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Study of railway track stiffness modification by polyurethane reinforcement of the ballast

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ABSTRACT

This paper presents the measured results of full-scale testing of railway track under laboratory conditions to examine the effect on the track stiffness when the ballast is reinforced using a urethane cross-linked polymer (polyurethane). The tests are performed in the GRAFT I (Geopavement and Railways Accelerated Fatigue Testing) facility and show that the track stiffness can be significantly enhanced by application of the polymer. The track stiffness is measured at various stages during cyclic loading and compared to the formation stiffness, which is determined prior to testing using plate load tests. The results indicate that the track stiffness increased by approximately 40–50% based on the measured results and from the previously published GRAFT I settlement model. The track stiffness was monitored during loading for a maximum of 500,000 load cycles. The paper concludes by presenting and commenting on, the application of the technique to a real site where the Falling Weight Deflectometer was used before and after polymer treatment to determine the dynamic sleeper support stiffness. The very challenging site conditions are highlighted, in particular the water logged nature of the site, and comment made on the effect of the water on polymer installation. The results of the FWD measurements indicate that a good increase in overall track stiffness was measured. These results are consistent with the laboratory tests which are performed on a different soil and use a different measurement technique and hence confirm that regardless of the soil and measurement system track stiffness increases are observed using this technique.

Introduction

Vertical track stiffness is the relationship between vertical applied force and displacement response of the rails. Thus track stiffness is a function of the structural properties of the rails, rail pads, sleepers, ballast, subballast and subgrade soil. For example, the vertical track stiffness is 7% greater for UIC60 rail than for BS113A (Hunt, 2005). Furthermore, sleeper spacing influences track stiffness with reduced spacing resulting in an increase in track stiffness. Hunt (2005) notes that the subgrade is typically the primary determinant of overall track stiffness. Fundamental analysis and mathematical models of track stiffness are often based on the idealised Beam On Elastic Foundation (BOEF) approach that considers the track as an infinite bending beam resting on a continuous linear elastic foundation. This approach introduces the concept of the track modulus, which is the stiffness of a spring (k) per unit length of track. Using the software GEOTRACK, (Selig and Waters, 1994) found that the track modulus can increase by around 10–20% for a decrease in sleeper spacing, as well as increases in ballast Young's modulus, ballast depth and rail moment of inertia. In general, relatively high track

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stiffness is beneficial as it provides sufficient track resistance to applied loads and results in decreased track deflection, which reduces track deterioration. Low track stiffness results in a flexible track with poor energy dissipation and ballast abrasion due to ballast flexural deformations. On the other hand, very high track stiffness leads to increased dynamic forces in the wheel–rail interface as well as on the sleepers and ballast, which can cause wear and fatigue of track components (Berggren, 2009). An optimum track stiffness value is likely to occur at some intermediate value. Track stiffness can also be measured as sleeper end stiffness (i.e. track stiffness which does not include the rail pad stiffness).

Based on reviews of track stiffness by Hunt (2005), Berggren (2009) vertical track stiffness (k) can be defined as the ratio between track load (F) and track deflection (z) as a function of time (t), where the force can either be axle load or wheel load:

$$k(t) = \frac{F(t)}{z(t)} \tag{1}$$

The stiffness of different components of the track structure is mostly non-linear, such as the rail pads and subgrade, and can vary with temperature and moisture content for example. Furthermore, the sleepers may have voids beneath them, leading to large deflections at low load levels. The secant stiffness is often used to eliminate the effect due to poor contact between ballast and sleeper and can be defined as:

$$k_{xy} = \frac{\Delta F}{\Delta z} = \frac{F_b - F_a}{z_b - z_a} \tag{2}$$

where ΔF and Δz are the difference between the values obtained at two predefined points with point a being taken at the seating load. However the points a and b can be selected based on various definitions to give both secant and tangent stiffness values (Hosseingholian et al., 2009). Hunt (2005) noted that for a realistic representation of non-linear behaviour a tangent stiffness to the design axle loading is a reasonably relevant parameter.

If the track stiffness is too low then the ballast will undergo large cyclic stress reversals leading to track settlement and hence track geometry faults. It is also likely that plastic strain accumulation in the formation will result in further track geometry issues (Brough et al., 2003; Burrow et al., 2007; Frost et al., 2004; Li and Selig, 1994, 1996, 1998; Sadeghi and Askarinejad, 2007) (if the track stiffness is low it is likely that the formation soil is weak). It is therefore clear that whatever methodology is used to determine the track stiffness, improvement of the track stiffness over poor (weak) ground is an important factor in railway track design and maintenance. This was discussed by Pita et al. (2004).

Table 1
Subgrade Kaolin clay parameters (Kennedy et al., 2013; Kennedy, 2011) from the GRAFT I test data.

GRAFT I test	Applied load (kN)	Subgrade tangent modulus (MPa)
CT1	130	35.5
CT2	90	32.7
CT3	90	51.4

Present work

Significant steps in strengthening and stiffening the ballast have been proven through the application of polyurethane polymer reinforcement of the ballast (the XiTRACK technique) (Woodward et al., 2005, 2011a,b; Kennedy et al., 2013). In this technique a rapidly reacting exothermic visco-elastic polymer (comprising an isocynate and a polyol) is applied to the surface of the ballast. The polymer penetrates to a predefined depth set by a catalyst to form a 3-dimensional ballast polymer matrix (GeoComposite). Forming this GeoComposite across the width, length and depth of the ballast will then form a geopavement over the track area. This geopavement slab has a high degree of strength and resiliency (Woodward et al., 2011a,b; Kennedy et al., 2013). In order to test the engineering characteristics of the GeoComposite, especially its resulting settlement and stiffness behaviour, it is ideally best to use a railway test rig capable of loading a ballast structure to realistic axle loads and hence stress levels (Kennedy et al., 2009a,b).

The research presented in this paper uses the full-scale GRAFT I (Geopavement and Railways Accelerated Fatigue Testing) facility at Heriot-Watt University to investigate the track stiffness improvement of the XiTRACK polyurethane polymer technique. The paper builds upon the work in Kennedy et al. (2013) where the settlement characteristics of the GeoComposite tests were presented. The results show the track stiffness improvement from the unreinforced control tests to the GeoComposite tests. Since the subgrade stiffness changes during testing an equation is used to determine the equivalent track stiffness of the GeoComposite at different load cycles and conditions. In addition the application of the technology at a very environmentally challenging site (the ballast was flooded by water) is discussed and measurement of the *in situ* track stiffness using the FWD presented. The objective of this part of the paper is to highlight how this type of reinforcement technique can improve the overall *in situ* track stiffness over weak subgrade soils at a real site.

Track stiffness measurement

From the above description of track stiffness a variety of methods can be used and different parameters produced depending on the measurement system. For the purposes of the work presented in this paper the following measurements are briefly described (following on from Eq. (2)):

Vertical track stiffness

The wheel vertical track stiffness is usually defined by the following equation:

$$k_w = \frac{L_w}{\delta} \tag{3}$$

where kw is the track stiffness in relation to the wheel load Lw (i.e. per rail side) and δ is the track deflection. The axle