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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 to 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.

Keywords: Railway track stiffness, polymers, GeoComposite, polyurethane reinforcement, XiTRACK

1 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 [1]. Furthermore, sleeper spacing influences track stiffness with reduced spacing resulting in an increase in track stiffness. Reference [1] 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, [2] found that the track modulus can increase by around 10 to 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 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 [3]. 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 [1,3] 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 [4]. Reference [1] 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 [5-11] (if the track stiffness is low it is likely that the formation soil is weak). It is therefore clear that whatever methodolgy 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 [12].

1.1 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) [13-16]. 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 [14-16]. 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 [17, 18].

The research presented in this paper uses the full-scale GRAFT I (Geopavement & Railway 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 [16] 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.

2 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 Equation 2):

2.1 Vertical track stiffness

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

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

Where, k_w is the track stiffness in relation to the wheel load L_w (i.e. per rail side) and δ is the track deflection. The axle track stiffness can also be represented through the axle load:

$$k_a = \frac{L_a}{\delta} \tag{4}$$

Where, k_a is the track stiffness in relation to the axle load, L_a is the axle load and δ is the track deflection.

2.2 Track modulus

The track modulus u representing the applied force per unit length of the rail per unit deflection can also be used and is given by:

$$u = \frac{k_w^{\frac{4}{3}}}{(64EI)^{\frac{1}{3}}} \tag{5}$$

Where, k_w is the wheel track stiffness (Equation 3) and EI is the rail bending stiffness. Reference [19] suggested that u=28 MPa should be considered a minimum for good track performance (approximately k_w=55 kN/mm). Track modulus values less than 13.7MPa indicate poor track performance, while values between 13.7MPa and 27.5MPa indicate average performance. Very high track modulus values above 137MPa can cause component failure including ballast degradation and sleeper cracking due to increased dynamic loads.

In Europe the wheel vertical track stiffness is often used as the preferred measurement since it allows for increases in track stiffness simply by increasing the rail section; it can also be measured directly through knowledge of the wheel load and track deflection. For high-speed tracks [12] suggested that an optimal value of k_w=70-80 kN/mm could be specified based on an energy cost and energy consumption basis. The optimisation of the vertical stiffness of the track has a favourable effect not only on the reduction in the vertical stresses exerted on the track by the vehicles, but also on the reduction in the level of vibrations generated in the ballast layer. However, [1] identified that further research is required to reach a consensus on the optimum track stiffness range for all tracks. It should be noted here that track stiffness and modulus values change when multiple axle loads are in close proximity to each other.

2.3 Track receptance and dynamic sleeper support stiffness

Reference [1] noted that as railway vehicle loading is never static, it is typical to distinguish between quasi-static loading with each axle pass and the dynamic loading due to wheel/rail or other irregularities. For most cases the quasi-static load and unsprung mass of the vehicle are the most important issues [1]. Dynamic track stiffness can be analysed for railway tracks using Fourier transforms and associated transfer functions if the stiffness is assumed to be linear about a certain reference preload. This assumption is approximately valid for a limited portion of the force-deflection diagram. The transfer function between force and displacement is called receptance (α) or dynamic flexibility:

$$\alpha(f) = \frac{z(f)}{F(f)} \tag{6}$$

Receptance is the inverse of dynamic stiffness and is often used in preference. The track stiffness therefore varies with excitation frequency. This can be measured using a quasi static load with a superimposed dynamic load at different vibration frequencies. A Fast Fourier analysis can then be performed and the transfer function between the force and displacement, termed the receptance or dynamic flexibility, can be estimated. Track stiffness in the field can be measured both at standstill at discrete intervals and continuously while rolling along the track. As track stiffness is a function of frequency it is necessary to select an appropriate measuring device depending on the frequency of interest [3]. Static and low frequency measurements of track stiffness (<50Hz) are related to the geotechnical track issues while high frequencies (>50Hz) relate to problems associated with noise and train-track interaction forces. The most important factors that decide the vertical frequency content in the train-track interaction are the train (speed, axle distance etc.), the track receptance and the track irregularities.

In the UK, the track stiffness is measured, as defined in the railway standard [20], by using the ‘Falling Weight Deflectometer’ (FWD) [21,22]. The FWD was originally developed for measurement of pavement/road stiffness but has been adapted for railway applications by replacing the road wheels by rail wheels. It is used to estimate the stiffness of the track structure excluding the rails. The FWD equipment consists of a mass that is dropped from a known height onto a set of rubber buffers mounted on a circular footplate. The resulting impact force is measured by a load cell on the centre of the plate, and geophones are used to measure surface velocity at various distances from the footplate [21]. These velocities are integrated to give vertical displacements. The magnitude of the applied load is measured in the centre of the loading beam and the geophones are positioned on the loaded sleeper and on the ballast as appropriate at various distances from the centre of the beam to produce a deflection basin. The track stiffness is calculated from the load and deflections measured at some of the geophones, depending on the application; a dynamic sleeper support stiffness (K) is calculated with units of kN/mm/sleeper-end. However, the FWD shows a large degree of scatter in the results [21] and as such a high degree of interpretation is required. Reference [20] defines the FWD stiffness measurement as a dynamic sleeper support stiffness and 60kN/mm/sleeper end is a minimum requirement for new track construction. Further interpretation is required here though as the influences of the rail and sleeper spacing are not included.

3 In-situ 3-d polyurethane reinforcement

Reference [23] performed full-scale laboratory studies of planar geogrids placed at the base of the ballast and found that they had no effect of the resilient track deflection (i.e. track stiffness) and very little effect on the formation bearing pressures. The results of the tests are presented in more detail in [24]. Other references about geogrids can be found in [25]. In order to improve the capability of the track structure to support bending stresses the ballast must be capable of supporting compressive, tensile and shear stresses and thus form a 3-dimensional geo-pavement (i.e. a slab). In order to use the ballast as a means of increasing the track stiffness then 3-dimensional ballast reinforcement, in which the ballast can be transformed into a GeoComposite capable of forming this geo-pavement, is therefore highly desirable. An obvious comparison is the application of concrete slab-track (or any kind of relatively rigid foundation) where bending stresses can be transmitted to provide a more rigid support structure. In ballast this can be achieved using in-situ polyurethane polymer-ballast reinforcement.

The polyurethane polymer reinforcement of railway ballast has been described by [13-16, 26]. The resin used is a urethane-cross linked polyurethane (PU) and it is applied to the surface of the ballast through mixing equipment that can apply the two components to form a rapidly-reacting polymer in a controlled distribution across the ballast bed. As the polymer penetrates the ballast (controlled by the catalyst level) it forms a reinforcing cage that allows the track to deflect in a controlled manner while significantly reducing the ballast settlement [16]. A typical application would reduce the void structure by around 26%, which still allows drainage within the ballast to be maintained [14,16]. Typically the polymer cures within 10 to 15 seconds, with around 90% of its stiffness formed within one hour. One of the major benefits of the technique is the ability to reinforce the ballast at any desired level or location and after the track has been placed at its correct track geometry. This allows the technique to ‘capture’ the track geometry through ballast reinforcement. In addition many switch & crossing and transition problems are related to ballast movement rather than formation movement and hence stabilising the ballast [27] will have a very beneficial effect.

4 GRAFT I FACILITY AND TEST CONSTRUCTION

GRAFT I (Figure 1) has been described in detail by [28, 29]. It comprises a track bed within a steel box of dimensions 1.072m wide x 3.0m long x 1.15m high. For the work presented in this paper three half sized hardwood sleepers of 250mm x 125mm x 600mm located at 650mm centres were used and the rail was simulated by a steel section I-beam which has properties similar to a 113lb rail section. Cyclic loading is applied to the centre of the I-section beam using a Losenhausen UPS200 hydraulic testing machine and the box is lined with neoprene to reduce lateral stress. Details about the materials used in the tests presented in this paper can be found in [28, 29]. In summary the ballast was to Network Standard RT/CE/S/006 [30] and was placed to a depth of 300mm with an internal friction angle of 57.1^{o}. Below the ballast was a 750mm deep Kaolin clay subgrade with an upper 70mm formation. It was placed in 5 layers and each layer was compacted using a Kango hammer and the Losenhausen testing machine through a large steel plate. The properties of the tests performed in the facility have been presented in [16, 28, 29]. In this published work the response of the GeoComposite and control tests under continuous cyclic loading at different subgrade modulus values and cyclic loads were presented. However for the purposes of this paper Figure 2 shows a review of all the different subgrade modulus values for the different tests performed during the GRAFT I series for measurement of the track stiffness with cyclic loading and hence settlement (test series CT1 – CT4 is shown). Please note that the geocell test and CT5 modulus values are included in this graph for completeness but their results will be published at a later date. For the GRAFT I tests presented in this paper a loading frequency of 3 Hz was used. The subgrade stiffness was measured through plate loading tests (Figure 3) using the following equation

$$E_{PLT} = \frac{2P(1-\nu^2)}{\pi r \delta} \tag{7}$$

Where, P=plate applied load; r=radius of the plate; ν=Poisson's ratio and δ=plate deflection. The term $E_{PLT(t)}$ is used to refer to the tangent Young's modulus drawn from the initial part of the second load cycle curve to avoid initial setup errors (i.e. plate-surface contact errors).

5 EXPERIMENTAL RESULTS

5.1 Unreinforced ballast tests

Example load-deflection curves at different load cycles for the subgrade modulus in test CT3 are shown in Figure 4 & 5. In Figure 4 the load-deflection data, including the track settlement, is presented. Figure 5 shows a close-up of the instantaneous data to show the shape of the load-deflection curve which are non-linear and show hysteresis; this is typical of most railway track behaviour. This non-linearity is due to the particle re-arrangement during densification. Hence, the stiffness of the track depends heavily on the applied load and when determining the track stiffness it is appropriate to apply a load similar to the maximum axle load for that section of track. Using the secant track stiffness definition in Equation (2), with point a being taken as the minimum applied load and resulting deflection and point b the maximum, the track stiffness and track-bed stiffness for individual cycles throughout the testing programme can be found. It should be noted here though that, as only 10 data points are recorded per cycle (cycling at 3 Hz and data recorded at 30 Hz), it is possible that the absolute maximum and minimum values may not have been recorded exactly. As a result the mean track stiffness and track-bed stiffness value for each test in GRAFT I have been taken from all the applied cycles. The mean track stiffness, track modulus and trackbed stiffness values found for the control tests in GRAFT I are shown in Table 2. It should be noted here though that these values are specific to GRAFT I and not generally exactly equivalent to the field (the load applied in GRAFT I simulates a particular axle load applied in the field through the conversion formula given in [29] due to the half sleeper configuration used). In addition, due to the depth of GRAFT I the track deflection values in GRAFT I underestimate the field. This has been discussed extensively by [28]. However the results clearly show that the track stiffness is increasing with each test. The peak cyclic loads applied are CT1, P (applied load in GRAFT I)=130 kN; CT2, P=90 kN; CT3, P=90 kN and CT4, P=90 kN. Information about each of these tests can be found in [28, 29].

It can be seen that the track stiffness values are around 104% greater on average than the estimated track-bed stiffness values. This is similar to the ratio shown in an example by [1] for a typical track section. This ratio depends on the rail bending stiffness and sleeper spacing. The advantage of estimating the trackbed stiffness in GRAFT I is that the effect on track stiffness of different rail pads can be estimated by determining the series stiffness of the two components as follows (after [1]):

$$\frac{1}{K_{series}} = \frac{1}{K_{railpads}} + \frac{1}{K_{trackbed}} \tag{8}$$

If rail pads with a stiffness of 150MN/m (typical rail pads) were used in GRAFT I then the trackbed stiffness for CT1 (in GRAFT I) would be reduced from 17.7kN/mm/sleeper end to 15.8kN/mm/sleeper end. Table 3 shows the effects that using different types of rail pads would have on the track-bed stiffness measured within GRAFT I for each test. The values highlight that the stiffer the rail pad used the greater the vertical track stiffness, as would be expected. Reference [12] found similar results when investigating the influence of rail pad stiffness on vertical track stiffness on both conventional and high speed lines in France and Germany. Therefore, it can be seen how the rail pads can play an important role when considering the optimum track stiffness for a specific track; [12] stated that if an optimum vertical track stiffness of 75kN/mm is desired with a track-bed stiffness for high speed lines taken as 98kN/mm then the rail pad should have a stiffness of approximately 30-50kN/mm (soft).

5.2 Reinforced ballast tests

Figure 6 shows the GeoComposite specimen under cyclic testing. A typical load-deflection curve found for the test after 10,000 cycles is illustrated in Figure 7. The mean GRAFT I track stiffness found from the LOS actuator displacement readings for the test over the 500,000 applied cycles was 47.1kN/mm/wheel with a mean track modulus value of 25.7MPa. Comparing this value to the stiffness values found for the unreinforced control tests (Table 2 and 3) it can be seen that the GeoComposite improves the track stiffness by around 43% when compared to unreinforced track with the same subgrade modulus as the reinforced test. When taking into account the higher applied load in this reinforced test, the improvement increases to around 55%.

An alternate approach is to use the estimated track stiffness for an unreinforced track which has the same subgrade modulus and applied load as in the reinforced ballast test. In order to do this the GRAFT I settlement model (already published in [16, 28]) can be used to account for the low settlement values measured at the end of the cyclic testing. Hence the equivalent track stiffness based settlement model for axle loads ranging from 25 to 37 tonnes can be written as follows after [28]:

$$y = (1.268(p/k) - 1.447)N^{0.23} \tag{9}$$

where y = settlement after N number of cycles in mm; p is the applied load in kN and k is the track stiffness in kN/mm/wheel. It should be noted here that the $\frac{p}{k}$ ratio equals the track deflection and as an alternative the track deflection could be used directly. The settlement value in Equation 9 was taken from the predicted GRAFT I settlement for unreinforced track after 500,000 cycles (after [28]). The calculation would therefore be:

$$y = (1.268(130/k) - 1.447) \times 500{,}000^{0.23} = 88.4\text{mm}$$

$$\therefore k = 28.6\text{kN/mm/wheel}$$

The equivalent predicted track stiffness for the unreinforced track at the same subgrade modulus as the GeoComposite test is therefore 28.6 kN/mm/wheel which is much lower than the actual measured reinforced track value of 47.1 kN/mm/wheel. Again indicating that the GeoComposite can significantly enhance the track stiffness.

6 EXAMPLE OF IN-SITU TRACK INSTALLATION AND MEASUREMENT

Figure 8 shows a typical cross-section of an in-situ site application to increase the track stiffness over very weak soils. In this example the track construction depth is set at 300mm upper unreinforced ballast, 300mm XiTRACK layer, a permeable geotextile separator and finally a 50mm sand layer (total construction depth is 650mm). This structure was constructed at a site which previously had unreinforced granular material to a depth of 550mm. FWD measurements were taken before and after treatment. Figure 9 shows however that very difficult conditions existed at the site at installation (the track is completely flooded below the sleeper bottom). The weakness of the underlying clay layers was clearly evident; it was observed that rods would easily penetrate the formation layer (simply under their own weight) indicating much lower values of clay strength than the 40 kPa that was assumed. Figure 10 shows application of the polymer, however, Figure 11 shows that water is rising through the ballast during polymer pouring (the polymer application line can be seen in the picture). The presence of water in ballast during application has a significant effect on the penetration of the polymer and hence its distribution within the ballast matrix and hence reinforcing capability. This is highlighted in Figure 12 where polymer is applied to two containers full of ballast, the presence of water (in the two left hand containers) has seriously curtailed the penetration of the polymer into the voids (this is because the polymer has a density that is only slightly higher than that of water).

For the FWD the deflection of the loaded sleeper (D_o parameter) is thought to give the equivalent dynamic track deflection for a passing 25 tonne axle load [20]. However the FWD measurement cannot directly measure the influence of different bogie and axle load configurations as the impulse load is applied to the sleeper and the rails are disconnected. Figure 13 shows the before and after treatment readings using the FWD for the site. The letters A-G refer to different locations on the site, separated by around 10m. For the pre-treatment case two readings appear to be inconsistent with the general trend of the other readings (locations D and F in the figure). Due to the observed scatter in the FWD results an attempt is made to compare the pre and post treatment responses by comparing measurements made at similar locations for both cases. In Figure 13 the solid red line represents a least squares fit to the post-treatment data set. A least squares fit is not provided for the pre-treatment results as there are insufficient sampling points over the area considered to give a meaningful result for comparison since deflections have only been sampled at 10m intervals (i.e. 5x less than post-treatment ones). This means that for the full 70 metres only approximately 7 values were measured pre-treatment; representing 1 value approximately every 15 sleepers; which represents an under sampled data set for accurate comparison purposes.

Table 4 shows that the average reduction in track deflection is 29% if the inconsistent pre-treatment results are included and 36% if the inconsistent pre-treatment (due to under sampling) results are not included in the average reduction calculation. It should be noted that in Figure 13 higher reductions are indicated at some locations, however these are not included in Table 4. It appears that even though the site is under flooding conditions, which would have effected polymer penetration and hence track stiffness improvement (excavation of the treated ballast showed significant polymer penetration issues in some places) a good overall increase in track stiffness is still measured by the FWD over the treatment site. This is consistent with the GRAFT I laboratory tests.

9 CONCLUSIONS

In this paper the results of laboratory testing of an unreinforced and polymer reinforced ballasted track was presented using the GRAFT I test facility to estimate the change in track stiffness with load cycles. In addition a section of real in-situ track was treated using the polymer technique and Falling Weight Deflectometer reading taken before and after installation to assess the change in track stiffness. The following conclusions are obtained:

1. The cyclic laboratory tests using GRAFT I showed a marked increase in track stiffness when the polymer was applied. It is likely that the improvement was around 40% for the particular polymer, loading level and ballast depth applied.

2. The Falling Weight Deflectometer measurements taken before and after treatment at a real site indicated that an increase in track stiffness was achieved and hence the formed Geoomposite load transfer platform (geopavement) can have a positive effect on reducing the track deflection without significant increases in track construction depth. This occurred even though the track suffered from significant water issues during treatment which has a negative impact on polymer penetration.

3. The significant inflow of water during the in-situ site treatment during application demonstrates the need to perform track drainage enhancements at these types of difficult sites prior to any track bed construction bed improvements. Additional laboratory penetration tests confirmed that standing water in the ballast significantly effects polymer penetration.

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

Table 1: Subgrade Kaolin clay parameters [16, 28] from the GRAFT I test data

GRAFT test	Mean Trackbed stiffness (kN/mm/sleeper end)	Mean Track stiffness (kN/mm/wheel)	Mean track modulus (MPa)
CT1	17.7	36.9	19.2
CT2	18.4	38.2	19.5
CT3	23.9	47.0	25.6
CT4	24.8	50.0	27.8

Table 2: Mean trackbed stiffness, track stiffness and track modulus values found in GRAFT I tests

Type of rail pad	Rail pad stiffness (MN/m)	CT1 trackbed stiffness (kN/mm/sleeper end)	CT2 trackbed stiffness (kN/mm/sleeper end)	CT3 trackbed stiffness (kN/mm/sleeper end)	CT4 trackbed stiffness (kN/mm/sleeper end)
Soft	75	14.3	14.8	18.1	18.6
Typical	150	15.8	16.4	20.6	21.3
Stiff	500	17.1	17.8	22.8	23.6

Table 3: The influence different rail pads would have on the trackbed stiffness values found in GRAFT I

	A	B	C	D	E	F	G
Pre-treatment Displacement (mm)	1.0	1.80	2.16	1.99*****	2.31	1.23*****	1.04
Post-treatment Displacement (mm) Using Least Squares Line	0.66	1.12	1.55	1.76	1.63	1.09	0.52
Estimated Reduction in Track Deflection One Week After Renewal With Track Flooded	34%	38%	28%	12%*****	30%	12%*****	50%

Table 4: Estimated reduction in track deflection with track location (measurements taken to the post-treatment least squares fit line)

Figure 1: GRAFT I testing facility in the Losenhausen UPS200

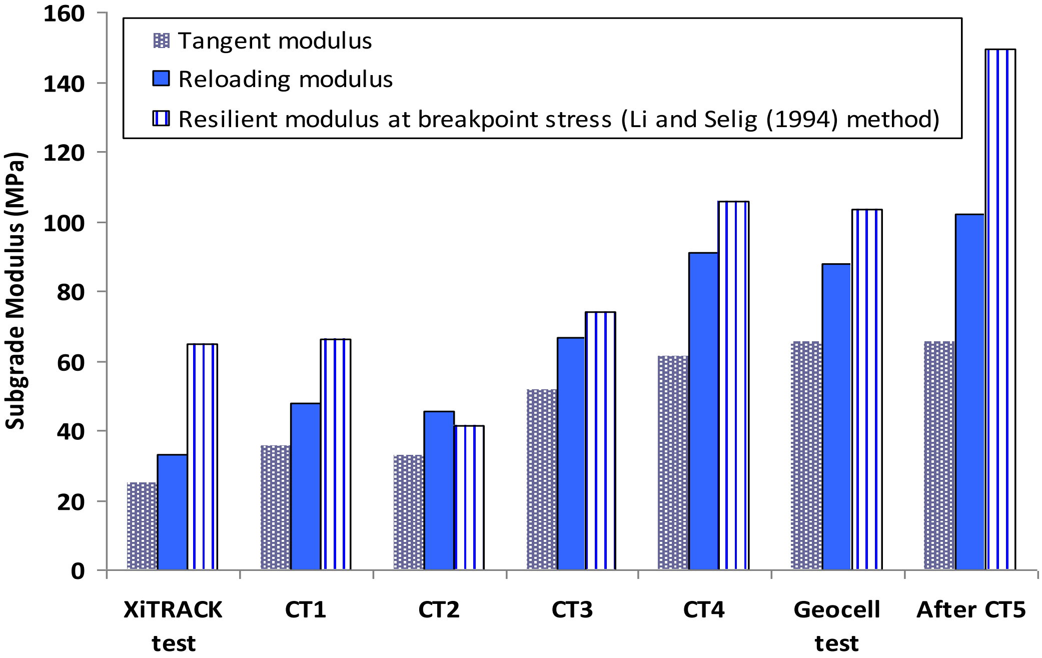

Figure 2: Variation of subgrade modulus throughout the testing programme

Figure 3: Typical plate load test undertaken in GRAFT I

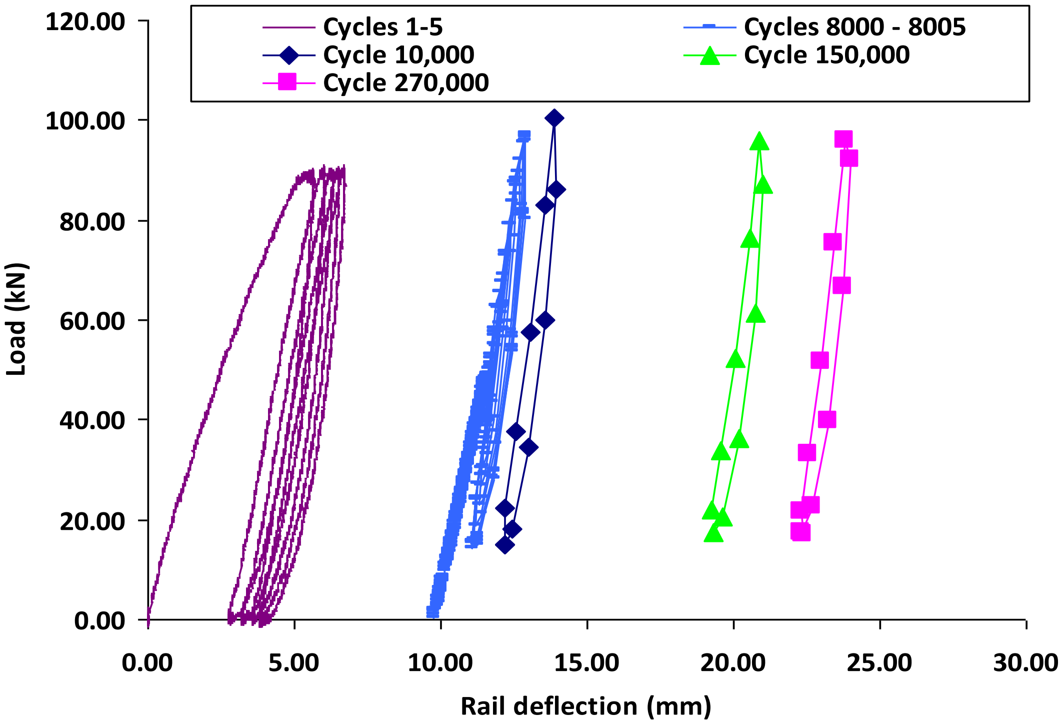

Figure 4: Typical CT3 vertical load-deflection curves measured on rail (deflection data is cumulative with cycles)

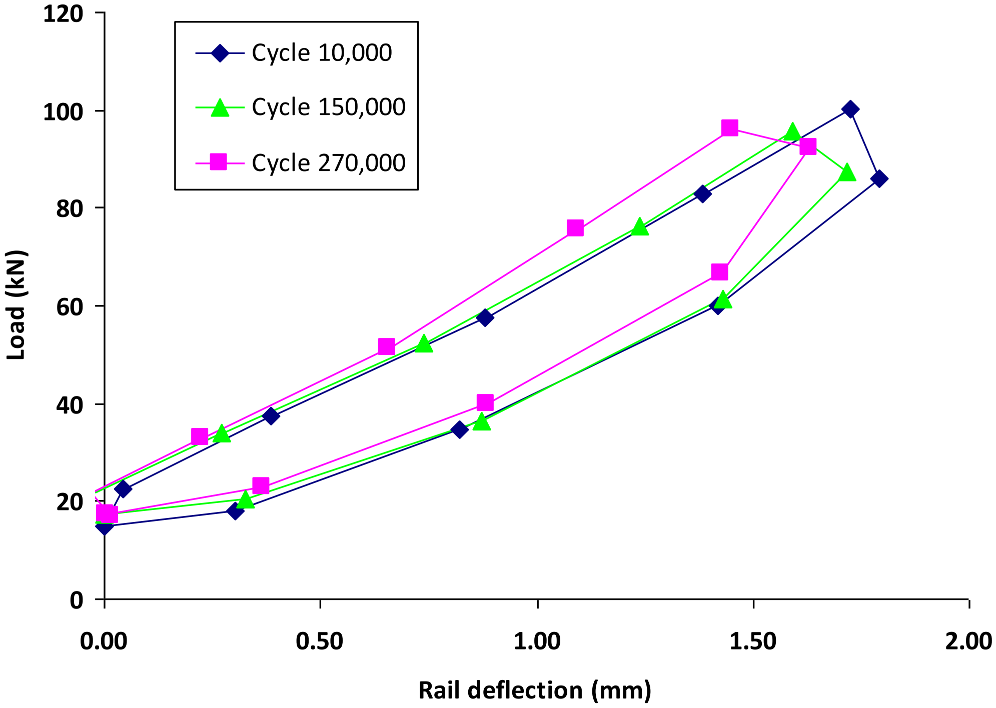

Figure 5: Typical CT3 vertical load-deflection curves measured on rail

Figure 6: GeoComposite under testing in GRAFT I

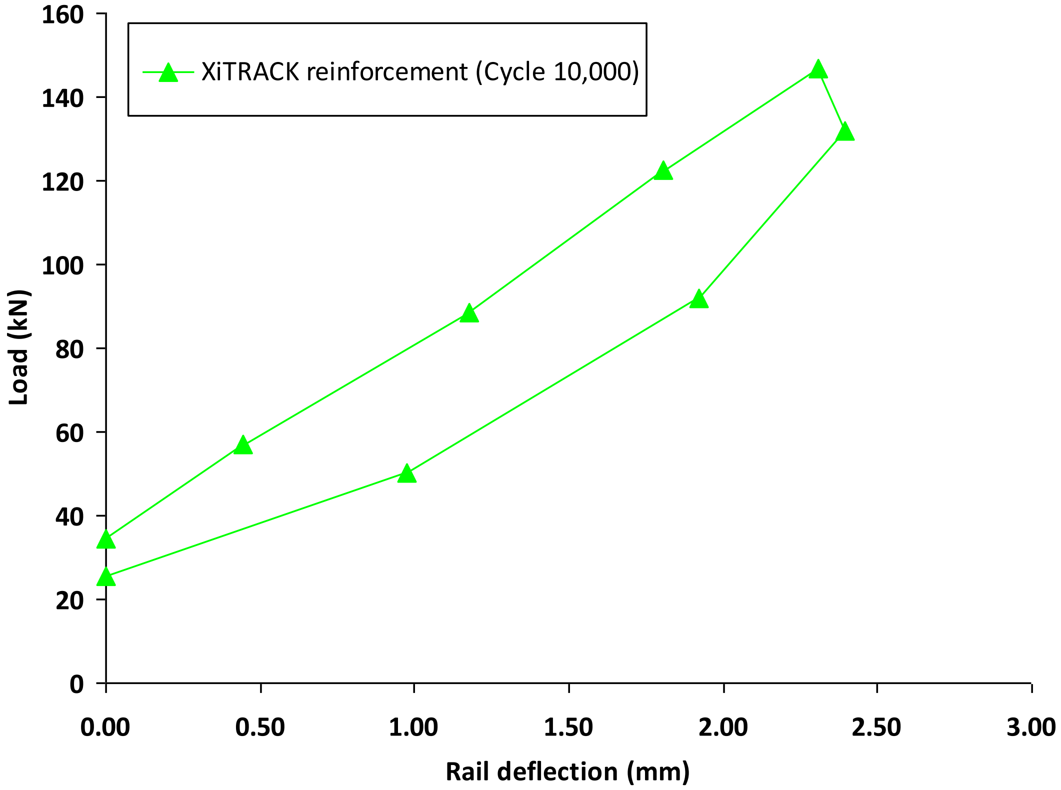

Figure 7: XiTRACK vertical load-deflection curve measured on rail

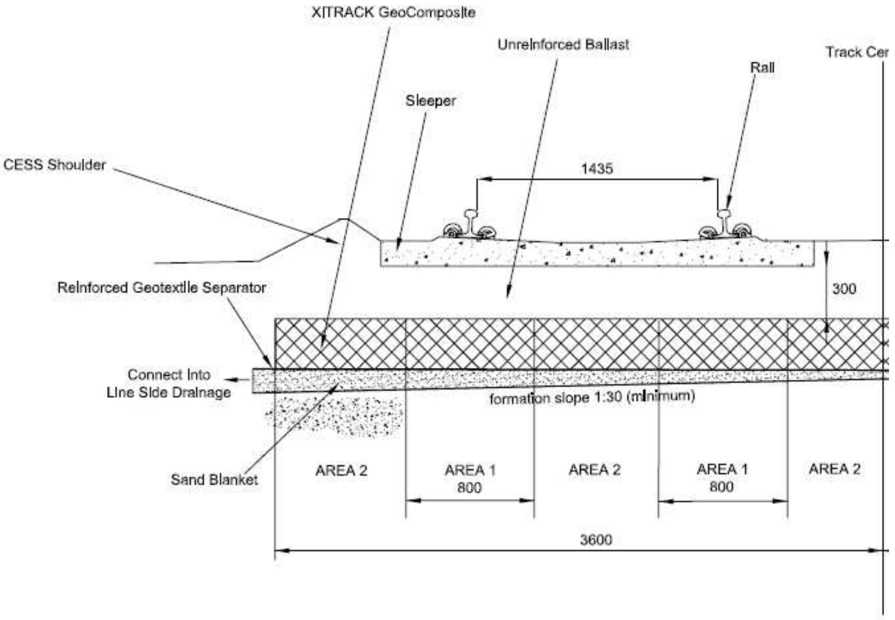

Figure 8: Cross-section of track construction

Figure 9: Application of pumps to try and drain water during installation

Figure 10: Pouring of the polymer at the site

Figure 11: Water rising up through the GeoComposite layer during polymer pouring

Figure 12: Reduction in polymer penetration depth due to ballast flooding

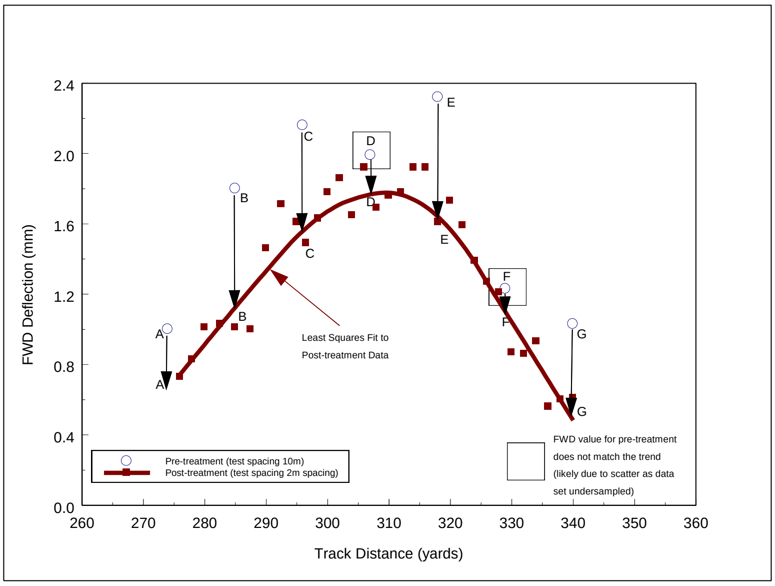

Figure 13: Reduction in FWD track deflection due to GeoComposite installation (using a least squares fit for the post-installation data set values)