Fibre-reinforcement of railway ballast to reduce track settlement

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**Abstract**

Most of the world’s railways run on ballasted track. However, ballast accumulates differential settlement with trafficking, hence the correct track level must be restored periodically, typically by tamping which is costly. To reduce the cost of maintenance, several interventions have been proposed with the objective of increasing the interval between tamps by reducing the rate of differential settlement. These include broader ballast gradings, geogrids and under sleeper pads. A possible alternative is the addition of unbound random fibres to the ballast. Fibres formed from polymer materials, randomly mixed with sands and gravels, have been shown to increase their shear resistance owing to the additional effective confinement associated with the mobilisation of tension in the fibres. However, the effect of the fibres on the permanent strain accumulated under cyclic loading has not been extensively investigated. This paper presents the results of an experimental programme carried out to assess the performance of full-size ballast reinforced with different proportions of polyethylene strip fibres of different lengths and widths. It shows that the addition of a moderate amount (0.6-0.7% of the volume of solids) of narrow fibres has negligible influence on grain packing and can reduce ballast plastic settlement without affecting track resilient stiffness.

**Keywords** **chosen from ICE Publishing list**

Reinforced soils; gravels; repeated loading.

**List of notations**

$D\_{50}$ average grain size or sieve size corresponding to a 50% passing

$∆e\_{1\%}^{dense}$ increase in $e\_{min}$ with the addition of fibres in a content of $V\_{fr}=1\%$

$∆e\_{1\%}^{loose}$ increase in $e\_{max}$ with the addition of fibres in a content of $V\_{fr}=1\%$

$∆e\_{1\%}^{diff}$ difference between $∆e\_{1\%}^{loose}$ and $∆e\_{1\%}^{dense}$

$e\_{i}$ initial void ratio

$e\_{max}$ maximum void ratio (loose conditions)

$e\_{min}$ minimum void ratio (dense conditions)

$e\_{max}^{UR}$ maximum void ratio for the unreinforced material

$e\_{min}^{UR}$ minimum void ratio for the unreinforced material

$I\_{D}$ density index

$L\_{f}$ length of the fibres

$L\_{N}$ length of the fibres normalised to the average grain size

$V\_{fr}$ volumetric fibre ratio

$V\_{f}$ volume of fibres

$V\_{g}$ volume of grains

$V\_{s}$ volume of solids

$V\_{v}$ volume of voids

$W\_{f}$ width of the fibres

$W\_{N}$ width of the fibres normalised to the average grain size

# Introduction

Ballasted railway track has been used in a form recognisable today for over a century. The ballast supports the track vertically and laterally, and facilitates periodic correction or adjustment of the line and level. Alternatives to ballasted track, such as slab track, are increasingly used on high-speed lines, especially where the anticipated level of service is high. However, ballasted track is still the predominant form and is used on some high-speed lines.

Modern ballast consists of uniformly graded, coarse gravel sized grains of crushed, high-quality rock such as granite. It allows free drainage, provides vertical support and lateral restraint to the sleepers and attenuates the vertical stresses associated with train passage transmitted into the subgrade to sustainable magnitudes. The ballast also inhibits vegetation growth and dampens noise and vibration. Under the repeated loading typical of train passage, ballast gradually spreads and settles. Settlement is generally non-uniform, leading to a gradual deterioration of track quality. Maintenance, usually by tamping, is carried out periodically to restore the track geometry, allowing continued safe operation and maintaining an acceptable ride quality. However, tamping is costly and damages the ballast grains, such that the rate of plastic settlement increases after each tamp until the ballast requires renewal (Selig & Waters, 1994; Sol-Sánchez et al., 2016). On a busy conventional railway, granite ballast to a modern specification might be tamped every 2-3 years and renewed after about 30 years.

The mechanical response of railway ballast to cyclic loading has been investigated since at least the 1970s (Shenton, 1978; Guérin et al., 1999; Lackenby et al., 2007; Aursudkij et al., 2009; Sun et al., 2014; Aingaran, 2014; Abadi et al., 2018). Methods to reduce its propensity to settle have been proposed in response to the growing demand for rail transport in many parts of the world (International Union of Railways (UIC), 2015; Network Rail, 2018). These include the use of:

* more broadly graded ballast, which has a greater bulk density and is less susceptible to permanent deformation (Raymond & Diyaljee, 1979; Indraratna et al., 2011; Abadi et al., 2018)
* geogrids, which inhibit ballast spreading and hence settlement (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); and
* under sleeper pads (USPs), which lead to a more uniform distribution of the stresses over the ballast layer reducing the permanent strain (Sol-Sánchez et al., 2016; Abadi et al., 2019).

A relatively untried approach to improving railway ballast is reinforcement using random fibres. This involves randomly placing fibres into the ballast to improve its mechanical properties. In soils, flexible (natural or polymeric) as opposed to inextensible (e.g. steel) fibres are preferred, as they increase not only the shearing resistance of the composite material but also its ductility (Gray & Ohashi, 1983), through the inhibition of dilation and post-peak loss of strength (Michalowski & Čermák, 2003; Heineck et al., 2005; Santos et al., 2010; Diambra et al., 2013; Ajayi, 2014). A similar effect has been observed in coarser granular materials (Lirer et al., 2012; Ajayi et al., 2017a). The most common materials for flexible fibres in soils are polyethylene and polypropylene. A major practical benefit of fibre reinforcement over geogrids is its relative insensitivity to track maintenance operations (usually mechanical tamping): geogrids must be installed deeper than 200 mm – rather greater than their optimal placement depth of 50-100 mm – to avoid damage by tamping (Bathurst & Raymond, 1987).

The additional resistance to shear stress shown by fibre-reinforced samples is attributed to the mobilisation of tension in the fibres, which provides an additional effective confining stress to the grains. Laboratory tests in which fibre orientation was varied relative to the direction of maximum tensile strain have shown that fibre reinforced soils behave anisotropically, as only fibres subjected to tension are effective (Gray & Ohashi, 1983; Michalowski & Čermák, 2002; Diambra et al., 2010; Mandolini et al., 2019). Analytical anisotropic models that account for the tension in the fibres and their orientation have provided realistic predictions of the shear strength of fibre reinforced granular soils and captured the key characteristics of the stress-strain behaviour (Diambra et al., 2010; Diambra et al., 2013; Gao & Zhao, 2013; Gao & Diambra, 2021). Conventionally, fibre-reinforced soils and their equivalent unreinforced counterparts have been characterised by different strength envelopes to account pragmatically for the effect of the tension in the fibres (Maher & Gray, 1990; Santos et al., 2010; Lirer et al., 2011). Ajayi et al., (2017a) developed a more rigorous approach in which the additional effective confining stress arising from the fibre tension was estimated and applied to the granular matrix of a fibre-reinforced gravel, whose behaviour was then shown to be consistent with the critical state framework for the unreinforced material.

In granular materials reinforced with filamentous fibres, the strengthening contribution provided by the fibres depends on their content, length and aspect ratio (the ratio between the length and diameter). The shear strength tends to increase linearly with increasing fibre volumetric content (Gray & Ohashi, 1983; Maher & Gray, 1990; Santoni et al., 2001; Michalowski & Čermák, 2003; Diambra et al., 2013; Shao et al., 2014; Ajayi et al., 2017b) until an upper-limit fibre content, beyond which no further benefit is provided by the reinforcement (Maher & Gray, 1990; Santoni et al., 2001). At a fixed fibre content and length, the shear strength has been found to increase linearly with increasing aspect ratio (decreasing fibre thickness), owing to the greater numbers of (thinner) fibres present in the composite (Maher & Gray, 1990; Michalowski & Čermák, 2003; Sadek et al., 2010; Ajayi et al., 2017b). Simple analytical models can be used to highlight the influence of the fibre content and aspect ratio on the shear strength (e.g. Zornberg, 2002). At constant fibre aspect ratio and content, the shear strength also increases with increasing length of the inclusions (Michalowski & Čermák, 2003; Sadek et al., 2010). This might be explained by a scale effect dependent on the relative size between the fibres and the grains (Michalowski & Čermák, 2003).

The ability of fibres to provide additional confining stress to a granular material suggests that they have the potential to reduce ballast settlement under cyclic loading, which reduces with increasing confinement (Suiker et al., 2005; Lackenby et al., 2007; Thakur et al., 2013). However, triaxial tests suggest that fibres do not increase the shearing resistance at vertical strains lower than 1-5%, but may actually reduce it (Michalowski & Čermák, 2003; Heineck et al., 2005; Santos et al., 2010; Diambra et al., 2013; Ajayi et al., 2017b). Similarly, plate loading tests carried out by Consoli et al. (2009) showed that the settlement response of reinforced sands diverged from that of unreinforced sands only after a displacement inversely proportional to the initial relative density. Hence the ability of fibre reinforcement to provide additional confinement may not be reflected in improved mechanical characteristics of railway ballast, as the fibres only become effective after a small but potentially significant initial strain.

The reduced mobilised shearing resistance (compared with the unreinforced material) of fibre reinforced granular soils at low strains may be explained by the fibres disrupting the packing of the grains. Minimum ($e\_{min}$) and maximum ($e\_{max}$) void ratios increase with the addition of fibres (Santos et al., 2010), with emax increasing generally more than emin. For example, Lirer et al. (2012) found that the addition of 0.6% fibres by volume to sandy gravel increased $e\_{min}$ from 0.19 to 0.23 and $e\_{max}$ from 0.60 to 0.85. Ajayi et al. (2014) showed that the maximum and minimum void ratios in sand and gravel increase approximately linearly with the fibre content.

In the railway context, the response of ballast to millions of repeated load cycles is important. The limited (triaxial) cyclic testing of fibre reinforced granular soils that has been carried out (Lirer et al., 2012; Sadeghi & Beigi, 2014; Gunaratne, 2018) suggests that fibre reinforcement does not reduce the resilient modulus; however, its effect on cumulative permanent strain is unclear.

To obtain an understanding of the potential of fibre reinforcement to improve the mechanical behaviour of railway ballast, an experimental study was carried out on a full-size single sleeper bay in the Southampton Railway Testing Facility (SRTF), using full-scale ballast reinforced with thin polyethylene strip fibres of varying dimensions and volume fraction. Bulk density tests were also carried out to understand the effect of the dimensions of the fibres on grain packing.

# Materials and methods

## Materials

Freshly-crushed granite ballast was obtained from Cliffe Hill quarry (Leicestershire, UK), representative of that used on UK railways. Grain properties are given in Figure 1, which shows that the ballast was slightly finer than the UK standard specification (cat. A of BS EN 13450, 2002). This is not uncommon for ballast in small batches up to 20 tonnes; segregation can occur during bulk handling and transit, and the grain distribution can vary depending on which part of the heap the material is taken from at the quarry.

The fibres were made from 0.5 mm thick reprocessed polyethylene damp proof course having a mass per unit area of 435 g/m2 (Figure 2). The fibre material was the same as that used in triaxial tests on fibre reinforced scaled ballast (Ajayi et al., 2017b), with the length and width of the fibres increased in proportion to the larger grain size used in the full-scale tests.

In this study, the fibre content is expressed in terms of volumetric fibre ratio $V\_{fr}=V\_{f}/V\_{g} $, where $V\_{f}$ is the volume of fibre and $V\_{g}$ the volume of the grains. It varied between 0.6%-1.2% (equivalent to 0.19%-0.37% by weight, i.e. the ratio of the weight of fibres to the weight of ballast grains), where the upper value of fibre content was selected to avoid extensive fibre overlapping. The thickness of the fibres was always 0.5 mm, with the same fibre material being used in all tests. The length ($L\_{f}$) and width ($W\_{f}$) of the fibres varied between 75-300 mm and 25-100 mm respectively. They will be expressed in normalised terms as $L\_{N}=L\_{f}/D\_{50}$ (length) and $W\_{N}=L\_{N}/D\_{50}$ (width), where $D\_{50}$ is the average grain size (Ajayi et al., 2017b). The length was limited to $L\_{f}$ = 300 mm (so for $D\_{50} $= 34 mm $L\_{N}=8.8$), the depth of the ballast layer. Based on earlier monotonic triaxial tests, a fibre length of $L\_{N}\geq 3.6$ should be sufficient to mobilise tension in the reinforcement (Ajayi et al., 2017b).

## Packing tests

Tests were carried out to assess the effect of different volume fractions ($V\_{fr}$) of fibres of varying dimensions on the packing of the grains expressed as the void ratio, defined as the ratio of the volume of voids ($V\_{v}$) to the volume of grains ($V\_{g}$) ($e=V\_{v}/V\_{g}$). In fibre reinforced soils, the volume of fibre ($V\_{f}$) can be considered as part of the solids ($V\_{s}=V\_{g}+V\_{f}$) or simply neglected ($V\_{s}=V\_{g}$). However, whether $V\_{s}=V\_{g}$ or $V\_{s}=V\_{g}+V\_{f}$ makes little difference if the volume of fibre is small compared with that of the grains ($V\_{fr}≲5\%$).

In each test, a cubic box with internal edges of 300 mm was filled manually with ballast/fibre mixtures and weighed. Loose conditions ($e\_{max}$) were obtained by placing the ballast gently into the box. Dense conditions ($e\_{min}$) were obtained by placing the ballast in three layers and vibrating each new layer for 2 minutes using a heavy-duty electric sieve shaker for coarse aggregates, with frequency of 50 Hz and amplitude of approximately 3.4 mm (Figure 3). The box was slightly overfilled and the final top surface levelled by adding and removing individual ballast grains manually. For the compacted (dense) specimens, levelling was aided by hand-pressing the lid against the ballast while vibrating to obtain a more uniform distribution of grain/lid contacts. Once the specimen had been compacted and levelled, the lid was placed on top of it and the actual height (300 mm + the gap between the lid and the box) measured. The compaction procedure is consistent with the procedures developed and used in previous studies to obtain the maximum achievable density without grain breakage (Ajayi et al., 2014; Ajayi et al., 2017, a; Abadi et al., 2018; Gunaratne, 2018). The maximum length of the fibres was the same as the specimen dimension (300 mm), which was limited by the size of the sieve shaker used for specimen preparation. Usually, larger ratios of the specimen dimension to the fibre length are used in laboratory testing of fibre reinforced soils to avoid boundary effects. However, in the full-scale tests as well as in the field, the minimum dimension of the ballast layer (its thickness) was the same as the dimension of the testing box (300 mm), hence representative of the full-scale problem. Moreover, the fibres affect the void ratio only in close proximity (Soriano et al., 2017), which further justifies the use of a fibre length to specimen dimension ratio close to one. For these reasons, the size of the specimens was considered adequate for assessing the effect of the fibres on the packing of ballast grains.

## Full-scale tests

The Southampton Railway Testing Facility or SRTF (Le Pen, 2008; Abadi, 2014) reproduces a full-scale single-sleeper section of a single-line ballasted track, including ballast shoulders, bounded in the cross-sectional plane of the track by rigid sidewalls (Figure 4). Tests were prepared as described in Abadi et al. (2016), with a distance between the rigid sidewalls of 650 mm ( corresponding to the sleeper spacing), a ballast thickness of approximately 300 mm, shoulder slopes of 45° (close to the natural angle of repose), and a G44 prestressed concrete sleeper of length 2.5 m and width 285 mm. These are all representative of typical UK practice. A 12 mm thick neoprene rubber mat was placed under the ballast to represent subgrade resilience: plastic settlement of the subgrade was not modelled. The dimensions of the test facility are the same as, and governed by, those of a real track. Any effects arising from the maximum fibre length being similar to the ballast depth would also be present in the field, while the inability of fibres to cross the plane strain boundaries in the laboratory rig similarly reflects the inability of one section to support the next during train loading along a length of real track.

To ensure repeatability, a four-day procedure was followed for the preparation of each test. Over the first two days, the rubber mat was laid on the strong floor and the rig filled to the level of the sleeper base. The ballast and fibres were then placed manually in the testing rig using buckets. Each bucket was filled with the desired proportions (by weight) of fibre and ballast grains and placed gently into the testing rig. On the third day the ballast was carefully compacted and levelled using 22 passes of an electric compactor, and the sleeper placed on top of it. On the same day, further ballast (~450 kg) was placed to reach the level of the upper surface of the sleeper. Then a steel loading beam was placed on top of the rails to distribute the load evenly between the rails. After 24 hours, on the fourth day, loading was applied to the loading beam (shown in Figure 5a) by a hydraulic actuator hanging vertically from a large reaction frame.

The procedure followed to mix, place and compact the fibre reinforced mixture led to a uniform distribution of the reinforcement with generally horizontal orientation of the fibres, as has previously been observed for fibre reinforced sands (Michalowski & Čermák, 2002; Diambra et al., 2007; Soriano et al., 2017). Under vertical loading, the horizontal orientation of the fibres is beneficial for mobilising tension (Gray & Ohashi, 1983; Michalowski & Čermák, 2002), and therefore likely to be advantageous in terms of increasing ballast confinement and reducing settlement under cyclic loading.

Loading comprised an initial slow cycle followed by 3 million sinusoidal loading cycles at 3 Hz. The minimum and maximum compressive forces were 5 kN and 98 kN respectively, representative of a 20-tonne axle load with 50% transfer away from a central sleeper. These tests are essentially accelerated static tests, as the loading frequency is too slow to elicit a dynamic material response and the impact loads likely to occur on real railways were not reproduced.

Sleeper vertical deflections were measured by 8 LVDTs positioned at the sleeper ends, the rail seats and at the middle of the sleeper. The longitudinal pressure in the ballast was measured using 4 pressure plates, each comprising a 250 mm × 300 mm steel plate supported on 4 load cells (Abadi et al., 2018). Pressure sensitive paper was placed between the ballast and the sleeper soffit to measure the area of the sleeper/ballast contacts exerting a pressure higher than 10 MPa (Abadi et al., 2015). Measurements from LVDTs and load cells were acquired at a frequency of 100 Hz. The pressure sensitive paper was placed before starting the tests and removed during dismantling, and provided a measurement of the cumulative area of contact over a test. The arrangement of the LVDTs, pressure plates and pressure sensitive paper is shown in Figure 5.

The length, width and volume fraction of the fibres used in the tests, the average initial void ratio before placing the sleeper ($e\_{i}$), and the maximum and minimum void ratios for each fibre mix are listed in Table 1. In tests C1 and its repeat C1r, no fibres were added to the ballast. In tests C2 and C3, fibres were placed only below the level of the sleeper soffit (that is, not in the upper 200 mm of ballast) and the fibre content is expressed relative only to the 300 mm of ballast below the sleeper soffit. In tests C3r to C9 the reinforcement was uniformly distributed throughout the whole of the ballast, as would probably occur in a field installation (Watson et al., 2021). However, under vertical loading the fibres above the level of the sleeper soffit remain unstressed and would not, therefore, be expected to affect the track response. This is confirmed by the results from tests C3 and C3r, which used the same fibre mix below the sleeper and gave the same results, although in test C3 no fibres were present above the level of the sleeper soffit. The similarity between the results from tests C1 and C1r with no fibres present, and between tests C3 and C3r with fibres, shows that the repeatability in terms of average sleeper settlement after 3 million loading cycles was better than 0.2 mm, provided that displacements are re-zeroed after at least one load cycle to eliminate the effects of initial bedding.

# Results

## Grain packing

The packing tests were carried out on specimens containing fibres of different lengths ($L\_{N}$ = 2.2, 4.4, 8.8) and widths ($W\_{N}$ = 0.7, 1.5, 2.9) but constant thickness. For each combination of length and width, packing tests were carried out to determine both the loosest ($e\_{max}$) and densest ($e\_{min}$) conditions. Tests were performed on different specimens containing a gradually increasing number of fibres until visual inspection indicated that further fibres could not be added without significant overlapping between them. The volumetric fibre contents used in the test were then calculated a posteriori, based on the weight/volume of the specimen and the total number of fibres. For the materials tested, the upper limit for the fibre content was $V\_{fr,max}$ ≅ 1.2% but fibres of different shape or soils of different grain size distributions may give different values of $V\_{fr,max}$.

The tests indicated that $e\_{min}$ and $e\_{max}$ increase approximately linearly with $V\_{fr}$, especially in the loosest condition ($e\_{max}$), as shown in Figure 6a for $L\_{N}$ = 8.8 and $W\_{N}$ = 0.7 and 2.9 and in Figure 6b for $W\_{N}$ = 0.7 and $L\_{N}$ = 4.4 and 8.8. This is consistent with previous studies using smaller aggregates (Ajayi, 2014; Ajayi et al., 2017b).

The disruption of the packing caused by the fibres is represented by the gradient of the lines fitting the experimental data in the $e$ vs $V\_{fr}$ plane (the dashed lines in Figure 6). This gradient corresponds to the increase in minimum or maximum void ratio caused by the addition of a fibre content of $V\_{fr}$ = 1% and is termed $∆e\_{1\%}^{loose}$ for loose conditions ($e=e\_{max}$) and $∆e\_{1\%}^{dense}$ for dense conditions ($e=e\_{min}$). An increase in the potential for the ballast to become denser under compaction is given by $∆e\_{1\%}^{diff}=∆e\_{1\%}^{loose}-∆e\_{1\%}^{dense}$.

The effects of $L\_{N}$ and $W\_{N}$ on $∆e\_{1\%}^{loose}$, $∆e\_{1\%}^{dense}$ and $∆e\_{1\%}^{diff}$ are shown in the contour plots of Figure 7. In loose conditions (Figure 7a) the void ratio increased significantly with $W\_{N}$ while the effect of $L\_{N}$ was relatively small. The disruption was not significant ($∆e\_{1\%}^{loose}\leq $ 0.02, in comparison with an estimated experimental error in determining $∆e\_{1\%}^{loose}$ and $∆e\_{1\%}^{dense}$ of 0.005 to 0.01) for the narrowest fibres ($W\_{N}=$ 0.7) but evident ($∆e\_{1\%}^{loose}=$ 0.08 to 0.12) for wide fibres ($W\_{N}=$ 2.2-2.9). The greater disruption of grain packing caused by the wide fibres may be explained by their 2D nature compared with the narrow fibres, which can be regarded as 1D. The transition between 1D and 2D behaviour seems to occur for $W\_{N}$ between 1.5 and 2.2, the region of Figure 7a where the contour lines are closest.

In dense conditions (Figure 7b) the disruption of grain packing was generally less pronounced ($∆e\_{1\%}^{dense}<$ 0.08) and the effect of $L\_{N}$ was predominant for $W\_{N}\geq $1.5. The increase in void ratio was negligible ($∆e\_{1\%}^{dense}$ $\leq $ 0.02) for $W\_{N}\leq $ 0.7 or $L\_{N}\leq $ 4.4, suggesting that these smaller fibres can be accommodated in the voids during compaction, reducing their effect on grain packing.

The potential of the ballast to be compacted, expressed by $∆e\_{1\%}^{diff}$, was strongly affected by $W\_{N}$, while $L\_{N}$ had very little influence (Figure 7c). The effect on $∆e\_{1\%}^{diff}$ was small for $W\_{N}\leq 1.5$, increased rapidly between $W\_{N}$ = 1.5 and 2.2, and was approximately constant for $W\_{N}\geq 2.2$.

Overall, the packing tests showed that fibres inhibit the packing of the grains, especially in the loosest condition, and increase the potential for plastic volumetric strain under compactive loading. However, the disruption to packing associated with the narrowest fibre tested ($W\_{N}$ = 0.7) was always small, regardless of the length. Thus it seems advantageous to use narrow, long fibres with the potential to reinforce the granular matrix without disturbing the natural arrangement of the grains.

## Settlement

The sleeper settlement is reported as the average sleeper displacement at the minimum load (~5 kN), re-zeroed after the first (slow) load cycle to eliminate the effects of initial bedding.

Results are shown in Figure 8 to Figure 10 for the variations in $W\_{N}$, $V\_{fr} $and $L\_{N}$ respectively. Parts (a) show the plastic settlement against the number of loading cycles (to a logarithmic scale), and parts (b) the plastic settlement at 3 million cycles (normalised to the baseline) against fibre width/length/content. Parts (b) also show the results with the settlement re-zeroed after 10 loading cycles to show that the results are not significantly affected by the number of cycles after which the settlement datum is set. As settlement results were very close, only the average curves are reported for the repeated tests (C1, C1r and C3, C3r).

In all tests the settlement increased with the logarithm of the number of cycles, consistent with previous observations (e.g. Bathurst & Raymond, 1987; Guérin et al., 1999; Raymond & Ismail, 2003; Brown et al., 2007; Lackenby et al., 2007; Aursudkij et al., 2009; Leshchinsky & Ling, 2013; Sun et al., 2014; Thakur et al., 2013; Aingaran, 2014; Abadi et al., 2016; Sol-Sánchez et al., 2016).

The variable with the greatest effect on settlement was $W\_{N}$ (Figure 8). A significant reduction in settlement (about 20%) was achieved by adding relatively narrow fibres, with $W\_{N}\leq 1.5$. In contrast, wider fibres with $W\_{N}=2.9$ increased the settlement. This may be explained by the wider fibres inhibiting the packing of the grains at initial placement and increasing the potential for the ballast to undergo plastic volumetric strain under compactive loading.

The influence of the volumetric fibre content on settlement is shown in Figure 9. For both wide ($W\_{N}=2.9$) and narrow ($W\_{N}=0.7$) fibres, the settlement after a given number of cycles is smaller for a moderate fibre content ($V\_{fr}=$ 0.6% - 0.7%) than for a higher fibre content ($V\_{fr}=$ 1.1% - 1.2%).

The length of the fibres had a more modest effect on the settlement response (Figure 10), with the settlement being only slightly (~4%) less for the longest fibres tested ($L\_{N}=8.8$) than the shortest ones ($L\_{N}=2.2$). This suggests that even the shortest fibres were sufficiently long to mobilise tension and contribute a confining stress.

Consistent with earlier findings (e.g. Consoli et al., 2009), the early evolution of settlement for the better performing fibre reinforced samples only deviated/improved relative to the case with no fibres after a threshold settlement was exceeded (e.g. see tests C5, C7, C8 in Figure 10 compared with the baseline C1).

To assess the influence of relative density of the fibre-reinforced ballasts on the long-term settlement, Figure 11 plots the settlement after 3 million cycles against two measures of potential densification. In Figure 11a the density is related to the unreinforced maximum and minimum void ratios through the density index, $I\_{D}={\left(e\_{max}^{UR}-e\_{i}\right)}/{\left(e\_{max}^{UR}-e\_{min}^{UR}\right)}$. In Figure 11b an alternative measure of the propensity to pack of the fibre reinforced material is taken as the range of reinforced void ratios divided by the range of unreinforced void ratios, $\left(e\_{max}-e\_{min}\right)/\left(e\_{max}^{UR}-e\_{min}^{UR}\right)$. The latter measure can be more reliably calculated compared with $I\_{D}$ owing to the difficulty in measuring the as-placed volume of material in the tests. Figure 9 shows that the wider fibre mixes with larger final settlements were characterised by smaller initial relative densities and greater ranges of possible void ratio compared with the unreinforced material. Figure 9 also confirms that the narrower fibres were associated with smaller settlements than, and a similar packing density range to, the unreinforced material.

## Resilient displacements

The resilient displacement was calculated as the difference between the maximum and minimum displacements recorded by the LVDTs on an unload cycle. In the laboratory, the resilient displacement is the sum of the displacement of the ballast, the rubber mat, and, close to the sleeper ends, the size of the gap between the sleeper and the ballast. In the central part of the sleeper the resilient displacements tend to reduce with increasing numbers of loading cycles due to ballast densification. At the sleeper ends, where ballast can spread laterally, the resilient deflections tend to increase, leading to the formation of a small gap below the sleeper soffit.

The change in resilient displacement at the middle and at the ends of the sleeper with increasing settlement is shown in Figure 12, where the lines between the markers indicating the 10th and the 3 millionth cycle are the actual data. In this Figure, the shaded region indicates the range associated with the two baseline tests (unreinforced ballast), the dashed lines indicate the tests using wide fibres ($W\_{N}$=2.9), and the solid lines those using narrow fibres ($W\_{N}\leq $ 1.5). In the central part of the sleeper, ballast reinforced with wide fibres exhibited larger resilient displacements than the unreinforced ballast at any given settlement (Figure 12a). In contrast, the displacements shown by the specimens reinforced with narrow fibres were initially larger but, as the ballast densified, tended to the same displacement as the unreinforced ballast (~0.2 mm). The fibre-reinforced ballast was initially less stiff than the unreinforced ballast but, with increasing settlement and ballast densification, its stiffness became increasingly close to that of the unreinforced material. With narrow fibres, the stiffness tended to that of the unreinforced ballast relatively quickly, after 104 loading cycles. With wide fibres, this condition was not achieved within the range of settlements developed in the laboratory tests.

The change in sleeper-end resilient displacement with increasing settlement was similar in all tests (Figure 12b). The resilient displacements remained approximately constant for settlements up to ~5 mm, beyond which they increased approximately linearly with increasing settlement indicating the formation of gaps beneath the sleeper ends. As a result, the final sleeper-end resilient displacements tended to be larger for the tests exhibiting larger final settlements (those with wide fibres) and smaller for those showing smaller final settlements (those with narrow fibres).

## Locked-in longitudinal stress

The longitudinal stress in the ballast was measured by the pressure plates and is here expressed in terms of the locked-in stress, i.e. the stress at the minimum load of each cycle. These results are presented as a function of the settlement in Figure 13, where the shaded region indicates the range associated with the two baseline tests (unreinforced ballast), the dashed lines indicate the tests using wide fibres ($W\_{N}$=2.9), and the solid lines those using narrow fibres ($W\_{N}\leq $ 1.5). The longitudinal stress below the central part of the sleeper, shown in Figure 13a, was calculated from the readings at plates 1 and 2. The stress in the ballast close to the sleeper ends, shown in Figure 13b, was calculated from the readings at plate 4.

At the middle of the sleeper (Figure 13a), the stress tended to increase with increasing settlement, consistent with ballast densification. Moreover, the tests with fibres showed smaller stresses; this may be explained by the fibres providing tensile reinforcement that inhibits the horizontal movements of the ballast grains. However, to be effective in reducing settlement, the reinforcement must not only mobilise tension but should also not disrupt the packing of the ballast grains.

Close to the sleeper ends, the stress remained approximately constant for settlements lower than 3-4 mm, above which the stresses reduced approximately linearly with increasing settlement as gapping developed between the sleeper ends and the ballast, reducing the proportion of load transferred. At this location, the locked-in stress at the sleeper ends was slightly smaller for the tests with fibres. However, this reduction was much lower than that at the middle of the sleeper, probably because of the reduced contact between the sleeper end and the ballast.

## Sleeper-ballast contact

In all tests except for the baseline, pressure paper sheets were attached to the sleeper soffit at the middle of the sleeper and below both rails to assess the cumulative sleeper/ballast contact area (red patches in Figure 14) as a percentage of the total area of the sheet.

Quantitative results are summarised in Table 2, which reports for each test the contact area beneath the middle of the sleeper, the average contact area under the rails, and$ $the differential contact area between the middle of the sleeper and below the rail. The range of variation of the contact area was 0.7%-1.3% below the rails and 0.2%-0.7% below the middle. The cumulative contact area was always greater under the rails, i.e. the differential contact area was always positive. This is explained by the proximity to the point of load application, the greater range of movements compared with the sleeper middle and hence the greater propensity of the grains to rearrange, resulting in a greater cumulative record of all the ballast contacts developed during the test. Figure 15 illustrates the approximately linear relationships between settlement or resilient displacement and the cumulative contact areas beneath the railseats.

# Conclusions

An experimental programme was carried out to assess the performance of railway ballast reinforced with random unbound polyethylene strip fibres. The programme comprised full-scale cyclic laboratory tests on a single sleeper bay section of railway track under conditions of plane strain. Packing tests were also conducted, to obtain insights into the effect of fibre dimensions on grain packing.

Under controlled laboratory conditions and for the specific materials tested, the full-scale tests showed that fibre-reinforcement with a moderate content of narrow fibres has the potential to improve the performance of railway ballast by reducing the accumulation of plastic settlement by ~20%, with little or no adverse effect on the resilient stiffness. Hence fibre-reinforced ballast could require less maintenance than unreinforced ballast, while still meeting trackbed resilient stiffness requirements. However, fibre reinforcement should be carefully designed in terms of fibre content and dimensions, using bulk density tests to select fibres that do not increase the void ratio. This is essential because the key performance parameter of ballast permanent settlement may be adversely affected by fibres that disrupt the packing of the ballast grains, hence increase the propensity to accumulate plastic strain.

The quantitative effects of the fibre content and dimensions on the performance of fibre reinforced ballast can be summarised as follows.

* The optimal fibre mix, which reduced the settlement by ~20%, consisted of narrow fibres with normalised width $W\_{N}\leq 1.5$ and normalised length $L\_{N}=8.8$, at a volumetric fibre content of $V\_{fr}=0.6\%- 0.7\%$.
* The fibre dimension with the greatest influence on performance was the width. Wide fibres with $W\_{N}=2.9$ led to a looser packing of the ballast grains, a greater susceptibility than the unreinforced material to permanent volumetric strain and settlement, and a reduced resilient stiffness. In contrast, narrow fibres with $W\_{N}\leq 1.5$ had very little effect on grain packing, reduced the plastic settlement and had little effect on the resilient stiffness beyond the initial loading cycles.
* The length of the fibres had little effect; the longest fibres tested (with $L\_{N}$=8.8) showed only 4% less settlement than the shortest ones (with $L\_{N}$=2.2). However, the effect of shorter or longer fibres should not be extrapolated; for example, very short inclusions may fall loosely within the voids and provide no significant contribution.
* Packing tests are strongly recommended to inform effective fibre mix design. This study has shown that the effectiveness of fibres in reducing the settlement under cyclic loading does not depend solely on their ability to increase the mobilised shear strength but also on their not interfering significantly with the ability of the grains to pack, i.e. ${\left(e\_{max}-e\_{min}\right)}/{\left(e\_{max}^{UR}-e\_{min}^{UR}\right)}<1.05$.

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**Research data**

The data presented in this paper are openly available on the University of Southampton online repository at https://doi.org/XX.XXXX/XXXXX/XXXXX.

**References**

Abadi, T. (2014) *Effect of Sleeper and Ballast Interventions on Rail Track Performance*. PhD thesis. Faculty of Engineering and the Environment, University of Southampton, UK.

Abadi, T. et al. (2019) Effect of Sleeper Interventions on Railway Track Performance. *Journal of Geotechnical and Geoenvironmental Engineering*, 145(4), p.04019009. http://ascelibrary.org/doi/10.1061/%28ASCE%29GT.1943-5606.0002022.

Abadi, T. et al. (2018) Improving the performance of railway tracks through ballast interventions. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, 232(2), pp.337–355. http://pif.sagepub.com/lookup/doi/10.1177/0954409716671545.

Abadi, T. et al. (2015) Measuring the Area and Number of Ballast Particle Contacts at Sleeper-Ballast and Ballast-Subgrade Interfaces. *International Journal of Railway Technology*, 4(2), pp.45–72. http://www.ctresources.info/ijrt/paper.html?id=82.

Aingaran, S. (2014) *Experimental investigation of static and cyclic behaviour of scaled railway ballast and the effect of stress reversal*. PhD thesis. Faculty of Engineering and the Environment, University of Southampton, UK.

Ajayi, O. et al. (2017a) A behavioural framework for fibre-reinforced gravel. *Géotechnique*, 67(1), pp.56–68. http://www.icevirtuallibrary.com/doi/10.1680/jgeot.16.P.023.

Ajayi, O. et al. (2014) Effects of Random Fibre Reinforcement on the Density of Granular Materials. In *International Symposium on Geomechanics from Micro and Macro*. Cambridge, UK, 01 - 03 Sep 2014: CRC Press; Balkema, pp. 1363–1367.

Ajayi, O. et al. (2017b) Scaling relationships for strip fibre-reinforced aggregates. *Canadian Geotechnical Journal*, 54(5), pp.710–719. https://doi.org/10.1139/cgj-2016-0346.

Ajayi, O.O. (2014) *The Effect of Fibre Reinforcements on the Mechanical Behaviour of Railway Ballast*. PhD thesis. Faculty of Engineering and the Environment, University of Southampton, UK.

Aursudkij, B.McDowell, G.R.& Collop, A.C. (2009) Cyclic loading of railway ballast under triaxial conditions and in a railway test facility. *Granular Matter*, 11(6), pp.391–401. http://link.springer.com/10.1007/s10035-009-0144-4.

Bathurst, R.J. & Raymond, G.P. (1987) Geogrid reinforcement of ballasted track. *Transportation Research Record*, (1153), pp.8–14.

Brown, S.F.Kwan, J.& Thom, N.H. (2007) Identifying the key parameters that influence geogrid reinforcement of railway ballast. *Geotextiles and Geomembranes*, 25(6), pp.326–335.

BSI (2002) *EN 13450. Aggregates for railway ballast*, London, UK.

Consoli, N.C. et al. (2009) Effect of relative density on plate loading tests on fibre-reinforced sand. *Geotechnique*, 59(5), pp.471–476. https://doi.org/10.1680/geot.2007.00063.

Diambra, A. et al. (2007) Determination of fibre orientation distribution in reinforced sands. *Géotechnique*, 57(7), pp.623–628.

Diambra, A. et al. (2010) Fibre reinforced sands : Experiments and modelling. *Geotextiles and Geomembranes*, 28(3), pp.238–250.

Diambra, A. et al. (2013) Fibre reinforced sands: from experiments to modelling and beyond. *Int. J. Numer. Anal. Meth. Geomech.*, 37, pp.2427–2455.

Gao, Z. & Diambra, A. (2021) A multiaxial constitutive model for fibre-reinforced sand. *Géotechnique*, 71(6), pp.548–560. https://www.icevirtuallibrary.com/doi/10.1680/jgeot.19.P.250.

Gao, Z. & Zhao, J. (2013) Evaluation on Failure of Fiber-Reinforced Sand. *Journal of Geotechnical and Geoenvironmental Engineering*, 139(1), pp.95–106. http://ascelibrary.org/doi/10.1061/%28ASCE%29GT.1943-5606.0000737.

Gobel, C.H.Weisemann, U.C.& Kirschner, R.A. (1994) Effectiveness of a Reinforcing Geogrid in a Railway Subbase Under Dynamic Loads. *Geotextiles and Geomembranes*, 13(2), pp.91–99.

Gray, D.H. & Ohashi, H. (1983) Mechanics of Fiber Reinforcement in Sand. *Journal of Geotechnical Engineering*, 109(3), pp.335–353. http://ascelibrary.org/doi/10.1061/%28ASCE%290733-9410%281983%29109%3A3%28335%29.

Guérin, N.Sab, K.& Moucheront, P. (1999) Identification expérimentale d’une loi de tassement du ballast. *Canadian Geotechnical Journal*, 36(3), pp.523–532. http://www.nrcresearchpress.com/doi/abs/10.1139/t99-004.

Gunaratne, W.D.S.P. (2018) *The Effect of Fibre Reinforcement on the Resilient Properties of Railway Ballast*. PhD thesis, Faculty of Engineering and the Environment, University of Southampton, UK.

Heineck, K.S.Coop, M.R.& Consoli, N.C. (2005) Effect of Microreinforcement of Soils from Very Small to Large Shear Strains. *Journal of Geotechnical and Geoenvironmental Engineering*, 131(8), pp.1024–1033.

Hussaini, S.K.K.Indraratna, B.& Vinod, J.S. (2015) Performance assessment of geogrid-reinforced railroad ballast during cyclic loading. *Transportation Geotechnics*, 2, pp.99–107. https://doi.org/10.1016/j.trgeo.2014.11.002.

Indraratna, B. & Nimbalkar, S. (2013) Stress-Strain Degradation Response of Railway Ballast Stabilized with Geosynthetics. *Journal of Geotechnical and Geoenvironmental Engineering*, 139(5), pp.684–700. https://doi.org/10.1061/(ASCE)GT.1943-5606.0000758.

Indraratna, B.Nimbalkar, S.& Christie, D. (2009) The performance of rail track incorporating the effects of ballast breakage, confining pressure and geosynthetic reinforcement. In *8th International Conference on Bearing Capacity of Roads, Railways and Airfields - Tutumluer & Al-Qadi (eds)*. London, UK: Taylor and Francis Group, pp. 5–24. https://ro.uow.edu.au/engpapers/854.

Indraratna, B.Salim, W.& Rujikiatkamjorn, C. (2011) *Advanced Rail Geotechnology - Ballasted Track*, London, UK: Taylor & Francis Group.

International Union of Railways (UIC) (2015) *A global vision for railway development*, https://uic.org/IMG/pdf/global\_vision\_for\_railway\_development.pdf.

Lackenby, J. et al. (2007) Effect of confining pressure on ballast degradation and deformation under cyclic triaxial loading. *Géotechnique*, 57(6), pp.527–536. https://doi.org/10.1680/geot.2007.57.6.527.

Leshchinsky, B. & Ling, H. (2013) Effects of Geocell Confinement on Strength and Deformation Behavior of Gravel. *Journal of Geotechnical and Geoenvironmental Engineering*, 139(2), pp.340–352. ttps://doi.org/10.1061/(ASCE)GT.1943-5606.0000757.

Lirer, S.Flora, A.& Consoli, N.C. (2012) Experimental Evidences of the Effect of Fibres in Reinforcing a Sandy Gravel. *Geotechnical and Geological Engineering*, 30, pp.75–83. https://doi.org/10.1007/s10706-011-9450-9.

Lirer, S.Flora, A.& Consoli, N.C. (2011) On the Strength of Fibre-Reinforced Soils. *Soils and Foundations*, 51(4), pp.601–609. https://doi.org/10.3208/sandf.51.601.

Maher, M.H. & Gray, D.H. (1990) Static Response of Sands Reinforced with Randomly Distributed Fibres. *J. Geotech. Eng.*, 116(11), pp.1661–1677. http://ascelibrary.org/doi/10.1061/%28ASCE%290733-9410%281983%29109%3A3%28335%29.

Mandolini, A.Diambra, A.& Ibraim, E. (2019) Strength anisotropy of fibre-reinforced sands under multiaxial loading. *Géotechnique*, 69(3), pp.203–216. https://www.icevirtuallibrary.com/doi/10.1680/jgeot.17.P.102.

Michalowski, R.L. & Čermák, J. (2002) Strength anisotropy of fiber-reinforced sand. *Computers and Geotechnics*, 29(4), pp.279–299. https://doi.org/10.1016/S0266-352X(01)00032-5.

Michalowski, R.L. & Čermák, J. (2003) Triaxial Compression of Sand Reinforced with Fibers. *Journal of Geotechnical and Geoenvironmental Engineering*, 129(2), pp.125–136. https://doi.org/10.1061/(ASCE)1090-0241(2003)129:2(125).

Network Rail (2018) *About Us - An Introduction to Network Rail*, https://cdn.networkrail.co.uk/wp-content/uploads/2018/04/Network-Rail-About-Us-full.pdf.

Le Pen, L. (2008) *Track behaviour: the importance of the sleeper to ballast interface*. Faculty of Engineering Science and Mathematics, School of Civil Engineering and the Environment, University of Southampton, UK.

Raymond, G. & Ismail, I. (2003) The effect of geogrid reinforcement on unbound aggregates. *Geotextiles and Geomembranes*, 21(6), pp.355–380. https://doi.org/10.1016/S0266-1144(03)00044-X.

Raymond, G.P. (2002) Reinforced ballast behaviour subjected to repeated load. *Geotextiles and Geomembranes*, 20(1), pp.39–61. https://doi.org/10.1016/S0266-1144(01)00024-3.

Raymond, G.P. & Diyaljee, V.A. (1979) Railroad ballast sizing and grading. *Journal of the Geotechnical Engineering Division, ASCE*, 105(GT5), pp.676–681.

Sadeghi, M.M. & Beigi, F.H. (2014) Dynamic behavior of reinforced clayey sand under cyclic loading. *Geotextiles and Geomembranes*, 42(5), pp.564–572. https://doi.org/10.1016/j.geotexmem.2014.07.005.

Sadek, S.Najjar, S.S.& Freiha, F. (2010) Shear Strength of Fiber-Reinforced Sands. *Journal of Geotechnical and Geoenvironmental Engineering, ASCE*, 136(3), pp.490–499.

Santoni, B.R.L.Tingle, J.S.& Webster, S.L. (2001) Engineering Properties of Sand-Fiber Mixtures for Road Construction. *J. Geotech. Geoenviron. Eng.*, 127(3), pp.258–268.

Santos, S. DosConsoli, N.C.& Baudet, B.A. (2010) The mechanics of fibre-reinforced sand. *Geotechnique*, 60(10), pp.791–799. https://doi.org/10.1680/geot.8.P.159.

Selig, E.T. & Waters, J.M. (1994) *Track geotechnology and substructure management*, London, Telford: ASCE.

Shao, W. et al. (2014) Experimental Investigation of Mechanical Properties of Sands Reinforced with Discrete Randomly Distributed Fiber. *Geotechnical and Geological Engineering*, 32(4), pp.901–910.

Shenton, M.J. (1978) Deformation of railway ballast under repeated loading conditions. In A. D. Kerr, ed. *Proceedings of Railroad Track Mechanics and Technology*. Princeton University, pp. 76-TR-1:40-41.

Sol-Sánchez, M.Moreno-Navarro, F.& Rubio-Gámez, M.C. (2016) Analysis of ballast tamping and stone-blowing processes on railway track behaviour: the influence of using USPs. *Géotechnique*, 66(6), pp.481–489. https://doi.org/10.1680/jgeot.15.P.129.

Soriano, I. et al. (2017) 3D fibre architecture of fibre-reinforced sand. *Granular Matter*, 19(4), p.75. http://link.springer.com/10.1007/s10035-017-0760-3.

Suiker, A.S.J.Selig, E.T.& Frenkel, R. (2005) Static and Cyclic Triaxial Testing of Ballast and Subballast. *Journal of Geotechnical and Geoenvironmental Engineering*, 131(6), pp.771–782. https://doi.org/10.1061/(ASCE)1090-0241(2005)131:6(771).

Sun, Q.D.Indratratna, B.& Nimbalkar, S. (2014) Effect of cyclic loading frequency on the permanent deformation and degradation of railway ballast. *Geotechnique*, 64(9), pp.746–751. https://doi.org/10.1680/geot.14.T.015.

Thakur, P.K.Vinod, J.S.& Indraratna, B. (2013) Effect of confining pressure and frequency on the deformation of ballast. *Géotechnique*, 63(9), pp.786–790. https://doi.org/10.1680/geot.12.T.001.

Zornberg, J.G. (2002) Discrete framework for limit equilibrium analysis of fibre-reinforced soil. *Géotechnique*, 52(8), pp.593–604. https://www.icevirtuallibrary.com/doi/10.1680/geot.2002.52.8.593.

**Figure captions**

Figure 1. Ballast grain size distribution and characteristics; grain specific gravity $G\_{s}$; median grain size $D\_{50}$; coefficient of uniformity $C\_{u}=D\_{60}/D\_{10}$; maximum and minimum void ratios for the unreinforced material $e\_{max}^{UR}$ and $e\_{min}^{UR}$

Figure 2. (a) Fibres and typical ballast grains; (b) fibre reinforced ballast during test preparation

Figure 3. Wooden box used in packing tests, placed on the base of the electric sieve shaker

Figure 4. Testing rig prior to placement of the loading beam

Figure 5. General arrangement and measurement systems, with dimensions in mm; (a) cross-sectional view of the sample and loading beam; (b) plan view of test set-up; (c) notations used to identify the measurement systems in the drawings

Figure 6. Effect of the addition fibres on the void ratio; (a) long fibres of different widths ($L\_{N}$ = 8.8, $W\_{N}$ = 0.7, 2.9); (b) wide fibres of different lengths ($W\_{N}$ = 2.9, $L\_{N}$ = 4.4, 8.8)

Figure 7. Effect of fibre dimensions on the packing; (a) loose conditions ($∆e\_{1\%}^{loose}$); (b) dense conditions ($∆e\_{1\%}^{dense}$); (c) compacting potential ($∆e\_{1\%}^{diff}=∆e\_{1\%}^{loose}-∆e\_{1\%}^{dense}$); the dots represent the data points used to generate the contours

Figure 8. Effect of fibre width on the settlement; (a) settlement vs logarithm of the loading cycles – few markers are represented for clearer representation; (b) settlement at 3M cycles normalised with respect to the baseline test (C1) vs fibre width

Figure 9. Effect of fibre content on the settlement; (a) settlement vs logarithm of the loading cycles – few markers are represented for clearer representation; (b) settlement at 3M cycles normalised with respect to the baseline test (C1) vs fibre volume ratio

Figure 10. Effect of fibre length on the settlement; (a) settlement vs logarithm of the loading cycles; (b) settlement at 3M cycles vs fibre length

Figure 11. Analysis of the effect of the packing of the grains on the settlement; (a) settlement vs initial density index; (b) settlement vs increase in range $e\_{max}-e\_{min}$ relative to the unreinforced material

Figure 12. Resilient displacements vs settlement; (a) middle of the sleeper – LVDTs 7 and 8; (b) sleeper ends, LVDTs 2 and 3; for each test the left marker corresponds to the 10th cycle, the right marker to the 3 millionth cycle

Figure 13. Locked-in longitudinal (along the track) pressure vs settlement; (a) below the middle of the sleeper – plates 1 and 2; (b) below the end of the sleeper, plate 4; (c) difference between the sleeper-end and the middle pressures; the markers on the left corresponds to the 10th cycle, those on the right to the 3 millionth cycle: the lines in between are the actual data

Figure 14. 10 MPa pressure sensitive paper sheets from tests with a moderate content of long narrow fibres (a) and a high content of long narrow fibres (b)

Figure 15. Sleeper/ballast contact area under the rails ($A\_{c,r}$) vs sleeper settlement (a) and vs the resilient displacement at the sleeper ends (b)

**Table captions**

Table 1. List of tests; r indicates repeats

Table 2. Sleeper-ballast contact area from pressure paper