FIBRE REINFORCEMENT OF RAILWAY BALLAST

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Abstract

Ballasted railway track is still predominant and compatible with high-speed applications. However, ballast tends to settle differentially with repeated train passages and therefore costly maintenance operations, usually mechanical tamping, are carried out periodically to correct track level and ensure safe train operations. Maintenance needs can be reduced by inhibiting ballast tendency to settle under repeated loading. Recent laboratory research has shown that fibre-reinforcement with unbound randomly distributed strip fibres has the potential to reduce ballast settlement. This study builds on previous research and assesses the potential of a different type of fibre, obtained from polypropylene rope, to reduce ballast settlement.

1. Introduction

Ballasted railway track is the most traditional track form but still predominant and compatible with high-speed applications. A great disadvantage of ballasted track, compared with slab tracks, is its tendency to develop permanent differential settlement under repeated train loading. Such settlement can be mainly attributed to ballast and leads to the deterioration of track level, reducing track safety and ride quality. Track maintenance, usually by tamping, is carried out periodically to restore track level. However, tamping is costly and tends to damage the ballast grains, increasing the rate of deterioration of track geometry after each tamp (Selig and Waters, 1994; Sol-Sánchez et al., 2016).

Ballast bed interventions have been proposed to reduce track settlement, e.g. the use of more broadly graded ballast (Raymond and Diyaljee, 1979; Indraratna et al., 2011; Abadi et al., 2016) or geogrids (Bathurst and Raymond, 1987; Gobel et al., 1994; Raymond, 2002; Raymond and Ismail, 2003; Brown et al., 2007; Christie et al., 2009; Indraratna and Nimbalkar, 2013; Hussaini et al., 2015). More recently it was found that the addition of unbound strip plastic fibres to ballast can increase its peak strength, inhibit its post-peak strength loss and reduce its settlement under cyclic loading representative of train passages (Ajayi et al., 2014; Ferro et al., 2016; Ajayi et al., 2017b, 2017a).

This study further investigates the potential of fibre-reinforcement to reduce ballast settlement but uses a different fibre material, obtained from polypropylene rope. Box tests were carried out to assess the effect of the fibres on the natural packing of the grains and full-scale tests in the Southampton Railway Testing Facility to assess the settlement response of the fibre-ballast composite.

2. Materials

Fibre-reinforced ballast was obtained by mixing ballast and fibres randomly to obtain a uniform mixture. The ballast was sourced from Mountsorrel quarry (Leicestershire, UK) and is representative of the material placed on many UK and Western Europe railways. It consisted of uniformly-graded, freshly-crushed, granite aggregates with specific gravity G_s=2.66, average grain size D_{50}=41 mm, coefficient of uniformity C_u=1.4, maximum void ratio e_{max}=0.94 and minimum void ratio e_{min}=0.68. Its grain size distribution, shown in Fig. 1a, complies with UK standards (Cat. A of BS EN 13450:2002).
The fibres were obtained from general purpose polypropylene three-strand rope, with diameters d_f of 4 mm to 12 mm (Fig. 1b).
The fibre-ballast composite was characterised in terms of number of fibres per ballast grain N_{fg}, normalised fibre length L_N and normalised fibre diameter (or thickness) d_N:

$$N_{fg} = N_f / N_g \tag{1}$$

$$L_N = L_f / D_{50} \tag{2}$$

$$d_N = d_f / D_{50} \tag{3}$$

where N_f is the number of fibres and N_g is the number grains, the latter calculated by dividing the weight of the ballast grains by the average weight of a single grain (0.12 kg for Mountsorrel ballast). Characterising the fibre-ballast composite in terms of N_{fg} and normalised dimensions allows scaling the reinforcement across different sizes of aggregates (Ajayi et al., 2017b). For a given fibre length and diameter, N_{fg} is representative of the number of grains that can be potentially engaged by each fibre.

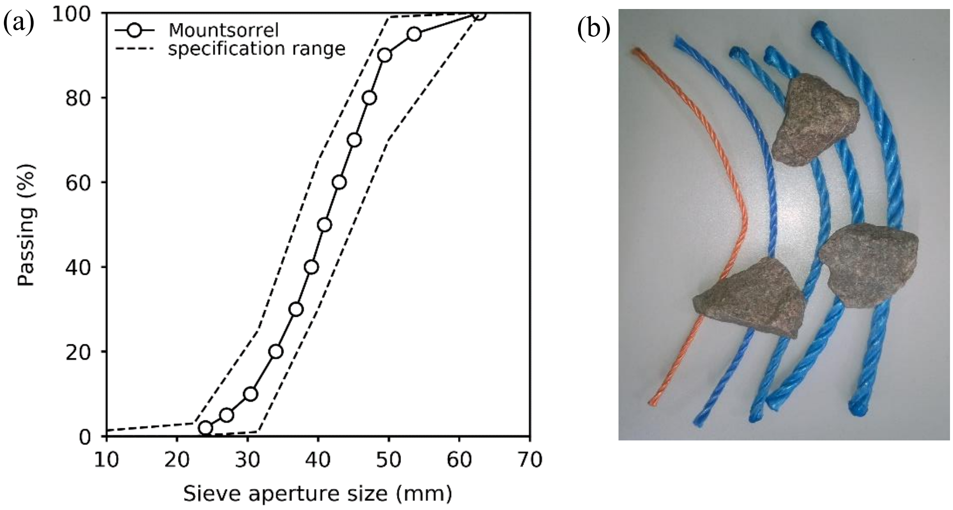

Fig. 1.(a) Grain size distribution and standard specification range; (b) photo ballast grains and polypropylene rope fibres with length of 300 mm and diameters of 4mm, 6mm, 8mm, 10mm, 12mm

3. Packing tests

The addition of fibres to granular materials tends to inhibit the packing of the grains (Casagrande, 2005; Santos et al., 2010; Lirer et al., 2012; Ajayi, 2014; Ferro et al., 2016). Excessive disruption of grain packing, for example due to the addition of strip fibres significantly wider than the average grain size,

may reflect in larger ballast settlement (Ferro et al., 2016).
Density box tests were carried out to assess the effect of the fibres on the packing of the ballast grains. In each test, a cubic box with internal edges of 300 mm was filled up with the desired proportions of ballast and fibres (Fig. 2). The void ratio e, which is representative of grain packing, was calculated as suggested in Ajayi et al. (2014):

$$e = V_v/V_g \tag{4}$$

where V_v and V_g are the volumes of the voids and grains respectively. Loose samples were prepared by gently filling the box (Fig. 2a); dense conditions by vibration using the base of a sieve shaker for coarse aggregates (Fig. 2b). The fibres used in the packing tests had length of 300 mm and diameters of 4 mm to 12 mm.

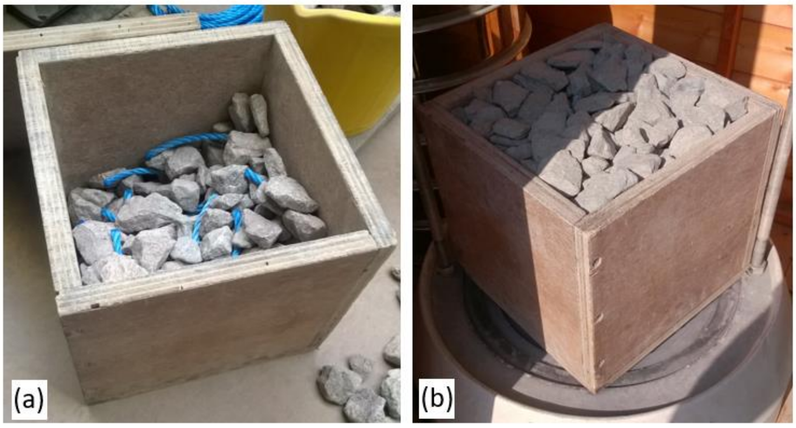

Fig. 2. Bulk density tests; preparation of a loose sample (a) and a dense one (b)

As an example, the effect of the fibres on the packing is shown in Fig. 3 for thin fibres with d_N = 0.15 (d_f = 6mm) and thick fibres with d_N = 0.29 (d_f = 12 mm). The void ratio increased approximately linearly with increasing fibre content, especially in loose conditions. The thicker fibres caused a greater increase in void ratio in loose conditions, while in dense conditions the effect of d_N was very small. In general, the effect of the diameter of the rope fibres was similar to that of the width for strip fibres, although the latter was more pronounced (Ferro et al., 2016).

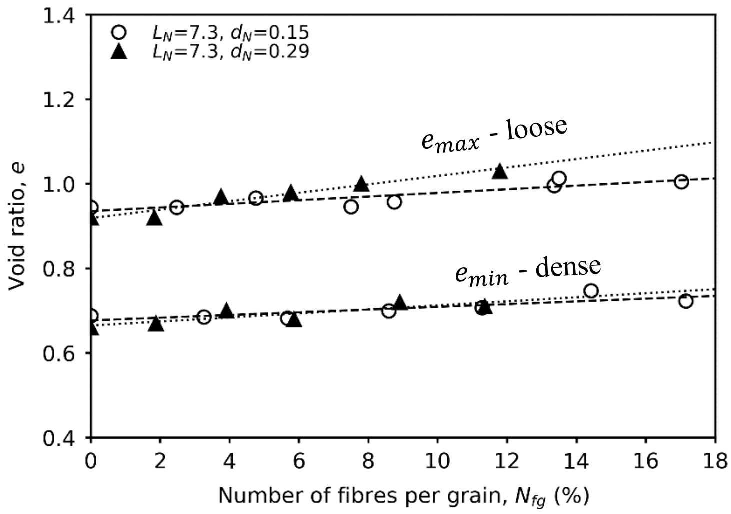

Fig. 3. Effect of fibre content and thickness on void ratio

4. Full-size tests

Full-size tests were conducted in the Southampton Railway Testing Facility (SRTF), a laboratory representation of a one-sleeper bay, widely used to investigate the effect of ballast and sleeper interventions on railway track performance (e.g. Abadi et al., 2016, 2019; Ferro et al., 2020). A schematic of test set-up is shown in Fig. 4. Each sample consisted of a 12 mm rubber mat to mimic the subgrade, a 30 cm layer of ballast, a G44 mono-block pretensioned concrete sleeper, crib ballast and two short rail sections installed on the sleeper. Vertical cyclic loading representative of a 20-tonne train axle was applied evenly to the rail sections at 3 Hz for 3 million cycles. The vertical displacements of the sleeper were measured by 8 LVDTs and sampled at 100 Hz. The sleeper settlement was computed by weighted area method considering all LVDTs. To improve test repeatability preparation protocols were followed strictly and the displacements were re-zeroed after the 10th load cycle to minimise the errors associated with initial bedding (Abadi et al., 2016; Ferro, 2019).

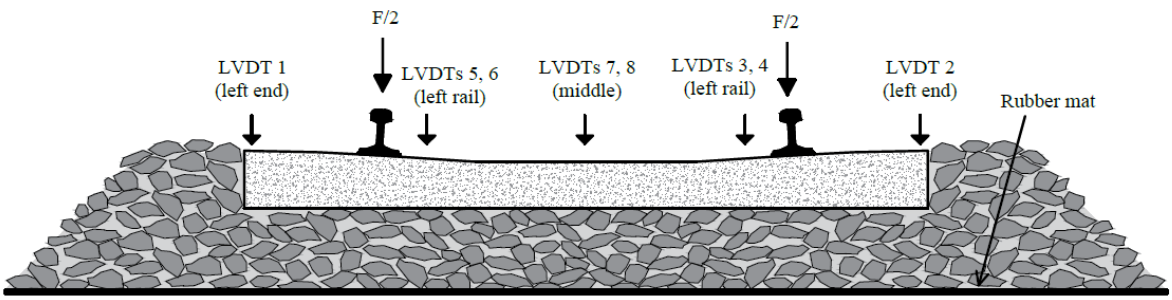

Fig. 4. Schematic of test set-up

The full-size tests showed that fibre-reinforcement with rope fibres, if properly designed in term of fibre content and diameter, can reduce ballast settlement by about 20% (Fig. 5). Such improvement was obtained by using 11 fibres per 100 grains (N_{fg} = 10.8%) with L_N = 7.3 (L_f = 300 mm), and d_N = 0.15 (d_f = 6 mm). The small thickness of the fibres minimised the disruption of grain packing. Moreover, compared with thicker fibres, it reduced drastically the total volume of reinforcement required. For a given N_{fg}, the volume of reinforcement is proportional to the square of the fibre diameter. The fibre content N_{fg} = 10.8% corresponded to approximately 60% of the maximum amount of fibre that, based on visual inspection, can be added to ballast without extensive fibre overlapping. The fibre length was arbitrarily limited to 300 mm, the thickness of the ballast bed, and should be sufficiently large to mobilise tension in the reinforcement (Ajayi et al., 2017b)

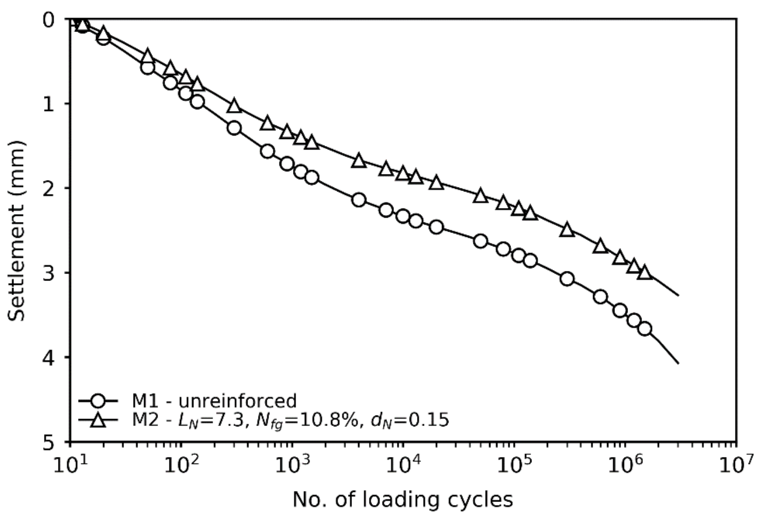

Fig. 5. Settlement response of unreinforced and reinforced ballast

5. Conclusions and final remarks

Full-size tests were carried out in the Southampton Railway Testing Facility to investigate the potential of fibre-reinforcement with rope fibres to reduce ballast settlement. It was found that the fibres, if properly designed in terms of dimensions and content, can reduce ballast settlement by ~20% in controlled laboratory conditions. A suitable fibre mix would be characterised by: small fibre diameter (d_n=0.15) to minimise the disruption of grain packing and the volume of reinforcement; fibre content of ~11 fibres per 100 grains, which is sufficiently small to avoid extensive contacts between the fibres; fibre length of 300 mm or L_N = 7.3, which should be sufficiently large to mobilise tension in the reinforcement. The settlement reduction offered by the rope fibres (~20%) is close to that offered by the strip fibres used in Ferro et al. (2016). However, the settlement of Mountsorrel ballast was particularly small and the effectiveness of fibre-reinforcement may increase with increasing ballast deformation, as observed for geogrids (Brown et al., 2007). The mechanics of fibre-reinforcement under cyclic loading remains unclear. As suggested by Ajayi et al., (2017a), fibres may restrict grain rotations and movements, and, at sufficiently large ballast deformation, mobilise tension that provides additional confinement. However, further research is required to fully comprehend the behaviour of fibre-reinforcement at the grain scale.

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