Feasibility Study of Random Fibre Reinforced Railway Ballast

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ABSTRACT

In response to the growing need for resilient track materials (including ballast) to cope with increasing train speed, load and frequency, means of optimizing its performance and minimizing maintenance requirements are required. The use of fibres of random orientation has been shown to significantly improve the mechanical properties of sand. It is reasonable to expect that such random reinforcement will have similar effects on ballast, provided that a thorough understanding of the reinforcement mechanisms at both the micro and macro-scale is reached. This work presents data based on image-based deformation measurements and macro-observations of fibre reinforced scaled ballast showing that fibres influence the micro-mechanical interactions governing volume change of the mixture rather than shear strength mobilization, which is enhanced by the tensile capability of the fibres in the mixture. The upscaling of the technique to reinforce railway ballast is discussed.

KEY WORDS: Ballast; fibre reinforcement; grain/fibre interaction; macro and micro mechanics; digital image correlation

INTRODUCTION

The ballast that supports a traditional railway track is the focus of the majority of routine railway maintenance and renewal activities. Despite recent research into its mechanical behaviour, a holistic understanding of the material and its response to typical loading and environmental conditions remains elusive and there is considerable potential for optimizing its performance and minimizing maintenance requirements. Previous research has shown that the use of fibres of random orientation can significantly improve the mechanical properties of sands. It is to be expected that ballast, which is also a granular material, would similarly benefit from such a reinforcement technique provided that a rigorous scientific understanding of the mechanics involved are achieved.

The use of randomly distributed fibres to reinforce soil has been investigated by a number of researchers (e.g. Michalowski and Cermak, 2002; Lirer et al., 2011; Diambra et al., 2013). The mechanical behaviour of the mixture may be influenced by fibre properties, soil characteristics and reinforced soil characteristics. However, different researchers have focused on different things, and an overall view of behaviour is difficult to obtain. In particular, the influence of density on the mechanical behaviour has attracted limited attention. One of the few investigations into the effect of introducing randomly oriented fibres into a granular medium was by Diambra et al. (2010) in which they showed that the addition of fibres to sand gradually reduces the maximum dry density of the mixture. Recently, Ajayi et al. (2014) presented evidence to suggest that fibres added to a granular medium interfere with the packing of the particles, generally displacing both voids and solids (particles) thus, emphasizing the need to take this behaviour into account when interpreting the mechanical behaviour of specimens with different fibre content.

This paper examines the effect of random fibre reinforcement on the structural packing and mechanical behaviour of fibre reinforced granular materials. It explains the relationship between the structural packing and mechanical behaviour of fibre reinforced granular materials through image-based deformation measurements and macro-observations. In a departure from the published literature, the materials used are large sized particles (i.e. D_{50} = 14 mm).

EXPERIMENTAL WORK

Materials

The granular material reported in this paper follows a 1/3 scale parallel gradation of standard Network Rail (NR) ballast (Figure 1) which offers an attractive and economical means of developing an understanding of the mechanics of full size ballast (D_{100} = 62 mm). Le Pen et al. (2013) demonstrated that although a measurable variation of form and roundness with particle size exists over a range of sieve intervals, these differences are slight and do not militate against the use of scaled material in investigating the factors influencing macro-mechanical behaviour.

The dimensions and the typical mechanical properties of the fibres used are presented in Table 1.

Laboratory Tests

The scaled ballast-fibre mixture used for the density and triaxial tests was prepared by mixing known masses of fibres and scaled ballast in a plastic container. The resulting mixture was random and homogeneous. The procedure for determining the maximum and minimum density of fibre reinforced granular are further described in Ajayi et al. (2014).

Conventional monotonic triaxial tests on specimens 150 mm in diameter and 300 mm in height were carried out on fibre reinforced and unreinforced scaled ballast specimens. The fibre-reinforced scaled ballast mixture was prepared in the same way as for the density tests and the reinforced specimen was then prepared to achieve the densest state corresponding to the minimum void ratio at a given fibre content. The triaxial tests were carried out on dry specimens at a confining stress of 30 kPa to replicate the typically low confining stresses within ballast reported in the literature (e.g. Indraratna et al., 2010; Sevi and Ge, 2012). The triaxial tests and the initial conditions of the specimen are summarised in Table 2. A digital image-based deformation measurement system for triaxial tests as described in Bhandari et al. (2012) was utilized to study the local deformation of the specimens.

RESULTS

Density Tests

The parameters used in describing the test results are as defined in Ajayi et al. (2014), in which the *void ratio*, e is defined as the ratio of the volume of voids (V_v) to the volume of the grains (V_s), hereafter termed "solids", and a new term called *Volumetric fibre ratio*, V_{fr} defined as the ratio of the volume of fibres (V_f) to the volume of solids is introduced. These definitions have the advantage of considering fibres independently of both the solids and the voids. The maximum and minimum void ratios (i.e. e_{max} and e_{min}) of the reinforced scaled ballast increase gradually with increasing V_{fr} (Figure 2), suggesting that the addition of fibres interferes with the packing of the particles. This result corroborates the findings of Ibraim and Fourmont (2007).

Triaxial Tests

The stress-strain plot shows the beneficial effects of increasing fibre content (V_{fr}) on the peak strength of reinforced scaled ballast, while the volumetric response of the unreinforced scaled ballast (1/3 SB) is typical of dense granular materials in exhibiting initial compression and then dilation (Figure 3). The reinforced specimen dilated less than the unreinforced sample, suggesting that the addition of fibres inhibits dilation.

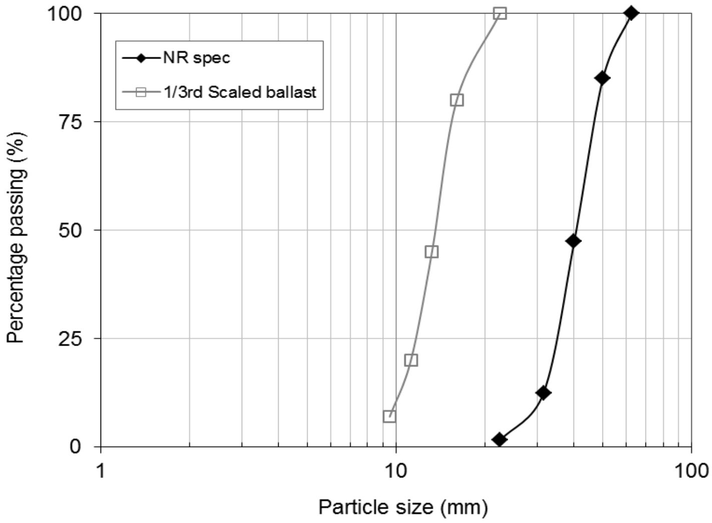

Figure 1. Particle size distribution of 1/3 Scaled ballast and Network Rail ballast gradation

Table 1. Typical values of the basic properties of polyethylene fibres

	Polyethylene
Fibre length	100 mm
Fibre width	35 mm
Fibre thickness	0.5 mm
Specific gravity	0.92
Tensile strength	~ 12 MPa
Softening temperature	85°C
Moisture absorption	< 0.1%

Table 2. List of the triaxial tests performed

Specimen	e_o	Fibre content, V_{fr} (%)
Loose SB	0.87	-
Dense SB	0.76	-
V_{fr} = 1.6%	0.85	1.6
V_{fr} = 3.2%	0.93	3.2

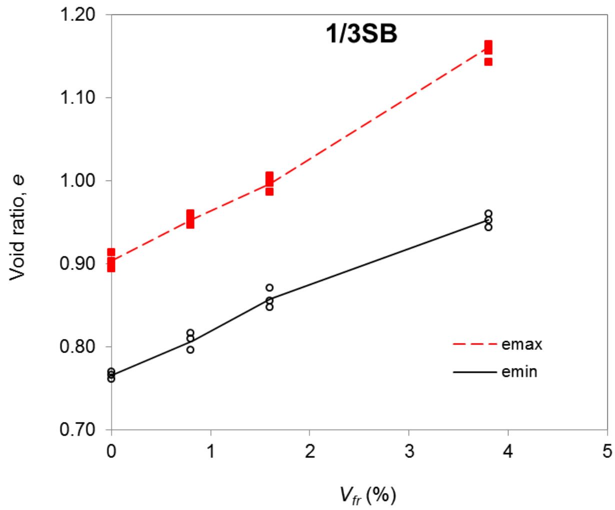

Figure 2. Effect of increasing V_{fr} on the void ratio of fibre reinforced 1/3 scaled ballast

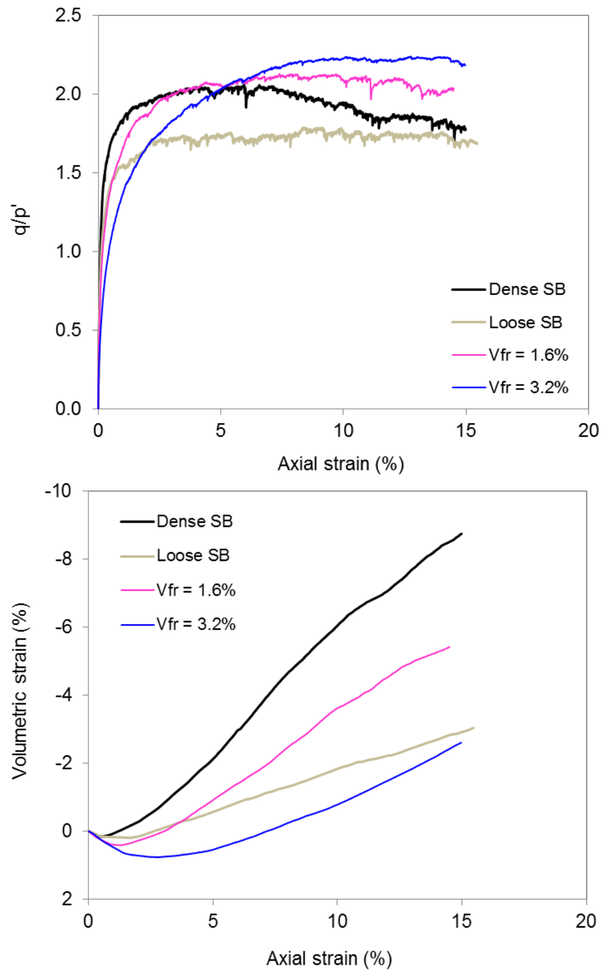

Figure 3. Typical plot of stress ratio, q/p' and volumetric strain against axial strain for unreinforced and reinforced 1/3 scaled ballast specimens

DISCUSSION

An important consequence of the data presented in Figure 2 is that changing the volume fraction of fibres V_{fr} at constant void ratio will affect the relative density of the specimen. For example, a specimen at a given void ratio could be relatively loose when V_{fr} is low but relatively dense when V_{fr} is high. This must be taken into account when comparing the mechanical behaviour of specimens of fibre reinforced materials having different V_{fr}. Fundamentally, when a volume of fibres V_f is added to a granular material it will bring about changes in the volume of solids and the volume of voids (as well as the volume of fibres) within a given constant total volume, V_{T0} (Figure 4). It can thus be deduced that the addition of fibres mainly prevents grains from packing while creating voids especially within the vicinity of the fibres. Hence fibre reinforced granular materials can be considered to have both macro voids (due to the packing of a smaller number of solids within a given total volume) and micro voids (arising from the inability of fibres to form perfect bonds with particles).

Figure 5a shows that at a given rate of dilation, the mobilized strength is greater in fibre reinforced specimens. Also, the maximum rates of dilation of the reinforced specimen (when V_{fr} = 3.2%) and the unreinforced loose sample appears to be similar. This is corroborated by the plot of angle of dilation, ψ against shear strain shown in Figure 6. The lower maximum rate of dilation, δ_{max}, exhibited by the specimens with higher e_o (i.e. loose SB and V_{fr} = 3.2%) is as expected as V_s in these specimens is smaller than in the specimens with a lower e_o (i.e. dense SB and V_{fr} = 1.6%). It could be argued that fibre reinforcements in granular materials (which leads to the creation of macro and micro voids) influence the micro-mechanical interactions governing volume change of the specimen (e.g. sliding, rolling, coordination number and local voids) but would not be expected to influence shear strength mobilization. It would then follow that shear strength mobilization is enhanced by the tensile capability of the fibres in the mixture.

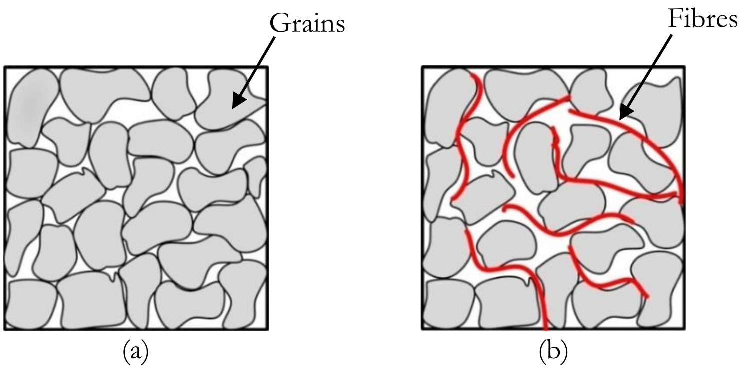

Figure 4. Illustration of the effect of adding volume of fibres, V_f (a) Unreinforced granular material i.e. V_{T0}, V_{V0} and V_S, and; (b) Fibre reinforced granular material at constant V_{T0}, $(V_S + \Delta V_S)$ and $(V_{V0} + \Delta V_V)$

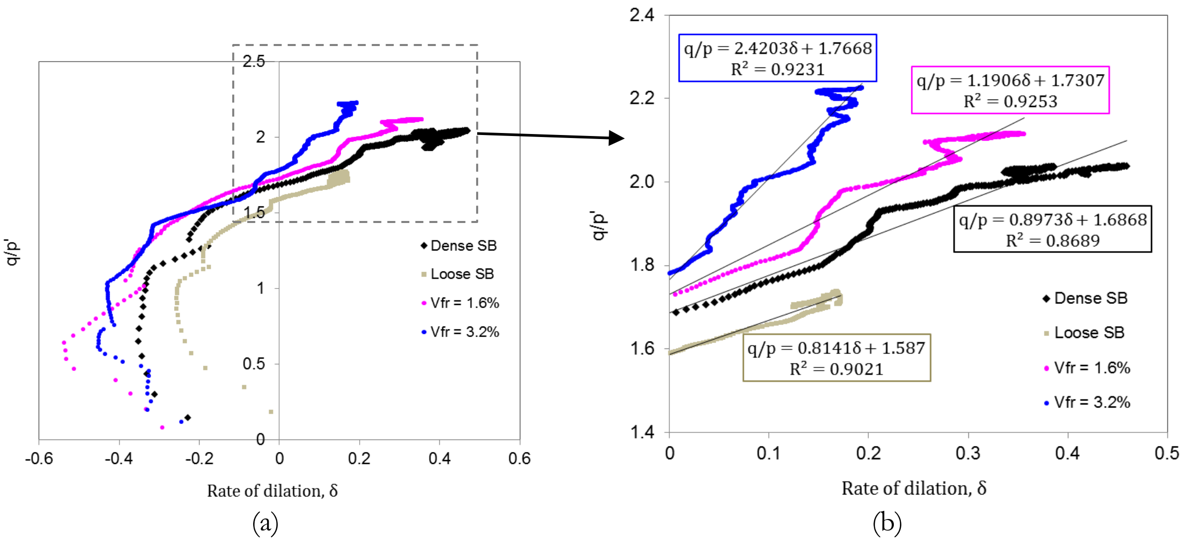

Figure 5. Fibre reinforcement effects on the rate of dilation

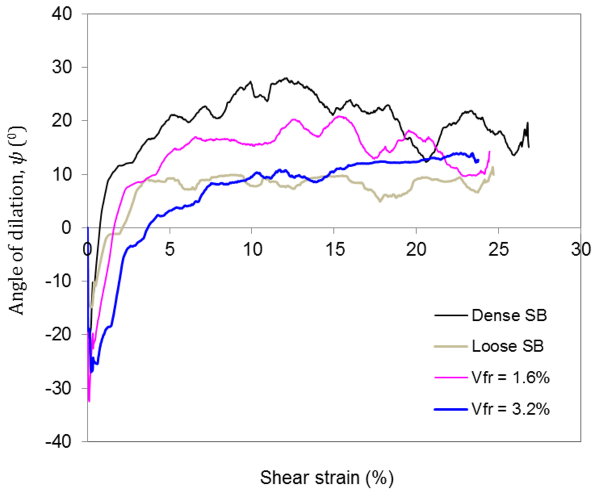

Figure 6. Effect of fibre reinforcement on the angle of dilation, ψ

The locations of images presented here are as indicated on **Error! Reference source not found.**. Figures 8 – 10 show the displacement vector, maximum shear strain and volumetric strain field plots for the specimens. The horizontal axis on the plots represents the circumferential length of the specimen, while the vertical axis represents the height captured in the image. The displacement vectors show that the predominant mode of deformation of the reinforced specimen is more nearly vertical than for pure scaled ballast (Figure 8). The reinforced specimen also exhibits a more homogenous distribution of shear and volumetric strains than the pure scaled ballast specimens (Figure 9 and 10).

The use of fibres in granular materials can thus lead to reduced lateral spread (minor principal strain) of the mixture, and the mobilization of higher stress ratios. This is potentially beneficial to the proposed use in railway ballast, and is similar to the improvement offered by geogrids in railway ballast by the reduction in permanent vertical settlement and lateral spread (e.g. McDowell et al., 2006; Indraratna et al., 2010; Chen et al., 2012). The latter is believed to be due to the restriction provided by geogrids to the lateral movement of ballast particles.

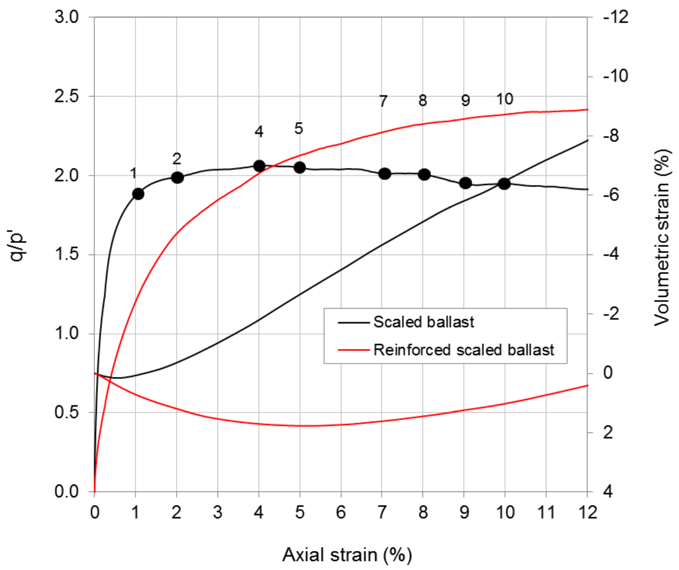

Figure 7. Stress ratio q/p' and volumetric strain plotted against axial strain for an unreinforced and fibre reinforced scaled ballast specimen

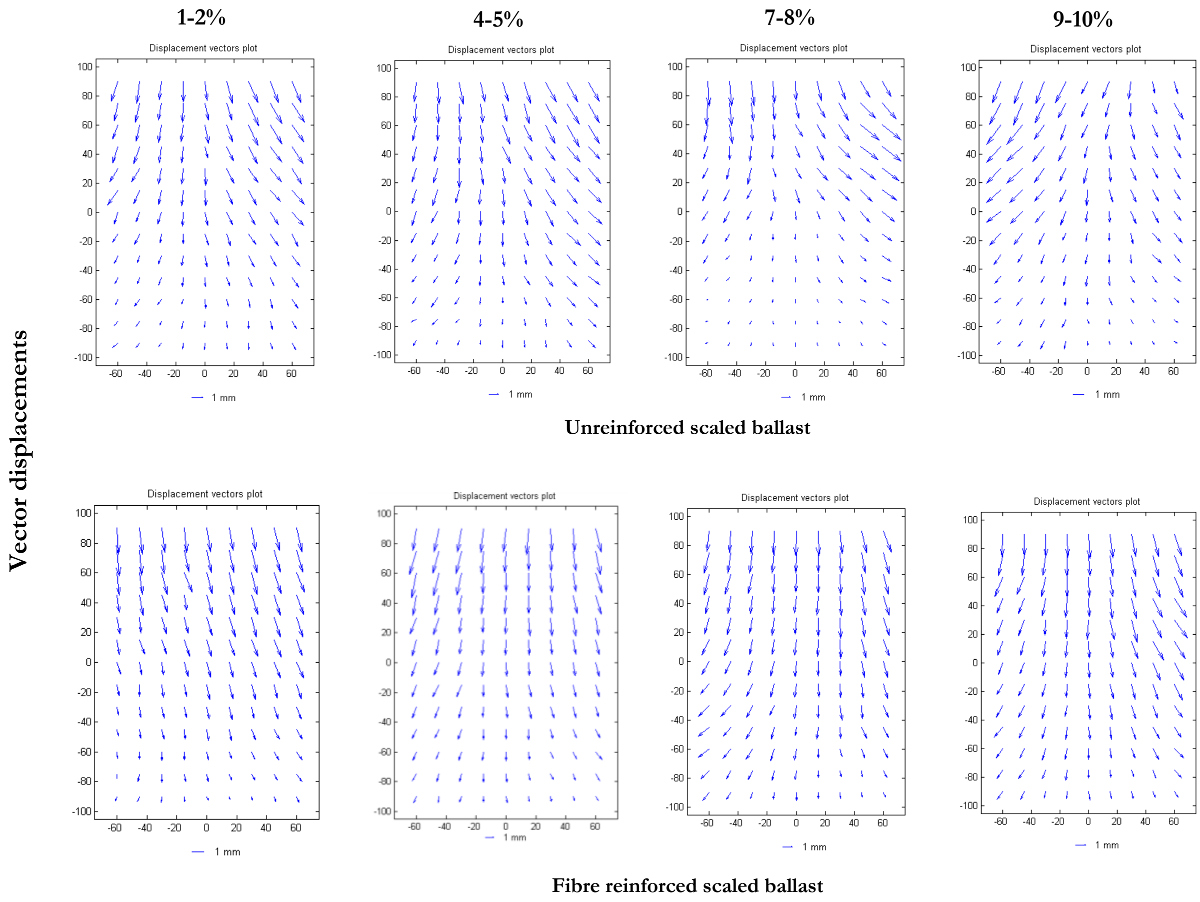

Figure 8. Displacement vectors for unreinforced and fibre reinforced scaled ballast specimens

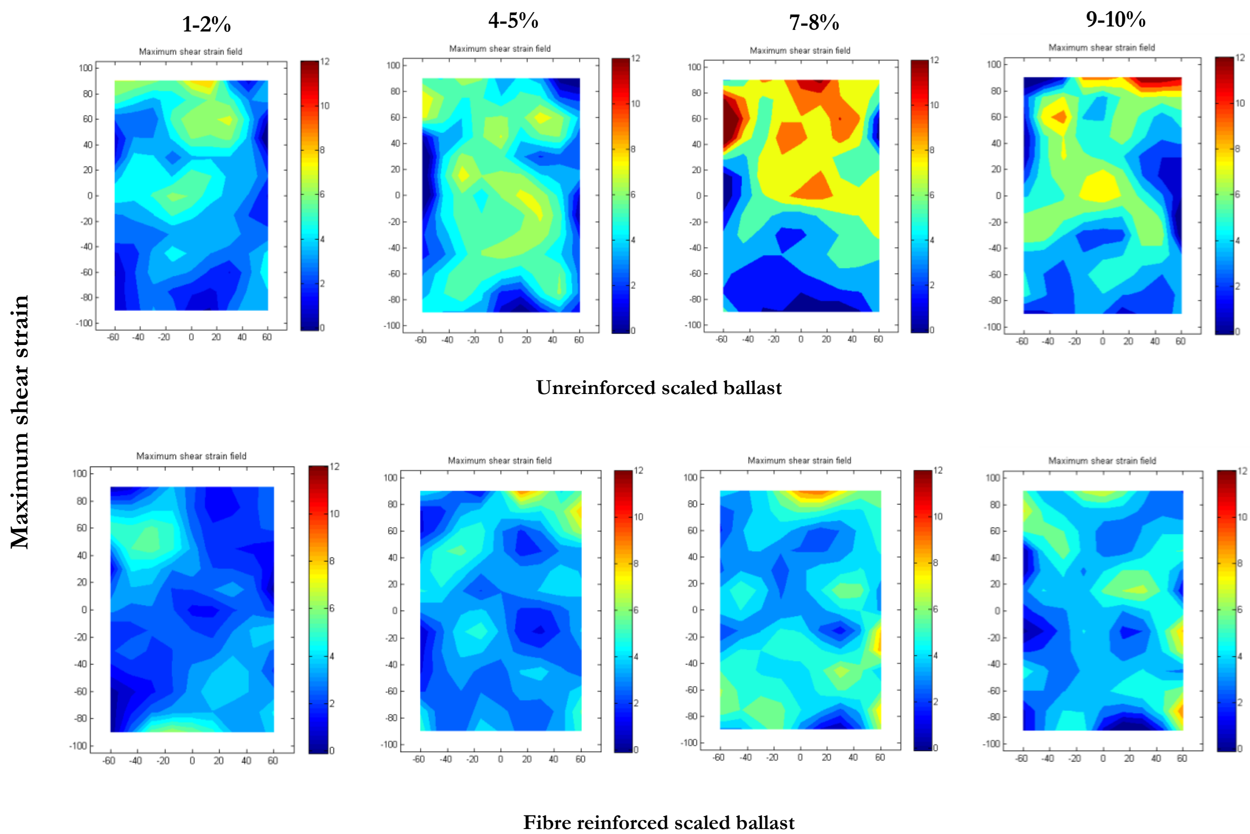

Figure 9. Maximum shear strain field for unreinforced and fibre reinforced scaled ballast specimens

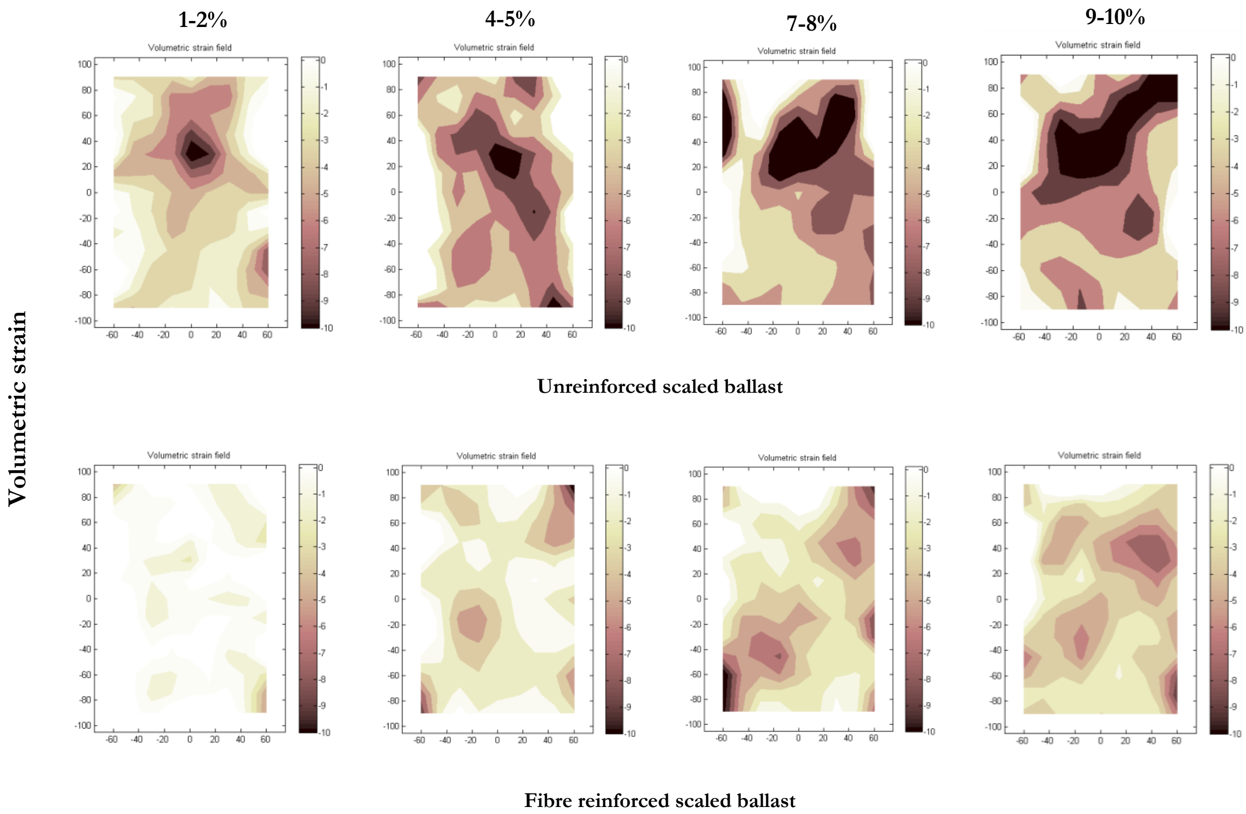

Figure 10. Volumetric strain field for unreinforced and fibre reinforced scaled ballast specimens

CONCLUSIONS

The structural packing and mechanical behaviour of fibre reinforced granular materials have been investigated through image-based deformation measurements and macro-observations of modified density and triaxial compression tests. Triaxial tests on a fibre reinforced specimen revealed that the rate at which its shear strength is mobilized for a given rate of dilation is greater than in unreinforced specimens. It is proposed that the micro-mechanical interactions governing volume change in a reinforced specimen is influenced by the disturbance resulting from the presence of the fibre reinforcements, while shear strength mobilization is enhanced by tensile resistance of fibres. The local deformation measurements revealed that the reinforced specimen exhibited more vertical deformation and a quasi-homogeneous distribution of shear and volumetric strains when compared to the pure scaled ballast specimen.

This work provides a basis for understanding fibre/particle interaction mechanisms at a macro-scale. It is intended that the presentation will include preliminary results from tests on full size railway ballast under realistic cyclic loading.

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