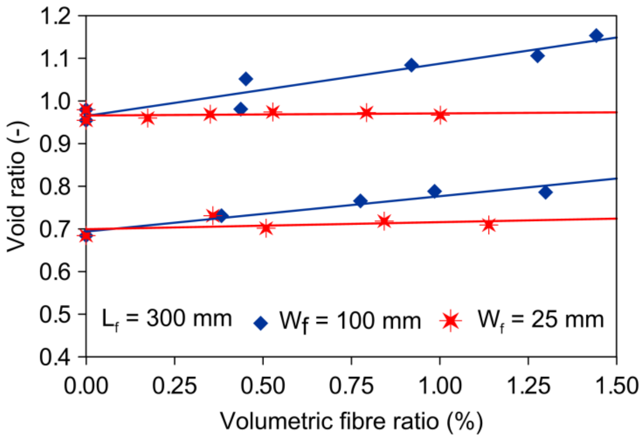

Figure 3. Effect of fibre addition on ballast maximum and minimum void ratio for wide and narrow fibres

The SRTF results are presented in Figure 4. The settlement vs cycles plots (Figure 4a) show that the addition of the narrower fibres reduced the settlement rate while the wider fibres actually show a slight increase in settlement. To better visualise the effect of fibres on ballast performance, the final normalised settlement is plotted against the fibre width (Figure 4b). The normalised settlement is defined as the ratio of the settlement to the settlement for the unreinforced case. Hence it equals 1 for the unreinforced case and is less or greater than 1 if the settlement is reduced or increased respectively. The settlement-width curves show that the addition of a 0.65% by volume of narrow fibres (W_f = 25–50 mm) reduced the settlement by about 25%. In contrast, wider fibres (W_f = 100 mm) increased the settlement by about 5%. This is believed to be related to the looser packing of particle associated with the addition of fibres (as illustrated in Figure 3).

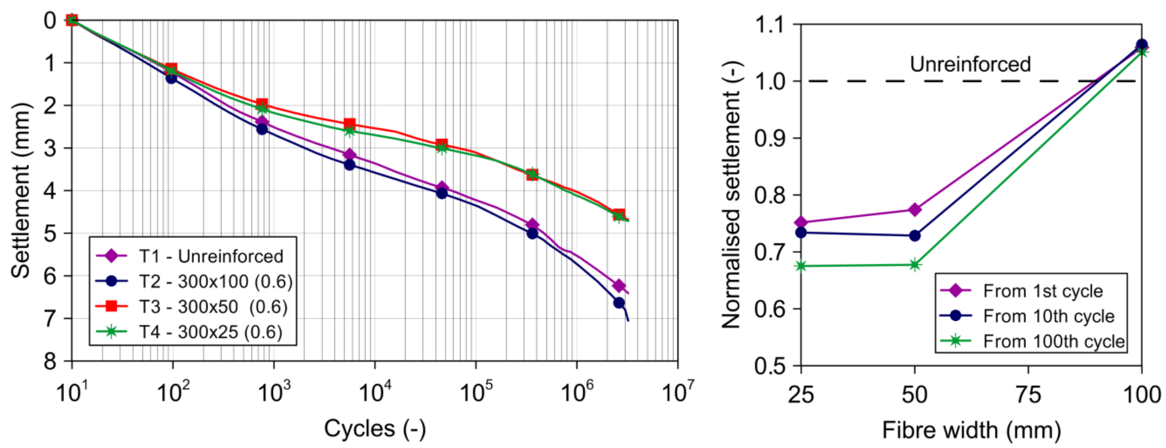

Figure 4. (a) Settlement from the 10th cycle and (b) settlement reduction at 3 million cycles

4. Conclusions

The performance of fibre reinforced ballast under vertical cyclic loading was investigated in the Southampton Railway Testing Facility through a series of full size tests. Experiments showed the potential for fibre reinforced ballast to reduce track permanent settlement. The main findings can be summarised as follows:

- Fibre reinforced ballast reduced ballast settlement by about 25% when narrow fibres were adopted (e.g. $W_f \leq 1.5\ D_{50}$); this is believed to be due to a small increase in the shear strength without significantly reducing the initial void ratio from the unreinforced case.
- Excessively wide fibres (e.g. $W_f = 2.9\ D_{50}$) are counterproductive; this is believed to be related to the inhibition of the packing of the particles, as shown by the density box tests.

In the light of the above, future tests will be aimed at investigating the effects of fibre length, content and material on ballast performance through both full size cyclic tests and density tests. This will identify the fibre properties required to optimise ballast performance, further understand the mechanics behind the improvements in performance and feed into in-field testing.

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