THREE-DIMENSIONAL TRACK REINFORCEMENT USING POLYMER GEOCOMPOSITES

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ABSTRACT

In this paper the application of advanced three-dimensional polymer reinforcement of railway ballast is presented. The technique is used to fully reinforce the ballast to create a very strong resilient ballast/polymer geopavement to significantly improve track geometry and reduce the need for track maintenance. The polymer used is of the urethane cross-linked type and can therefore be formulated to accommodate the large forces present in modern day railway tracks. The polymer can be applied in many different ways to stabilise the ballast, including the ability to still allow conventional track maintenance operations such as tamping and stone blowing. During application the polymer flows through the void structure (while still allowing track drainage) to a predetermined depth, set by the catalyst level. During this process the polymer is curing and interconnecting to form a complete three-dimensional matrix. If this process occurs while the ballast is in its correct position (i.e. after compaction and geometry correction) then the polymer ‘captures’ the track geometry. Studies in the UK have shown that the technique has been extremely successful in reducing track maintenance at many different locations across the UK network. The paper describes the general process of three-dimensional ballast stabilisation, including experimental test data and a typical track installation case history. Three-dimensional finite element simulations illustrating a typical stress distribution on the track formation are also presented to show how the polymer reinforcement improves track performance.

INTRODUCTION

It is generally understood that the carbon foot-print of trains, per paying passenger, is less than that of an airline passenger. This has led to a resurgence of railways across the world as a principal means of mass transport. In order for railways to be viable, in terms of journey times and economics, the need for increased train speed and axle weight has become of paramount importance. Apart from the 186mph (298kph) Channel Tunnel Railway Line (CTRL) the maximum speed of trains in the UK is generally 125mph (200 kph). In France the TGV now operates up to 200mph (320 kph), but a land speed record of 356mph (570 kph) was recently set on the Paris to Strasbourg line. Increased train speed means that the railway network can start to directly compete with the airline industry and, when combined with the freight carrying capacity of the railway, the future of rail industry looks increasingly positive.
However, the problems facing the railway community to transform its railway infrastructure into a modern high performance high-speed and high-freight carrying capacity network are significant. The railway infrastructure in many countries has evolved over the last 120 years and hence large sections would not have been originally designed to accommodate current axle weights and line speeds. However, many countries are looking to increase these as well as increasing track usage. To provide a safe and reliable system for high speed lines track geometry will need to be consistently good. For heavily used mixed lines ballast and formation maintenance are also of high priority due to the level of stresses induced by freight, particularly when ballast depths are limited. It is therefore likely that as increases in track usage rise, to meet the increasing demand, significantly more track maintenance will be required. In addition high-loading sites, such as cross-overs and turnouts, generate significant maintenance issues due to problems like voiding and high lateral loading generating track misalignments as trains accelerate towards the main line speed. Bridge transitions also generate significant maintenance issues, especially when considering heavy axle loads or trains travelling at high-speed. Granular materials (i.e. railway ballast) suffer particular problems over poor formations due to the development of tensile strains at the formation interfaces. The continued rotation of the principal stresses causes ballast densification and hence settlement, this increases over the soft formations due to low track stiffness values and hence higher induced ballast plastic strains.

However, increases in track usage mean reductions in track maintenance access, at the very time it is needed. The dilemma facing the industry is therefore clear; how can the railway track performance be significantly increased without increasing maintenance costs and track downtime? It is therefore highly desirable that new methods are developed in order to provide the necessary track improvements to meet these demands. Using laboratory, computer and field installations as examples, this paper describes such a technique.

THREE-DIMENSIONAL BALLAST REINFORCEMENT

In order to significantly improve the performance of geo-synthetic railway ballast reinforcement it is desirable to reinforce the ballast in 3-dimensions. Three-dimensional ballast reinforcement was developed to rapidly reinforce and stabilise railway ballast to form a continuous resilient geopavement.
over the treatment area. Typically the polymer used to treat the ballast is of a rapidly reacting urethane-crosslinked composition (polyurethane), which is supplied as two components. These two components are mixed in situ through mixing equipment and poured on the track; the polymer is therefore not sprayed or injected. The rheology of the cross-linked polymer can be specifically formulated for each track treatment; this allows its engineering properties to be pre-defined to ensure that the resulting polymer/ballast GeoComposite meets the requirements for the particular track application (1, 2).

The variable engineering properties of the polymer include, stiffness, strength, damping ratio, viscosity, cure rates etc. Tensile strains at break within the polymer can be set to exceed 100% and hence the polymer exhibits a high degree of ductility. When applied to ballast, the polymer uses the void structure within the ballast to penetrate down to a predefined depth (set by the catalyst level). During this process the polymer cures to form reinforcing elements in all directions; these reinforcing elements link together to form a 3-dimensional GeoComposite. Typically the polymer cures within 10 to 15 seconds, with around 50% of its stiffness formed within minutes and around 90% of its stiffness formed within one hour. Figure 1 shows a typical cross section of the GeoComposite; the interconnectivity of the polymer to form a 3-dimensional reinforcing structure can be clearly seen. In a typical application around 26% of the void structure is taken up by the polymer; which still leaves a very high GeoComposite permeability.

Installation Equipment

Figure 2 shows that the installation equipment required to pour the polymer is simply a small generator, pump and two IBC’s (Intermediate Bulk Container) containing the polymer components. There are no special precautions that need to taken when the polymer is being applied. The polymer can be applied to any type of ballasted track structure, for example, it is perfectly safe to apply in tunnel environments where, for example, an increase in track fixity maybe required due to tolerance issues. In order to show the potential of the technique the paper now describes example finite element simulations, recent laboratory test data of the reinforcement and a typical installation.
NEW GRAFT FACILITY

GRAFT (Geopavement and Railway Accelerated Fatigue Testing) is a new geopavement and railway testing facility at Heriot-Watt University, Edinburgh, UK. GRAFT can simulate (at full scale) the behaviour of railway track subjected to cyclic loading (3).

GRAFT consists of a trackbed constructed within a steel tank 3.515ft wide x 9.836ft long x 3.770ft high (1.072m x 3.0m x 1.15m). The track includes tie sections overlain by an I-section and cyclic loading is applied to the track from a Losenhausen UPS200 (LOS) testing machine. The LOS machine is a closed loop control hydraulic machine which operates from two pumps and has a 200T maximum capacity, of which 150T can be applied cyclically. The LOS loading actuator can easily apply realistic loads of both typical passenger and freight traffic, generating realistic stress levels in the ballast and subgrade layers. The movement (load or displacement) response of the hydraulic actuator is controlled through a servo valve which reacts to an electrical signal command to deliver oil pressure and flow specific to match that of the signal.

The LOS testing machine can support the required loading of the test track through a thick steel base and cross head reaction frame. The steel tank to hold the trackbed specimen for testing was designed to fit the dimensions of the LOS base and crosshead columns while also being capable of being lifted by the two available 5T capacity lifting cranes. This led to a tank that weighs around 7.5T when a full trackbed is constructed within it. The tank is supported laterally from four steel angles around the top of the tank and two channel sections welded continuously around the tank at 7.874in (200mm) and 19.685in (500mm) from the base. In addition, five 0.787in (20mm) steel tie rods are bolted laterally through the tank with three at 7.874in (200mm) from the base and two at 19.685in (500mm) from the base. In order to prevent the tank from buckling vertically while being lifted by the cranes a support lattice of two longitudinal joists and nine traverse joists were constructed and are bolted to the bottom of the tank. Figure 3 shows the tank being lifted into position under the loading actuator of the LOS machine via two lifting beams attached to the overhead cranes at either end of the lifting frame. To limit the lateral support to the substructure (provided from the rigid walls of the steel tank and to provide lateral support similar to the horizontal residual support experienced in the field) the tank was lined with 0.472in (12mm) thick neoprene rubber. Finite element modelling was used to simulate the
tank lined with neoprene to ensure that the confining pressure in the tank reflected that of the free field track. The GRAFT facility can incorporate a removable pipe running the length of the tank at a height of 2.787ft (850mm) from the base which acts as a drain to enable flooding and drainage during specific tests. In this way wet-beds (slurried track) can also be investigated.

**COMPUTER MODELLING OF GRAFT FACILITY**

In order to illustrate the performance of the 3-dimensional reinforcement system a preliminary 3-dimensional finite element simulation of a GRAFT test is shown in Figure 4. The clay and formation clay properties are taken to be the same throughout the soil depth and are assumed as $E_t=2.90\text{Mpsi}$ (20MPa) and $C_u=11.61\text{kpsi}$ (80kPa) for the Undrained Young’s Modulus and Undrained Shear Strength respectively. The ballast depth is assumed to be 11.811in (300mm) with a ballast stiffness of $E_b=14.51\text{Mpsi}$ (100MPa). Three wooden ties are assumed with the following dimensions 11.811in x 9.449in x 4.921in (300mm x 240mm x 125mm); this represents a wooden version of half a twin-block type tie. The piston load simulated is 43.8klbf (195 kN). As with the actual test tank a neoprene lining is simulated. The finite element analyses use an elasto-plastic Mohr-Coulomb failure criterion (4). The rail simulated is equivalent to a UK 113lb rail.

**Unreinforced Ballast Simulation**

For the unreinforced ballast analysis the simulated full elasto-plastic deflection at the peak load for this particular simulation is 0.425in (10.8mm). Formation deviatoric stress ratios (induced deviatoric stress divided by the maximum available deviatoric stress) are in the region of 0.7-0.9. These high values of deviatoric stress ratios illustrate that high stress concentrations in the formation are occurring which would mean that high plastic strains would develop and hence permanent track deformation. Figure 5 shows contours of the simulated induced vertical bearing stress at the formation level.

**Reinforced Ballast Simulation**

In this analysis the same mesh and properties are used but the ballast layer is assumed to be reinforced using the polymer reinforcement technique. The 3-dimensional polymer ballast slab is shown in Figure 6 underneath the simulated ties. The simulated ballast stiffness is now 65.3Mpsi (450 MPa). The new value of the simulated elasto-plastic deflection at the peak load for this particular
simulation is 0.268in (6.8mm) and the formation deviatoric stress ratio’s are in the region of 0.35-0.45. The new displacement suggests that the track stiffness in the GRAFT simulations has increased by nearly 40% by addition of the polymer to the ballast. This analysis suggests that a high degree of performance should be expected from the 3-dimensional reinforcement system. Figure 7 shows contours of the new simulated induced vertical bearing stress at the formation level. The contour plot indicates that a more even distribution of the bearing stress is predicted across the formation with average bearing pressures significantly less than the unreinforced case; thus supporting the predicted reduction in the formation deviatoric stress ratio. While these results are preliminary (the computer models are currently being calibrated to the GRAFT data as it becomes available) the analysis does indicate that a strong performance from the GeoComposite tests should be expected.

In order to demonstrate the potential of the 3-dimensional reinforcement technique in a controlled environment, and to support the preliminary results obtained from the computer analysis, a GeoComposite sample was prepared in the GRAFT machine and tested to 500,000 load cycles as part of an ongoing study into railway track behaviour in GRAFT.

**GRAFT TESTING OF 3-DIMENSIONAL POLYMER GECOMPPOSITE**

In this particular experimental test, a sinusoidal piston loading range from 1.12klb to 29.21klb (5 to 130kN) was adopted. This approximately represents a UK 29.6T axle load (accounting for some pressure overshoot in hydraulic feedback system) with a 0.5T seating load for a ‘conventional’ track with UK tie lengths of 8.525ft (2.6m). However, only one half of a ‘twin-block tie’ type arrangement (using 3 ties) was used (similar to the finite element modelling); this gives an estimated increase in the formation contact pressure of around 1.5 to 1.8 when compared to conventional length ties, which means that the equivalent ‘conventional tie length’ axle load is likely to be around 1.6x29.6=47.4T, i.e. equivalent to US axle load of 35T with a dynamic load factor of approximately 1.35. It should be noted that the exact value depends on many factors, including tie type, spacing & dimensions, rail used and so on, hence equivalent axle load calculations should only be used as a guide. Kaolin clay was used for the subgrade and formation in order to have a high level of control over the consistency. After compaction the unconfined bearing strength of the formation was approximately 24.67kpsi (170kPa). The frequency of the applied loads in the GRAFT facility for these particular tests was selected to be
3Hz as this frequency was found to operate best with the required load amplitude range. Figure 8 shows a typical specimen of the 3-d reinforced ballast GeoComposite under test. This test was used to research further the GeoComposite under controlled laboratory conditions, in order to accurately measure its track performance enhancement potential since site experience had clearly demonstrated the track potential of the technique. The results of the tests are shown in Table 1 against some typical results for unreinforced ballast tests published in the general literature for information. As shown, the permanent settlement of the 3-dimensional reinforced trackbed after 500,000 cycles is considerably less than would be expected from a typical ballasted track test. Typical GRAFT results for unreinforced ballast range from 0.71in (18mm) to 1.97in (50mm) depending on the piston load and number of cycles. Experimental modelling of the 3-dimensional GeoComposite therefore supports the observations seen from the numerical modelling in that a significant improvement in track behaviour can be achieved by using the technique. Figure 9 shows that after 500,000 cycles the polymer treated ballast showed no signs of deterioration (it is being lifted out of the GRAFT facility) and Figure 10 shows that the GeoComposite is still totally free draining after the testing.

Both the computer modelling and laboratory testing illustrate the track improvement possible using the technique under controlled conditions. This track performance increase is also confirmed by the sites treated using the technique over the 9.3 years in the UK; which include: bridge transitions, level crossings, cross-overs, turnouts, clearance issues, tunnel formations, track over poor ground, concrete slab-track transitions, lateral track stability issues and so on. The longest period that a track has been treated so far is the track at Bletchley Points 215D on the West Coast Main Line, UK which was treated in March 2000. The Points form part of a turn-out from the main line; the main line itself operates at 125mph with axle loads up to 25T. Due to the induced vertical and lateral forces, the track required geometry correction every three months prior to treatment. Since the track has been reinforced the points have required no more maintenance, representing over 9.3 years maintenance free operation (at the time of writing this paper), representing at least 250 MGT of loading.

The computer simulation, laboratory measurement and field performance illustrate that by using the reinforcement technology to reduce the formation bearing pressures, while significantly reducing the ballast densification process; then a significant reduction in track maintenance can be achieved. Since
the technique can be applied to any ballasted track it can therefore be applied at track renewal, or indeed retrofitted to existing ballast tracks (provide a ballast void structure stills exists). A typical installation sequence of the reinforcement technique over poor ground is now presented to illustrate the construction process.

EXAMPLE INSTALLATION: Newham Bog, High-speed East Coast Main Line, UK

The East Coast Main Line is the premier high-speed railway line in the UK. The track was constructed to allow passenger trains to run at 125mph. However the line is a mixed line and as such is heavily used by rail freight. Since opening of the line several areas of the track have generated significantly more maintenance than others. One of these problem sites is the track area around Newham Bog, which lies to the South of the City of Newcastle.

Newham Bog is an area of track on the East Coast Main Line that has suffered from long standing track related issues. High track deflections in this area, due to the underlying alluvium and peat giving rise to high track compressibility and hence track deflection, have been recorded since the site was first constructed. In addition, due to the low stiffness of the peat, track critical velocity issues arise as the line speed increases; due to the train speed approaching that of the Rayleigh surface wave in the peat, creating the potential for track resonance to occur. Various reinforcement options had been used to try and stabilise the site since is was constructed, however poor site performance always continued to occur; Figure 11 shows the weak soil conditions at the site. In order to try and improve the track performance the following formation work was undertaken in 2008:

1. Improve the drainage system.
2. Remove all conventional track reinforcement products.
3. Install a sand blanket.
4. Add ballast and treat using the 3-dimensional polymer reinforcement technique.
5. Add a further 300mm of ballast over the 3-dimensional reinforcement to conform with the remainder of the railway line (this conforms to the current track depth at the site).

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The purpose of the ballast reinforcement was to help reduce differential track settlement and hence help improve track quality for both the high-speed trains and the freight wagons. To allow for a track transition the polymer loading was reduced from the main area of treatment to allow for a graduated ballast stiffness transition to the unreinforced ballast. This type of transition is a typical feature (and benefit) of 3-dimensional ballast reinforcement, i.e. the ability to tailor out the ballast stiffness to form a simple, but robust transition. Figure 12 shows the polymer being installed at the site. The figure shows the application ‘wand’ which is at the end of the delivery pipe (seen as the yellow pipe exiting the pump on truck bed in Figure 2). Within the delivery ‘wand’ are static mixes used to mix the polymer components together to form the polyurethane. Although the reaction is exothermic it is desirable to keep the polymer components warm during winter application to ensure that the pump can deliver the appropriate flow rates. The red lines shown in Figure 12 are the timing points to ensure that the correct amount of polymer is being poured per section. Within minutes of the polymer being poured the upper unreinforced ballast was placed to allow the site to comply with the existing track structure (i.e. so that the entire track length is fully maintainable using all conventional railway track equipment). The figure also shows that excavators can run over the track within minutes of the polymer being poured allowing a continuous track treatment process to be developed, significantly reducing track down time.

At the time of writing this paper the treatment area is performing very well and comments from the main contractor indicate a significant improvement in track quality has been observed. A video of the 3-dimensional polymer GeoComposite application at Newham Bog can be found on YouTube. Simply type ‘XiTRACK’ into the YouTube search engine. The video was compiled by the main contractor for the site works.

CONCLUSIONS
In this paper the application of advanced 3-dimensional polymer reinforcement of railway ballast was presented. The reinforcement technology is able to fully reinforce the ballast throughout the predetermined treatment depth and hence can be used to fully reinforce the entire ballast depth or only parts (as required). The polyurethane polymer used is of the urethane cross-linked type and the paper illustrated how the polymer can be applied to accommodate the large forces present in modern
day railway tracks. The performance of the formed GeoComposite was illustrated through computer simulations of a new railway test facility called GRAFT through both unreinforced and 3-dimensional reinforced ballast simulations. Full scale laboratory testing using the new GRAFT facility was used to verify the performance of the reinforcement technique over 500,000 load cycles at US size ballast contact pressures (axle loads), thus confirming the significant reductions in track maintenance observed from field applications of the technique in the UK. The paper also presented a typical 3-dimensional ballast reinforcement installation for high-speed track over poor ground, here for track at Newham Bog on the East Coast Main Line; which is the premier UK high-speed railway line.

REFERENCES

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TABLES

<table>
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<tr>
<th>Trackbed test undertaken</th>
<th>Approximate settlement after 500,000 cycles or equivalent MGT of traffic (mm)</th>
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<td>XiTRACK reinforced test in GRAFT facility</td>
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<td>Unreinforced ballast test in prismoidal triaxial rig at the University of Wollongong (5)</td>
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*1in=25.4mm

TABLE 1 Comparison of XiTRACK Test Results to Similar Trackbed Tests

FIGURES

FIGURE 1. Typical Cross Section of 3-dimensional Polyurethane GeoComposite Showing Polymer Interconnectivity

FIGURE 2. Typical Installation Equipment Required for 3-dimensional Polymer Reinforcement

FIGURE 3. Trackbed Being Lifted into Position

FIGURE 4: Typical 3-dimensional Finite Element Representation of GRAFT Facility

FIGURE 6. Polymer/ballast GeoComposite Underneath the Ties

FIGURE 7. Induced Vertical Bearing Pressure at the Formation Level for the Reinforced Ballast Simulation

FIGURE 8. 3-dimensional Ballast Reinforcement under Test in the New GRAFT Facility

FIGURE 9. GeoComposite Removal after 500,000 Load Cycles

FIGURE 10. The free draining properties of the GeoComposite after 500,000 Load Cycles

FIGURE 11. Weak Soils Present at the Site

FIGURE 12. Installation of the Polymer at Newham Bog
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