IMPROVING THE SAFETY OF THE RAILWAY TRACK INFRASTRUCTURE USING INSITU POLYURETHANE GEOCOMPOSITES

P.K. Woodward, J. Kennedy and G. Medero

School of Built Environment, Heriot-Watt University, Riccarton, Edinburgh, EH14 4AS, UK

Dr Peter Woodward: P.K.Woodward@sbe.hw.ac.uk (**correspondence)
Mr Justin Kennedy Jhk5@hw.ac.uk
Ms Gabriela Medero G.Medero@hw.ac.uk

Telephone: 0044 (0) 131 451 8010

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ABSTRACT

There are many issues related to the safety of the railway track infrastructure, such as tolerance issues in stations and tunnels, poor track formations, critical track velocity effects for high-speed lines (both subseismic and transeismic regimes), voiding at rail discontinuities such as crossovers and bolted joints, voiding at transition zones onto both concrete slab-track and steel/concrete bridge decks, track safety at level crossings, vibration reduction at crossing point motors, and so on. However, the track technology required to solve these safety critical issues has not, in general, advanced to meet the rising demand placed on the railway infrastructure by increasing track usage, axle weight and train speed.

In this paper the application of in situ polyurethane GeoComposites to improve railway track safety and performance is discussed. Specifically the paper shows, through examples, how typical safety critical areas can be reinforced and stabilised to improve the overall track safety regime and operation. The paper then presents a complete example of how the technique can be used to solve a typical high-speed ground vibration issue, including a full installation example and track measurement data as appropriate. The GeoComposites are formed by pouring a urethane cross-linked polymer onto the ballast matrix which cures to form a very resilient and strong GeoComposite. The polymer can be applied in many different ways to stabilise the ballast, but importantly can be applied to still allow conventional track maintenance operations such as tamping and stone blowing if desired (it can be applied to virtually eliminate all ballast maintenance as appropriate).

INTRODUCTION

The application of polyurethane polymer reinforcement of railway ballast is now a well established method of improving the performance and safety of railway track. In this technique a urethane cross-linked polymer is applied to the ballast surface where it proceeds to penetrate the ballast matrix forming ‘runnels’ which interlock to form a complete 3-dimensional ballast/polymer GeoComposite (1). The GeoComposite exhibits many desirable properties, such as significant increases in strength, stiffness (as appropriate), good drainage and ductility. The rapid curing properties of the polymer mean that gel times are within a few seconds and excellent polymer strength is achieved within
minutes. This results in a very efficient and flexible delivery and application technology that is quick and importantly cost effective. The technology is generally referred to as the XiTRACK technique and has been applied at many sites over the last 10 years in the UK and is shortly to be applied in Italy. It is also under consideration by the German railway company DeutcheBahn as a method to stabilise their railway track, particularly high-speed turnouts and bridge transitions.

In this paper the application of the technology to several typical sites that present challenges to the railway track engineer, particularly safety related issues, are presented to show how the technology works and how it is applied. The track problems presented include tolerance issues (gauge clearance), crossings and turnouts, transitions, level crossings and poor ground conditions leading to high ground vibration. Specifically the performance of two of these problems, namely the level crossing at Purfleet Deep Wharf and the ground vibration problem at Gravel Hole, are presented through measured tie accelerations, Falling Weight Deflectometer readings and transient tie deflections using Total Station monitoring techniques.

The examples presented in this paper clearly shows that the use of 3-dimensional polyurethane reinforcement can have a very positive impact on the performance of the railway track and can solve many of the ballasted track related issues facing the railway track engineer.

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.

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. In a typical application around 26% of the void structure is taken up by the polymer; which still leaves a very high GeoComposite permeability. If the penetrating depth is set high, but the ballast depth is relatively low, then the polymer can be used to provide a solid polymer layer at the base of the ballast.

**Installation Equipment**

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 provided it is able to penetrate the ballast matrix.

**TOLERANCE ISSUES**

It is often necessary to ensure that sufficient gauge clearance exists between the kinematic envelope of a passing train and the track infrastructure (2). For example, if a train is passing through a tunnel it is necessary to ensure that a minimum safe distance is maintained between the train and the tunnel wall. Depending on the distance three categories are often used: Low Fixity, Medium Fixity and High Fixity. Low fixity tends to rely on a given ballast distance, medium fixity usually refers to adding a means of extra ballast fixity and high fixity usually means virtually no movement of the track is allowed. Polyurethane reinforcement has been used to stabilise track within all three of these categories. For example it was used at Hoxton Station UK in 2009 and at Grove Hill Tunnel UK in 2007 to provide a
high fixity solution (within 0.06in [1.5mm] movement) to ensure that gauge clearances are maintained and hence track safety assured. Figure 1 shows the application of the polymer reinforcement at Hoxton Station, which is situated on the East London Line UK. As can be seen the polymer is being used to ensure that trains accessing the station will not interfere with the platform. The reinforcement can be designed to give the required stiffness and strength to ensure that lateral movement is minimised. In tunnel situations the polymer can be used to also ensure that vertical tolerances are maintained as well as lateral ones. This situation arises when track is being lowered in a tunnel, perhaps to allow electrification works or to allow wider vehicles to pass through.

**CROSSINGS AND BOLTED JOINTS**

A particular safety critical area is crossings, diamonds and turnouts. At these track assets very large vertical and lateral forces can be generated due to rail discontinuities and track radii. Elastic and plastic movements of the track substructure can lead to voiding issues within the ballast and hence superstructure movements, such as a high degree of vibration, which increases the track damage and hence the likelihood of excessive maintenance and/or safety issues rapidly developing. There have been many cases where excessive maintenance of these assets has led to train derailments and subsequently passenger fatalities. It is therefore very beneficial to be able to stabilise the asset’s substructure, in particular the ballast, to reduce voiding affects and to be able to better redistribute and dampen the significant vertical and lateral forces.

Figure 2 shows the application of polyurethane reinforcement at a turnout on the West Coast Main Line in the UK (line speed 125mph [200 kph]). The polymer reinforcement was applied in March 2000 and removed in April 2010 as part of the general line upgrade. During this 10 years of service (approximately 300 MGTs) no maintenance of the turnout has been required; prior to reinforcement the asset required maintenance every 3 months. This means that reinforcement of this asset has saved between 30 to 40 maintenance cycles. A cost/benefit analysis estimated that the payback period was around 1.5 years. The significant improvement in track performance at the turnout led to the technique being used to reinforce adjacent bolted joints and an adjacent high-speed diamond. Prior to reinforcement this diamond required regular maintenance and increased renewals due to the
development of rail fractures and excessive vibration. Since polymer reinforcement no issues have been reported and the asset is performing very well at full line speed.

**BRIDGE AND CONCRETE TRACK TRANSITIONS**

Discussion into the behaviour and cause of bridge transition problems can be found in (3,4,5). Often voiding under the tie can be found at the transition due to movement of the ballast and/or formation. Movement of the formation maybe related to overstressing due to the increase in ballast forces at the track stiffness discontinuity. Development of voiding in the ballast increases the track forces leading to higher voiding and hence track forces and so on. This mechanism can then start to propagate from the bridge interface and/or develop further along the track due to induced oscillations in the trains’ suspension systems. Once voiding develops it will therefore continue to develop. The situation is often made worse by the general inability to perform adequate track maintenance in this area, especially if the track is directly fixed along the bridge. At some bridges the track is skewed which means that a full length tie cannot be used at the interface. This causes a ‘twist fault’ to develop which can have serious safety implications for the train, possibly leading to a derailment risk. Often the transition problem is directly related to ballast movement and hence techniques that attempt to increase the formation/subgrade strength will often still not solve the problem, even if an increase in track stiffness is created. The use of polyurethane reinforcement in the ballast matrix has been found to be very successful as it is able to help prevent the three-dimensional movement of the ballast, i.e. to stop ballast migration and subsequent voiding development. In addition the ballast matrix can be stiffened, increasing the overall track stiffness value. The amount and stiffness of the polymer applied has a direct affect on the ballast (and hence track) stiffness (see Gravel Hole example below); increases in track stiffness of 50% have been measured in the GRAFT facility (6,7). Application of the polymer can occur as a continuous slab, partial slabs, ladder structures and so on.

Figure 3 shows the application of polyurethane reinforcement at New Cross Fly Over on the East London Line in 2009. Here the technique is being used to support the track at a bridge transition which also serves as an expansion joint. The track was placed in its line and level and a ladder structure used to retain the track geometry during movements of the bridge and to prevent voiding due to the
change in track stiffness. Figure 4 shows the application of the technology at Tottenham South Junction bridge transitions in 2005. This location was well known to generate problems as the point motors for the turnouts are located within the bridge transition itself. Voiding under the point motor ties generated excessive vibration leading to poor performance of the points and safety issues. The ballast in these areas was therefore reinforced in both the vertical and lateral direction (tied together through a beam and lower transition slab) to give a highly stable platform for the points. Figure 5 shows another bridge transition problem, here at Keadby Draw Bridge. The bridge is moved back into a ‘draw pit’ when canal traffic needs to pass through the site. This leads to significant transition problems due to the rail discontinuities; this situation is amplified due to the high tolerance required to ensure that the bridge is in its correct position to allow trains to pass over. Polyurethane reinforcement was used in 2006 to reinforce the entire transition area (but still allow vertical track maintenance). The site has performed very well given that it carries over 60% of the entire UK rail freight tonnage.

LEVEL CROSSINGS

In 2004 polyurethane reinforcement was used to reinforce the level crossing at the Coble Fret Ferry Port at Purfleet Deep Wharf UK. The track was to be closed due to safety concerns that trains would derail as they went over the level crossing as formation failure had occurred. The use of ground reinforcement using VCC (vibro concrete columns) had been suggested, but this would have closed the level crossing for a considerable period (weeks) and be prohibitively expensive. Closure of the level crossing for more than a few days would result in a significant issue for the operational running of the port and hence the UK import/export market as a whole. The decision to use polyurethane reinforcement of the ballast was made and the site was treated in July 2004 using two polyurethane reinforced ballast layers. Two reinforcement layers were used due to the critical nature of the site and its requirement to stay in constant use as freight vehicles run over the site every 15 to 20 seconds; as well as its heavy use by rail freight traffic on the Tilbury Loop Line.

Figure 6 shows the installation of the polymer at the site and Figure 7 shows the crossing after renewal. Despite the very heavy loading the site experiences, its performance has been excellent. Figure 8 shows the reduction in vibration measured at the site (the dotted line is the pre-treatment
acceleration response and the solid line is the post treatment acceleration response, taken at the same tie location). The figure clearly shows that there has been a significant reduction in track vibration (track deflection). This reduction in track vibration can be clearly felt at the site.

GROUND VIBRATION AND DYNAMIC ISSUES

The ability to reduce track vibration forms an important aspect of polyurethane track reinforcement techniques. For example, if the speed of a train were too continually increase along a particular track a point will eventually be reached whereby a Rayleigh ground wave will start to develop in the formation and subgrade (8). The Rayleigh wave will propagate from the source of loading resulting in a significant increase in track deflection and ground vibration. A typical analogy is that of an aircraft passing through the sound barrier. The magnitude of the ground vibration is heavily influenced by the dynamic characteristics of the ground, such as frequency content and damping values. In relatively soft subgrades the velocity of the Rayleigh wave falls within the speed of conventional trains and hence the phenomenon can cause serious issues for the operational running and safety of the train.

Two different methodologies can be adopted to allow the trains to run on the site:

Methodology 1

The first method is to prevent the Rayleigh ground waves from forming in the subgrade. This can be achieved by stabilising the subgrade through techniques like deep soil mixing (lime and cement stabilisation) or soil replacement. Concrete piled platforms can also be used. These techniques can however be time consuming and expensive, requiring the line to be shut down for long periods of time.

Methodology 2

The second method is to help control the ground vibration by polymer stabilising the ballast to form an efficient geopavement across the poor formation. In this method polyurethane is used to reinforce the ballast layer and thereby limit the deflection of the ground (the geopavement acts as an efficient load distributing mechanism) and hence the magnitude of the ground vibration. It is important to note however that generally these techniques do not fully stop the development of the Rayleigh ground wave as the clay subgrade is not being stiffened/strengthened, i.e. they are a method of vibration
control not elimination. However the track can still be fully maintainable and the ground deflection can be modified to lie within a specified safe limit. Polymer stabilised ballast has typical added benefits of improving track dynamics (the ballast is stiffer), allowing a reduction in induced formation deviatoric bearing stresses, increasing the ballast mass participation, preventing ballast decompaction due to ground vibration in the lower ballast layers, improving track ductility and so on. The polymer can be installed very rapidly, requiring significantly less downtime than Methodology 1 and in many cases the overall costs are also less. It can therefore be used as a technique to allow the line speed to be raised over difficult ground without major civil engineering work, i.e. it can be achieved within normal possession periods.

The application of Methodology 2 has been used at two locations in the UK for line speeds of 125mph (200 kph) and maximum axle loads of 25T. One of these locations, Gravel Hole, is now described and site measurements of track performance presented.

**Gravel Hole**

Figure 9 shows the Gravel Hole site which is located near Lancaster on the West Coast Main Line UK. The track structure is underlain by very weak clays and a high water table; in fact track flooding is regularly experienced at the site as shown in Figure 10. The granular track depth was around 21.65in (550mm) prior to treatment and a line speed restriction of 80mph (128kph) was in place due to the development of large rail deflections, poor geometry retention and vibration being felt by nearby properties. The presence of ground vibration when train speeds had approached 125mph (prior to the line speed restriction) clearly indicated Rayleigh ground wave transmission and hence the start of a resonant track condition and operational safety concerns.

Since the full line speed is 125mph (200kph) the restriction of 80mph (128kph) caused delays to the operational running of the UP line and hence there was a real desire to remove this speed restriction and allow trains to run safely at full line speed. However the time available for the track work was very limited and hence a cost effective solution that would allow the line speed to be raised within the possession period available was required. This was achieved using the polyurethane ballast
reinforcement. The granular depth of the track was extended from 21.65in (550mm) to 25.59in (650mm) and the sequence of track construction from the formation upwards was a 1.97in (50mm) sand blanket, a geotextile separator, 11.81in (300mm) polyurethane reinforced ballast layer and a 11.81in (300mm) unreinforced upper ballast layer. The purpose of the sand layer was to help prevent mud pumping. Using the data supplied, $E_u=2.9$ ksi (20 MPa) and $C_u=5.8$ psi (40 kPa), the dynamic track deflection at full line speed for the post-installation case was predicted to be around 0.19in (4.7mm). This represented up to a 42% reduction in track deflection once the drainage conditions (track flooding) had been addressed. The national UK standard allows for up to 0.31in (8mm) deflection when track reinforcement is used at these so called ‘critical velocity’ sites. Figure 11 shows the application of the polymer which occurred in two relatively short possessions.

Before and after installation (1 week after) an estimate of the track response was measured using a Falling Weight Deflectometer (FWD) by an independent external consultant. Unfortunately in the pre-installation case the sampling distance used was 32.81ft (10m); for the post-installation case it was reduced to 2m (6.56ft) representing a 5 fold increase in sampling points. Figure 12 shows the results of these measurements. As is normal with the FWD a large degree of scatter can be seen (the FWD measurements are influenced by many factors and a large degree of interpretation is required) however the general trend (a least square fit is applied as appropriate) shows a good overall improvement in track response. A statistical analysis suggests that an average 36% reduction in track deflection over the whole treated area is observed. This reduction has been achieved despite the fact that no improvement in drainage has yet taken place and hence the track is still flooded (this was considered necessary to achieve a 42% reduction). To verify the improvement, Total Station measurements of the transient track response were taken post-treatment by the client, which showed that the peak tie deflection was around 0.16in (4mm); this is 50% of the allowable transient track deflection and is very close to the predicted value of 0.19in (4.7mm). In addition it is estimated that this will reduce as the track ‘beds’ in and the drainage issues are addressed. Observation of the track behaviour, and feedback from the local maintainer, verifies that a significant improvement in track behaviour has been achieved; in particular a noticeable reduction in track vibration at full line speed is clearly felt. This reduction in ground vibration was the principal objective of the treatment and confirms the types of measured reductions seen at other sites, such as at Purfleet Deep Wharf (Figure 8).
The measured results from the site clearly prove that polyurethane reinforcement is an effective tool in reducing track deflection at full line speeds, both improving the safety of the track and allowing line speeds to increase, all achieved within very short possession (construction) times.

CONCLUSIONS
In this paper, improving the railway track efficiency and safety through the use of 3-dimensional polyurethane reinforcement of railway ballast was presented. The application of the technique at typical railway track problems was presented namely: tolerance issues (gauge clearance), crossings and turnouts, transitions, level crossings and poor ground conditions leading to high ground vibration. The use of the XiTRACK technique over the last ten years in the UK has conclusively shown that it can be applied to almost any ballasted track related issue to improve the track performance and importantly the track safety.

From the examples presented the performance of the system was proven through measured ground vibration reductions (acceleration measurements at Purfleet Deep Wharf level crossing) and through measured reductions in transient track deflections (Falling Weight Deflectometer and transient tie deflections at Gravel Hole).

REFERENCES


FIGURES

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Figure 3: Installation of Polyurethane Reinforcement at New Cross Flyover on the East London Line, UK

Figure 4: Installation of Polyurethane Reinforcement at Tottenham South Junction Bridge Transitions UK

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