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Reinforcing Railway Tracks Using Insitu Polymer GeoComposites

P.K. Woodward. Heriot-Watt University, Edinburgh, UK p.k.woodward@sbe.hw.ac.uk
J. Kennedy. Heriot-Watt University, UK jhk5@hw.ac.uk
G. Medero. Heriot-Watt University, Edinburgh, UK G.Medero@hw.ac.uk

ABSTRACT
Three-dimensional polymer reinforcement of railway ballast is now a well established treatment method on the UK railway network. The technique involves the application of urethane cross-linked polymers to the railway ballast, using an onsite mixing and pumping system. As the polymer flows through the ballast it cures to form a fully interlocking three-dimensional insitu reinforcing cage. This significantly increases the strength and resiliency of the ballast and provides a very effective geopavement for train load distribution onto the formation. In this paper the application of the technique to the solution of track misalignments at highly loaded switch and crossings is presented. In these situations increased vertical and lateral forces from the track turnout can generate misalignments on the main line, causing main line geometry faults. The polymer technique has proven to be very successful in solving these issues. The paper also discusses railway track stiffness and the performance of conventional planar geogrids.

1. INTRODUCTION

1.1 Typical Problem Sites

Figure 1 shows a typical example of a turnout from a mainline here at Tottenham South Junction, UK. As the trains are diverted to the turnout they increase the lateral forces on the rails and hence increase the likelihood of displacing the rails laterally generating a misalignment on the mainline itself.

Figure 1. Example turnout from mainline with added bridge transition complication
(Tottenham South Junction, UK)

In addition the rail discontinuities, due to the nose and knuckles of the switch and crossing (e.g. the diamond), increase the track vertical forces and vibrations. These forces and vibrations can significantly increase as the line speed increases. The mainline can therefore develop geometry faults in both the vertical and lateral direction. If the line speed is low, it maybe that only lateral stability issues need to addressed as the trains accelerate towards the mainline speed. For higher line speeds significant vertical geometry faults can develop leading to heavy maintenance cycles or possible speed restrictions.

Often in order to try and solve vertical track geometry faults one of the following methods have been used:

- Increasing the ballast depth
- Using geogrid reinforcement
- Reducing sleeper spacing

Increasing the ballast depth reduces the bearing pressure on the formation, however large settlements can occur within the ballast, particularly due to shock loading at the rail discontinuities, or due to low track stiffness. Settlement of the ballast can therefore lead to further geometry faults. The application of geogrids has also been used to try and reduce geometry faults. These two methods will be discussed later in this paper. Reducing sleeper spacing is also used, however this can generate significant maintenance issues for the maintenance crews. For lateral geometry faults the use of anchors or sleeper end plates have often been used. This aspect of track construction will also be discussed later in the paper.

Before the effect of stabilising the track using polymers are considered the issue of track stiffness is first discussed as it has an important role in both the mainline track behaviour and the turnout.

2. TRACK STIFFNESS

2.1 Static Vertical Track Stiffness Measurement

Figure 2 shows a typical mesh from the finite element program SART3D (Static Analysis of Railway Track 3D) analysis software. In this example the ballast depth simulated in Run 1 is 300mm and in Run 2 is 500mm. The ballast directly overlies the subgrade, which is assumed to be soft clay given by the following relationship:

$$\frac{E_u}{C_u} = 250 \qquad [1]$$

Hence, E_u=10 MPa and C_u=40 MPa. Due to the low formation strength and stiffness the ballast stiffness is assumed to be 90 MPa. The rail is assumed to be conventional UK 113lb and the wooden sleepers are 2.6m in length at 0.7m spacing. The analysis assumes that full plasticity can develop within both the ballast and subgrade.

The analysis is for a conventional two bogie scenaro, with each bogie having two wheels; representing the interaction between two freight wagons (i.e. four wheels in total). The analysis is taken up to an axle load of 300kN (wheel load = 150 kN). The analysis uses a Mohr-Coulomb failure criteria implemented within a visco-plastic algorithm. Figure 3 shows a typical magnified displaced mesh, here for Run 1 at an axle load of 250kN.

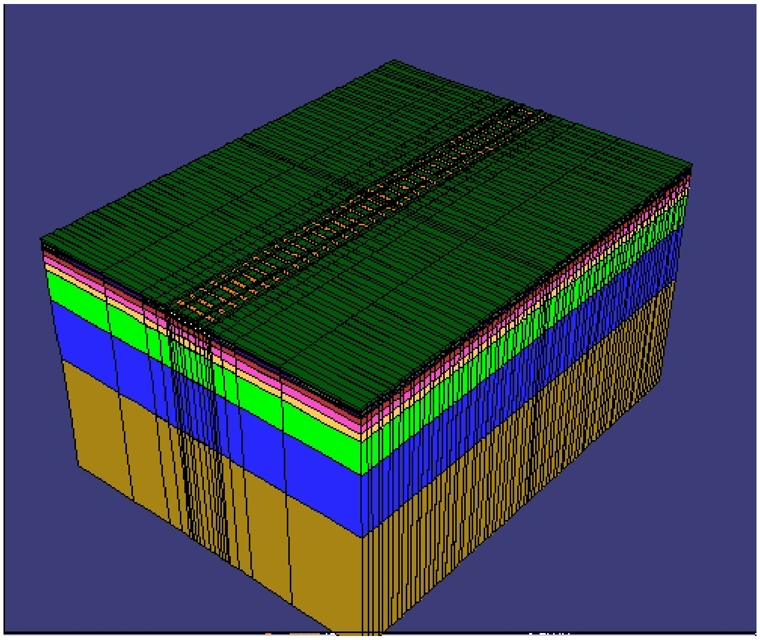

Figure 2. Example 3-dimensional finite element mesh of railway track

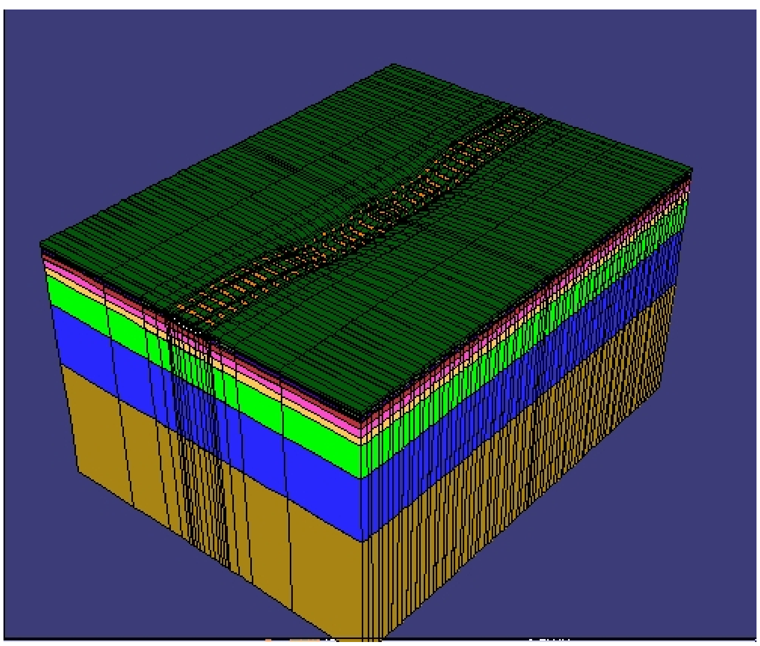

Figure 3. Typical displaced finite element mesh of railway track for Run 1 analysis (displacement magnification x50)

Figure 4 shows the initial track deflection for a typical wheel in mm versus the axle load in kN for the 300mm ballast depth (Run 1) and the 500mm ballast depth (Run 2). Non-linear effects can be seen by the changing gradient of the graphs, representing a change in track stiffness with axle load.

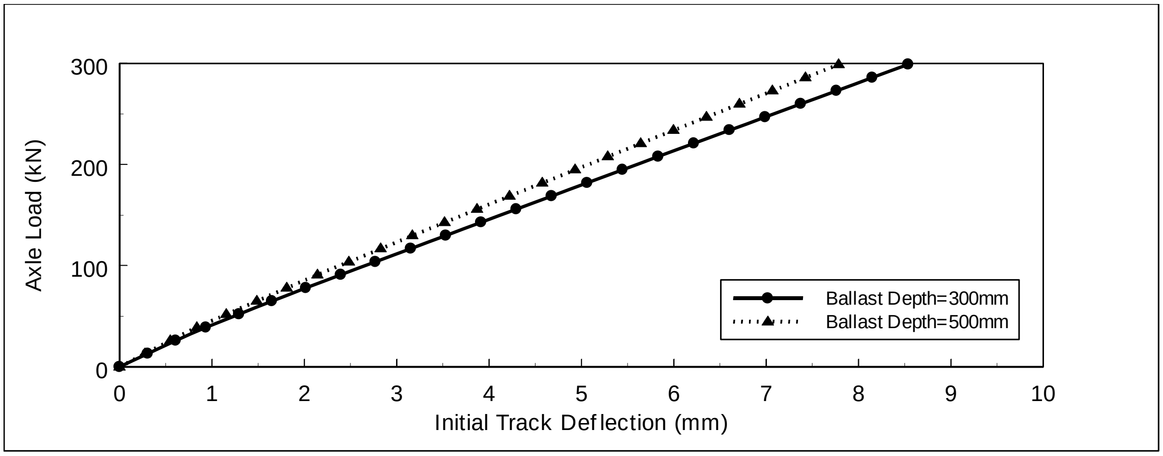

Figure 4. Example effect of ballast depth on unreinforced track deflection
(axle track stiffness related to axle load)

The vertical track stiffness is usually measured through the following:

$$k_w = \frac{L_w}{\delta} \qquad [2]$$

Where, k_w is the track stiffness in relation to the wheel load, L_w is the wheel load (i.e. per rail side) and **d** is the track deflection. It can also be represented as:

$$k_a = \frac{L_a}{\delta} \qquad [3]$$

Where, k_a is the track stiffness in relation to the axle load, L_a is the axle load and **d** is the track deflection. Often the track modulus u is also used. The track modulus is the applied force per unit length of the rail per unit deflection and is usually given by:

$$u = \frac{k^{\frac{4}{3}}}{(64EI)^{\frac{1}{3}}} \qquad [4]$$

Where k is the track stiffness (see above) and EI is the rail bending stiffness. The difference between the track stiffness and the track modulus is therefore that the track stiffness includes the effect of the rail and the track modulus does not. In Figure 4 the track stiffness can be found by simply measuring the tangent modulus of the graph at the desired axle load, for example for the 300mm ballast depth k_w=17.6 kN/mm at an axle load of 250kN. Modifications can be made to allow for sleeper voiding. Selig & Li (1994) have suggested that u=28 MPa should be considered a minimum for good track performance (approximately k_w=55 kN/mm). For high-speed tracks Pita *et al* (2004) suggested that an optimal value of k_w=70-80 kN/mm could be specified. It should be noted that the track stiffness and modulus values will change when multiple axle loads are in close proximity to each other. The Authors' have termed these as 'multiple axle track stiffness'.

The track stiffness represented in Figure 4 is therefore very low for both the 300mm and 500mm ballast depths due to the very soft subgrade. The induced formation deviatoric shear stress ratio σ_r^d directly under the railhead is defined as:

$$\sigma_r^d = \frac{\sigma_m^d}{\sigma_f^d} \qquad [5]$$

Where σ_m^d is the mobilised formation deviatoric shear stress and σ_f^d is the maximum available formation deviatoric shear stress. For the 300mm ballast depth a value of ratio σ_r^d=0.45 to 0.5 is obtained and for the 500mm ballast depth ratio σ_r^d=0.35 to 0.4 is obtained. This analysis represents a very interesting study as it clearly shows that although the formation deviatoric stress ratio can be reduced using increased ballast depths, the vertical track stiffness can still remain very low. This is due to the low stiffness subgrade and the inability of the unreinforced ballast to form an effective geopavement. Low track stiffness can have a very detrimental effect to track geometry; this is because the ballast will undergo large reversing shear strains due to the large track deflection. These large ballast shear strains generate ballast settlement and hence increase the likelihood of track maintenance (geometry correction) being required. Variations in track stiffness can therefore lead to variations in track settlements along the track and hence greatly increase the requirements for track maintenance due to differential movements between sleepers (poor geometry), particularly at the turnouts where track forces and vibrations are high.

2.2 Dynamic Vertical Track Stiffness Measurement

The above analysis illustrates that the track stiffness varies with axle load due to non-linear effects of (for example) the subgrade soil. The track stiffness also varies with excitation frequency. In order to analyse the variation of the track stiffness with frequency it is desirable to assume a quasi static load (from which it is assumed that the track behaves in a linear way) and then excite the track with a superimposed dynamic load. An analysis is then performed using Fourier transforms and transfer functions; the transfer function between the force and displacement is termed the receptance or dynamic flexibility. Receptance is therefore the inverse of dynamic stiffness. Figure 5 illustrates a typical form of the track receptance.

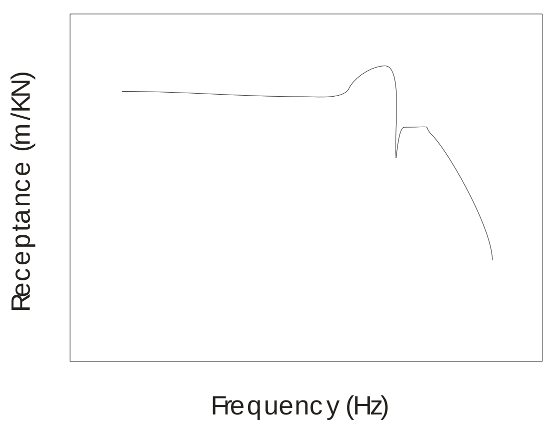

Figure 5 Typical form of the track receptance for dynamic track stiffness measurement

An increase in dynamic receptance represents a decrease in the dynamic track stiffness after due to the coincidence of the loading frequency with a track natural frequency. This coincidence will be related, for example, to the natural frequency of a subgrade soil. A detailed picture of track dynamics can therefore be determined; this type of approach has been used by the Swedish network operator Banverket,

In the UK, the railway standard (NR/SP/TRK/9039) make reference to the ‘Falling Weight Deflectometer’ (FWD) as the principal means of measuring the dynamic track stiffness, quoted as the ‘dynamic sleeper support stiffness (K)’ with units of kN/mm/sleeper-end. In an FWD test a sleeper is decoupled from the rail and a weight is dropped onto it. Geophones are used to determine the track deflection through a backwards integration process of the raw data. From these deflections a dynamic sleeper support stiffness is calculated. The FWD was originally developed for use on roads and pavements and to the Authors’ knowledge no rigorous independent testing of the FWD has been published in the public domain in order for the general railway community to determine its accuracy in assessing dynamic railway track stiffness. In the Authors’ opinion significantly more research is required on the use of the FWD as a means of measuring dynamic railway track stiffness; in particular the results of any measurement should be compared to the static track stiffness representations quoted above and to the results of static testing with superimposed dynamic loads through a range of frequency contents, such as the Banverket track stiffness trials to determine track receptance. The dynamic analysis of railway track can be simulated using the SART3D sister finite element program called DART3D (Dynamic Analysis of Railway Track 3D). This finite element program can be used to simulate effects such as critical track velocity (Madshus & Kaynia, 2000 and Banimahd & Woodward, 2007a), track vibration & receptance (Banimahd & Woodward, 2007b).

3. 2D PLANAR REINFORCEMENT AND GEOCELLS

2-dimensional geogrids have been proposed to reinforce the railway track over poor formations or at high loading points. The geogrids are typically situated at the bottom of the ballast and operate by helping to provide a simple ballast locking mechanism at ballast/subgrade or ballast/subballast interface. This locking mechanism is used to try and reduce penetration of the ballast into the underlying material and hence to help retain ballast integrity. Laboratory testing of geogrid reinforced railway track has been performed by Brown *et al* (2007); Table 1 summerises the results of their settlement measurements.

Table 1. Measured ballast settlements for unreinforced and geogrid reinforced ballast tests (data approximated from Figure 12 in Brown *et al*, 2007)

Load Cycle	Unreinforced ballast (mm)	Geogrid reinforced ballast (mm)
100,000	5.0	4.2
1,000,000	10.1	7.8

The results shown in Table 1 indicate little effect of the geogrid at around 100,000 cycles. At 1,000,000 cycles the settlement has reduced from approximately 10mm to approximately 8mm. Interesting Brown *et al* (2007) also showed that adding geogrid reinforcement to the ballast had had no effect on the resilient track deflection and very little effect on the formation bearing pressures. This is to be expected since, in order to reduce formation bearing pressures, the ballast must be capable of supporting bending stresses and hence transmit shear stresses much more effectively to form a robust geopavement. Geogrids are very flexible systems (they can easily be deformed with figure pressure) and hence their performance in this respect is very limited.

Geocells have also been used to try and improve the bearing capacity of structures over poor soils or at high loading points. However experience has shown that the geocells apparently do not attain high values of vertical stiffness due to compaction issues and non-interlocking of materials across the geocell walls. The Authors’ themselves have conducted tests on geocells and recorded very low vertical stiffness, sometime as low as 18 MPa, depending on the material used and the number of cells used in the experiment. For modelling purposes geocells effectively increase the cohesive component of the added geocell material to help increase bearing capacity, but the low stiffness values can cause problems. Their use in railway tracks would therefore seem to require significantly more research.

4. 3D POLYMER REINFORCEMENT

A technique that has been gaining popularity in the UK is the 3-dimensionl reinforcement of the railway track (Woodward *et al*, 2007a) by applying urethane cross linked polymers directly to the *insitu* ballast (generally referred to as the XiTRACK technique). The polymer is formed from two components, an isocyanate and a polyol, which are mixed together and poured directly onto the ballast surface. The ballast and track can be reinforced in a multitude of different configurations to attain the desired track performance. For example, a lower level of ballast could be treated to provide formation protection, or a side beam could be formed (after tamping) to 'capture' the lateral track geometry.

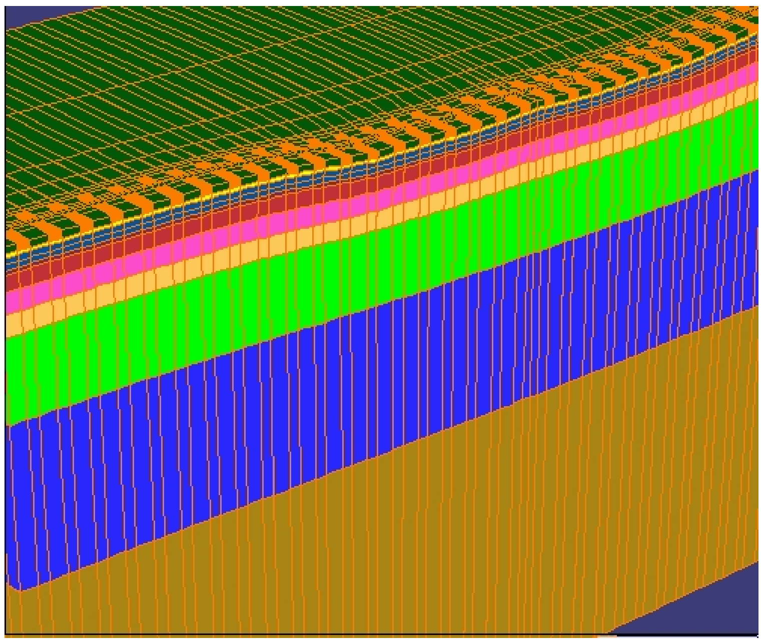

Figure 6. Typical cut-away displaced finite element mesh of polymer reinforced railway track (displacement magnification x100)

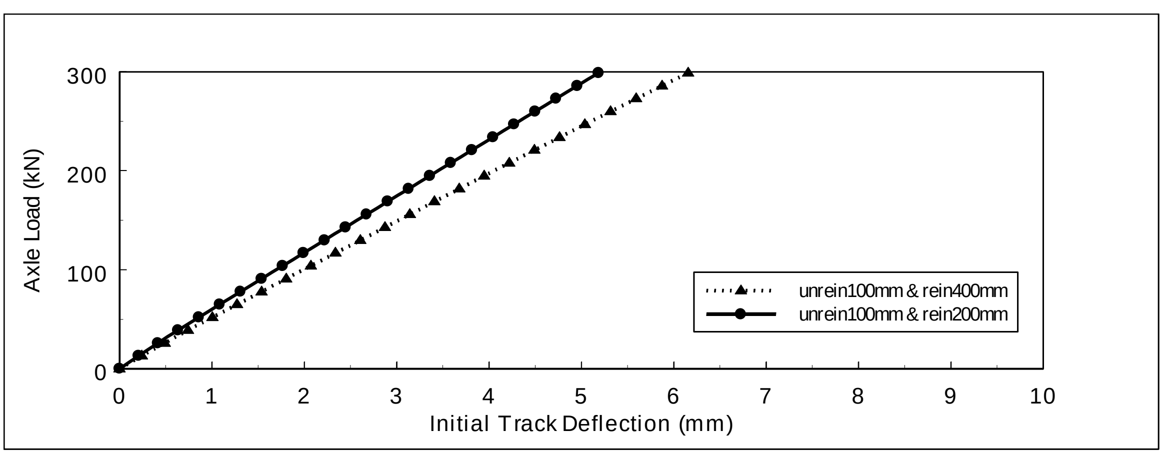

Figure 7. Results of Run 3 and Run 4 simulations on polymer reinforced track deflection

In order to illustrate the improvement in the track stiffness and formation bearing pressures, the mesh shown in Figure 2 is used to analyse the effect of the polymer at two different reinforcement levels. Two analysis are considered for comparison, Run 3 in which 100mm of free ballast is left untreated overlying 200mm of polymer reinforced ballast (to compare to Run 1) and Run 4 in which 100mm of ballast is left untreated overlying 400mm of reinforced ballast (to compare to Run 2). In Figures 6 & 7 the improvement in the track stiffness is clear when compared to Figure 4. For Run 4 the track stiffness k_w=30 kN/mm representing a significant increase in track stiffness. In addition, since the ballast is reinforced with the polymer, the generation of settlement of the ballast due to reversing ballast strains is significantly reduced, both because of the increase in track stiffness and because of the 3-dimensional caging effect of the polymer GeoComposite; this has been shown experimentally by Woodward *et al* (2007b). For Run 3 the computed value of formation deviatoric stress ratio σ_r^d=0.2 to 0.25 and for Run 4 the ratio σ_r^d=0.1 to 0.15 is obtained, representing a significant reduction in the formation deviatoric stress state when compared to unreinforced ballast.

4.1 Example Lateral and Vertical Track Reinforcement

The track shown in Figure 1 was treated using the polymer reinforcement technique as shown in Figure 8 below. The polymer technique allowed for the change in track stiffness from the bridge to the transition and hence onto the turnout and diamond.

Figure 8. Formation of the lower polymer reinforcement at Tottenham South Junction, UK

As shown in Figure 1 the track exiting the bridge is complicated by the point motors at the bridge interface which generates additional transition issues (it is necessary to significantly reduce track deflection and vibration to prevent the switch units from registering a misalignment fault). The track was therefore first treated in the vertical direction to provide a reinforced geopavement over the transition area. The level and amount of the polymer applied can easily be changed to provide a ballast stiffness transition profile. Unreinforced ballast was left above the treated ballast to allow for track geometry correction after the renewal and for any post correction if necessary. Once the upper track had been replaced and the geometry corrected the shoulders were treated with the polymer (Figure 9) to form reinforced side beams. The polymer was allowed to run through into the lower geocomposite to provide a fully interlocking mechanism; this means that lateral stability is provided by an anchored full depth reinforced side beam. This side beams imparts a significant level of lateral resistance and in essence forms a complete reinforced ballasted channel section. This imparts tremendous vertical and lateral stability to the track.

Figure 9. Formation of the upper polymer reinforcement at Tottenham South Junction, UK (upper reinforcement tied into lower reinforcement to form complete reinforced channel section)

4.2 Example Lateral Track Reinforcement

If the track only requires lateral stability then a reinforced side beam can easily be formed in the shoulder area. The polymer can (for example) be set to penetrate down to 400mm. Typically the beam is around 400mm wide and hence the application of the polymer forms a continuous reinforced side beam for the whole track length. The reinforcement can be applied immediately after a tamp (geometry correction) and hence the treatment can capture the track alignment. Figure 10 shows the formation of such a side beam.

Figure 10. Formation of polymer side beams to increase passive resistance at Knighton Junction, UK

The formation of the side beam significantly increases the lateral resistance of the track shoulder as it engages a significant area of passive resistance. Conventional techniques, such as sleeper anchors and end plates, are very limited in the level of lateral resistance improvement as they are based on the area of the plate itself; in addition they can cause issues when the track requires maintenance. The formation of side beams has found to be highly successful, holding the track alignment when conventional techniques have failed.

The first trial of the technique for turnouts took place at a site on the West Coast Main Line in the UK in March 2000, which required track geometry correction every 3 months. Since treatment no correction has been necessary, representing a current saving of over 28 maintenance cycles (currently over 9years worth of track maintenance saved). In addition, as shown by Woodward *et al* (2007a), application of the polymer can significantly reduce track vibrations.

5. CONCLUSIONS

In this paper the application of an *insitu* polymer reinforcement technology to the ballast in order to significantly improve track performance has been presented. The system has had a high degree of success in the UK, being applied to typical problems such as bridge transitions, bolted joints, tunnels, high-speed track over poor formations, level crossings, railway track over embankments, curves, S&C sites, concrete slab-track transitions, lateral tolerance improvement and so on. High profile sites in the UK include increasing track performance over poor ground (critical track velocity site) on the East Coast Main Line and reinforcing track at complex multiple S&C sites, such as Clapham Junction.

The paper showed how the formation of a reinforced geopavement can be used to improve both track stiffness and formation bearing pressures. A discussion of typical work published in the area of geogrid reinforcement of railway track and a review of static and dynamic track stiffness was also presented.

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