METHOD OF STABILIZING PARTICULATES

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Appl. No.: 10/362,034
PCT Filed: Aug. 17, 2001
PCT No.: PCT/GB01/03679

ABSTRACT
Particulates, partially ballast in a railway track, are stabilised by adding a multi component system synthetic material selectively to the ballast in accordance with the results of analysing the results of a site survey with a mathematical model, to produce a structure of stabilised elements in the ballast, with unstabilised parts, to provide required structural reinforcement.
METHOD OF STABILIZING PARTICULATES

[0001] This invention relates to a method of stabilizing particulates.

[0002] It is known from a number of prior proposals to attempt to modify the properties of particulate engineering structures, such as railway ballast, for example to improve stability, by effectively ‘holding’ the stones together. Examples are EP-A-0, 502, 920, EP-A-0, 641, 407 and DE-A-394142 wherein multi-component systems, (MCS) such as epoxy or polyurethane resins are used to bind the particulates together.

[0003] The engineering behaviour of particulate supported structures is modified when MCS are applied. In particular, the engineering strength and stiffness characteristics are increased. Addition of MCS also modifies the dynamic characteristics, modifying properties such as the damping ratio and the speed of the stress shock waves (for example, compressive, shear and surface waves).

[0004] When applying a multi-component system to particulates it is desirable to ensure that the reinforced and stabilised structure performs to an acceptable level during its life cycle. The MCS is preferably applied in the correct spatial position and down to the correct depth to ensure that the desired engineering behavioural improvements are obtained. The MCS is also preferably designed chemically to ensure that its desired properties are correct for the particular application under consideration, for example stiffness, strength, viscosity, fatigue limits, acoustic damping, temperature range, biocidal and hydroscopic properties and curing time. Each particular application of the MCS is likely to be different, since each site application will be different with respect to geometry, surface/subsurface structural conditions and engineering characteristics. Additional additives for the MCS may be required to achieve the desired behaviour and predictability, for example, cement or asphalt based fillers.

[0005] Incorrect application of MCS may lead to premature failure of the modified structure. In very severe cases, this may lead to unplanned responses and/or catastrophic failure.

[0006] It is an object of the invention to provide a method for the treatment of particulate based structures which enables these desirable objectives to be attained.

[0007] According to the invention therefore, there is provided a method of stabilising particulates comprising the steps of:

[0008] a) surveying the surface and substructure of a site using sensing apparatus and combining with any available existing site data;

[0009] b) analysing the results so obtained to determine;

[0010] i) where a multi-component system (MCS) is to be applied;

[0011] ii) the quantities of MCS to be applied;

[0012] iii) properties of the MCS; and

[0013] c) carrying out selective application of MCS to the structure as determined by the analysis.

[0014] Additionally, the method preferably also includes the steps of:

[0015] analysing the load characteristics required, and

[0016] analysing the structure of in-situ particulates.

[0017] The invention also provides a stabilised ballast structure in a railway track made by this method.

[0018] The method may include the additional step of selecting or formulating a suitable, for example polyurethane based, MCS coating material. The method makes possible the adaption of offsite and/or modular creation of components to achieve stabilisation of particulates and surrounding structures.

[0019] MCS may preferably be used to increase the vertical and/or lateral structural stability (eg. stiffness and strength) and needs to be carefully controlled to ensure that the stresses and forces dynamically, transiently or statically are within the fatigue or strength limits of the MCS reinforced structure with a given factor of safety for the desired life cycles under consideration. Using an inappropriate MCS may lead to premature and/or unpredictable failure or undesirable performance deterioration of the reinforced structure.

[0020] Addition of MCS modifies the static and dynamic behaviour of the particulate structure and therefore the whole or partial structural response. The change in the static and dynamic behaviour is related to the particular variant of MCS being applied and to the spatial location and properties of the structure (eg in a railway track application, the rails, ties, cutting, embankment, or in a roadway, the pavement, sidewalk, drainage, road surface and subsurface), ballast, subballast, subgrade etc.). This change needs to be assessed to ensure that it is not detrimental with respect to the static and dynamic behaviour of the applied static and transient loads.

[0021] The development of an MCS membrane or barrier, through inappropriate MCS application, may prevent dissipation of surface and substructure excess pore pressures leading to failure or undesirable performance of the structure. Therefore further design considerations need to be taken into account before MCS is applied, particularly if a desired design objective is the creation of an impermeable interlayer to ensure the desired properties of performance (eg. drainage etc.) are achieved.

[0022] Using MCS to stabilise and reinforce the ‘wet-spot’ areas (ie. areas prone to mud-pumping under load) also needs to be carefully controlled. Addition of MCS creates a change in the static and dynamic interaction behaviour and may create further problems and therefore needs to be assessed.

[0023] Using MCS as a tailored ‘lead-in’ to dynamically differently performing natural or manmade structures such as geological features or bridge decks needs to be assessed to ensure that the modified dynamic characteristics are appropriate. This is to prevent for example additional vibrations being induced, leading to ‘load-bounce’ or return shockwaves.
[0024] Particulates Reinforced and Stabilised by the Treatment Method of the Invention may be used for:—

[0025] Short/long term stabilisation of overstressed structures (eg. mud-pumping and ‘wet-spots’ in railway track);

[0026] Vertical, lateral and longitudinal stabilisation (in railway track for example, of transition curves, super-elevations, junctions/points/crossings and main lines, including high speed lines) for example, to reduce maintenance.

[0027] Stabilisation of particulate structures in tunnels;

[0028] Stabilisation of retaining walls, inclines, taxiways and landing areas;

[0029] Reinforcement of bridge decks including increasing particulate stiffness before and after bridges to prevent loads baulking.

[0030] Reinforcement and stabilisation to ensure tight tolerances are maintained eg. (in rail systems for normal, double-decker and high speed tilting trains and other types of trains.

[0031] Reduce subgrade stresses through increased MCS stiffness and strength properties.

[0032] Reduce subgrade stresses by increasing particulate stiffness to help prevent local pocketing of subgrades.

[0033] Reduce induced particulates plastic strains and attrition, particulate segregation, (eg. through chipping), by reducing particulate movement, reducing the incidence of fouled particulates. Application of MCS membrane (for example at interfaces of different structural materials) to prevent subballast subgrade infiltration.

[0034] Help prevent hydraulic erosion of the surface and substructures.

[0035] Allow for increases in applied loads and speed of transient loads without significantly increasing structural maintenance, and for reducing structurally induced damage due to applied loads.

[0036] Prevent surface movement of the particulates through transient wind forces and through surface waves due to imposed loading.

[0037] Reduction of ambient noise generation and transmission. Allow power washing of the reinforced structures to retain cleanliness at reduced cost.

[0038] Improve the static and dynamic performance of the structure.

[0039] Some examples of procedures for stabilising ballast, and of the resulting stabilised ballast structures in accordance with the invention will now be described by way of example with reference to the accompanying drawings, wherein:

[0040] FIG. 1 is a diagram of a track assembly including ballast and subgrade, to illustrate the terms and general track features used in the following description;

[0041] FIGS. 2 and 2a are respectively transverse and longitudinal (in the running direction) and cross sectional views of a first embodiment of track structure according to the invention;

[0042] FIGS. 3a and 3b to FIGS. 10a and 10b are similar respective transverse and longitudinal cross-sectional views of further embodiments of track structures according to the invention;

[0043] FIG. 11 is a view showing applications of ballast with MCS to a rail bed, FIG. 12 is a longitudinal section of a bridge deck installation; and

[0044] FIG. 13 is a flow diagram of the evaluation method used in particular case.

[0045] A diagram of a simplified track structure as shown in FIG. 1. This comprises spaced apart rails 10 extending parallel in the running direction of the track, supported on ties 11 which rest on a ballast layer 12. This in turn is carried by a layer 13 of sub ballast which rests upon subgrade 14. Subgrade 14 may comprise any natural or engineered terrain such as an embankment, the floor of a cutting, or a bridge or viaduct deck. In the following figures, sections are taken transversely across the track structure on the line X-X of FIG. 1 and longitudinally in the running directions on the line Y-Y of FIG. 1.

[0046] FIGS. 2a and 2b relate to stabilisation of points, crossing and other similar types of structures which are often subjected to lateral loading due to train inertia forces. Conventional stabilisation methods include the addition of plates at the end of the tie and/or the formation of a running beam adjacent to the ties. Both of these methods rely on increases in passive resistance, but often do not perform satisfactorily due to progressive plastic movement of the shoulder ballast. The technique used to overcome this problem (in this design example) is the Crib Tie-back Method (CTBM). In this technique, a polymer ballast composite beam (15) is constructed adjacent to the ties to help prevent the ties 11 from moving laterally as before. However, the beam (15) is now tied-back into the cribs using the polymer ballast composite anchors (16) which extend across the track generally between and below ties (11). The force required to restrain the crib anchors (16) is provided by the weight of the train. Therefore the technique makes use of the train’s own weight to restrain the beam (15) against permanent lateral movement (in addition to the frictional resistance under the ties). The width of the anchorage may or may not cover the full width and/or depth of the crib area depending on the level of anchoring force required.

[0047] The composition of the polymer is selected based on the required stiffness and strength properties required of the composite. In particular, the tensile strength and shear strength properties of the polymer are determined as part of the design process.

[0048] FIGS. 3a and 3b show a structure to stabilise the vertical movement of ties to problems involving poor formations, or in switch areas prone to high vertical rail forces, a conventional ‘ladder type’ of design is used. In this design only the ballast below the tie bottom is stabilised as shown in FIGS. 3a and 3b. The ladder comprises a beam 17, 18 extending along the sides of the ballast, and a plurality of cross-beams 19 extending across the track between the beams 17, 18, and between the ties 11. All the beams 17, 18 and cross-beams 19 are below the level of the ties and utilize the full depth of the ballast layer, and are formed of polymer stabilised the ladder design (Type 1 stabilisation) can only be used when the depth of the ballast 12 is sufficient to allow
frictional locking of the unstabilised ballast under the tie (i.e. the frictional properties of the unstabilised ballast are used to 'lock' the unstabilised ballast into the adjacent crib stabilised/reinforced ballast). In poor formation areas the polymer properties (for example polymer stiffness) are designed to ensure that an efficient 'pad' type of ballast stabilised foundation is constructed over the weak area. If the polymer stiffness is high enough, then a more even distribution of stress at the subgrade interface is produced. For high maintenance switches the polymer properties are selected to ensure that the large vertical forces are more efficiently distributed under the switch, but still retaining good composite damping properties.

[0049] FIGS. 4a and 4b show a type 2 design for poor formations and high maintenance switches wherein the ballast depth is not sufficient to ensure that the unstabilised ballast under the tie is locked into the stabilised crib ballast (or vertical track forces are too large). Movement and penetration of the ballast under the tie into the formation is therefore possible. Lifting of the tie to stabilise the ballast directly under the tie is possible (this would require a separate design), but often undesired as it has a detrimental affect on the track alignment. In this design holes 20 are drilled into the ties 11 at various locations to allow polymer to be poured/injected into the underlying ballast and fully/partially stabilise it as shown in FIGS. 4a and 4b producing in addition to the 'ladder' construction of FIGS. 3a, 3b comprising parallel side beams 17, 18 and cross beams 19 below and between the ties 11, a plurality of anchoring pillars 21 below the ties.

[0050] In the design of FIGS. 5a and 5b for wet-spot stabilisation it is assumed that the ballast 13 is heavily fouled due to subgrade infiltration (mud-pumping) and must be replaced prior to polymer treatment. The replaced ballast 12 is then stabilised using the polymer producing a stabilised layer 22. The polymer is also designed to enable it to ‘pool’ at the ballast/subballast interface forming an integral polymer membrane 23. The membrane stops subgrade infiltration, but should only be applied if confidence in the capability of the drainage layer is high. The depth of stabilised ballast (from the ballast/subballast interface) may extend up to the base of the tie if considered appropriate but is shown with a layer of unstabilised ballast 12.

[0051] FIGS. 6a and 6b show a design wherein the polymer is used to ensure that track lateral tolerances are within specified limits. For example, this design would be used to ensure that track clearances in tunnels and at track platforms are within the correct limits. The depth of polymer application is generally set from the surface of the tie top level to below the tie bottom, as shown in FIGS. 6a and 6b. It is generally not necessary to stabilise all of the crib areas, however this depends upon the level of loading and longevity required. The polymer stiffness is usually set high to ensure that the composite stiffness remains high (ensuring low composite displacements). As shown, this produces side beams 24 of stabilised ballast up to the upper surface of the ties and cross beams 25 between alternate pairs of ties 11.

[0052] As shown in FIGS. 7a and 7b, polymer is used to provide a continuous stabilised blanket 26 on the ballast surface around the ties 11 as shown in FIG. 7. The purpose of this blanket 26 is to stabilise the ballast surface only (although the blanket depth may extend below the ties if a high degree of stabilisation is required).

[0053] The blanket 26 is used to provide ballast stability against train generated wind forces, loss of compaction due to ballast vibration and other detrimental problems like vandalism. For the vibration problems, the polymer stiffness is generally set low to increase the damping properties of the polymer. The vibration may originate from many sources including ground waves generated by high-speed trains (these can become high on embankment structures or railway track over weak foundations) or by excessive vibration of other track structures, such as bridge decks vibrating at their characteristic frequencies.

[0054] FIGS. 8a and 8b show an embodiment for stabilisation of cyclic-top. Cyclic-top problems generally originate from track misalignment problems or from dynamic motion of the locomotive and/or carriages. For example, a wet-spot site may generate oscillations in the train suspension system causing a sinusoidal type of motion, giving rise to changes in the dynamic forces on the rail with track length. This sinusoidal motion gives rise to permanent movement of the ballast at given wavelengths. Cyclic top can also originate from problems like an uneven subgrade. The design for this type of problem is based on the formation of two polymer/ballast composite ‘running beams’ 27, 28 that encompass the area of concern. The beams can be continuous (as shown in FIG. 8) or may make use of the ballast locking mechanism comprising cross beams 29 under the ties as described in Examples 2 & 3 above. On straight track lateral movement may not be significant and hence stabilising the crib ballast is only necessary at certain crib locations (for example, every third of fourth crib).

[0055] The purpose of these crib stabilisations is to ensure that the beams 27, 28 remain laterally connected. Since this type of stabilisation is generally for long track lengths, the polymer properties are selected based on the varying formation properties. For example, a uniform track modulus value may be selected as the design criteria in the determination of polymer stiffness.

[0056] Finally FIGS. 9a and 9b show an arrangement of stabilised ballast for stabilisation of curves on embankments. The design proposed in FIGS. 2a and 2b for increasing the lateral stability of railway track may not be sufficient (generally the shoulder passive resistance is lower than for track not situated on embankments). In these situations a ‘ballast key’ 30 may be required to increase the lateral stability. This ballast key 30 (or keys) extends beyond the normal depth of stabilisation and is used to increase the passive resistance of the stabilised track as shown in FIGS. 9a and 9b. The ballast keys may be formed from stabilised ballast as shown in FIGS. 9a and 9b, or they may be formed from another type of material that can be used to provide an additional anchor force (such as steel soil nails). The polymer properties are selected based on the criteria discussed in Example 1. The entire upper part of the ballast 31 defining the camber of the curve is stabilised by adding polymer. The ballast keys 30 extend longitudinally of the track below the rails.

[0057] Stabilised beams 31 may be applied at both sides of the ties 11 to resist trains that are both faster and slower than the design track curve speed. Complete embankment stabilisation can be achieved (perhaps for ‘weak embankments’) by using a soil nailing technique to increase embankment...
strength and stiffness in combination with the polymer stabilisation technique to increase lateral (and vertical if necessary) track stability.

[0058] FIGS. 10a and 10b show an arrangement for mainline ballast maintenance reducitivity. It is generally accepted that when constructing new railway track the maintenance of the track can be reduced by ensuring that the subgrade surface is shaped so that it is parallel to the rail. This helps to prevent problems like ballast memory, in which the ballast surface (ie. at tie level) takes the same shape as the uneven subgrade surface. When constructing the new line, at the point of ballast placement on the track, the polymer can be applied to ensure that a given ballast layer 32 remains parallel to the rail. This ballast layer 32 is applied at a specified level and extent within the ballast, depending on the design and longevity required as shown in FIGS. 10a and 10b. This type of approach helps to prevent ballast pocketing and hence reduces the likelihood of track irregularities.

[0059] When upgrading existing track the same technique can also be applied to increase upgraded track longevity for uneven/even subgrades. During the ballast cleaning/renewal process the polymer can be applied in a similar way to that described for the new track. The polymer is again used to form a lower composite ballast layer that is parallel to the rail. The design would be based on (for example) stabilising the ballast from its mid-point down to the uneven subballast/ subgrade interface. Not stabilising the upper ballast layer allows for normal tamping operations. As with the new track design, the polymer properties and loading would be matched to the subgrade and to the level of loading required, through design based criterion like the track modulus value. FIG. 11 shows a typical application of the polymer to form a composite lower surface ballast layer 32 during a ballast cleaning operation with an uneven subballast and/or subgrade layer. Since this technique would be applied to long lengths of track the polymer properties would need to change to match the changing track properties. It is therefore likely that techniques such as ground penetrating radar would be required to examine the sub-surface profile along the track. A divided choice ballast layer 33 is used to place a first layer of ballast in front of an application nozzle 34, and then a further layer of untreated ballast 12 above the stabilised ballast layer 32.

[0060] The designed polymer stabilisation technique can be used to form transition zones to allow a more uniform change in track modulus at sudden changes in track stiffness. For example, the polymer/ballast composite maybe used to form a transition zone from a relatively weak embankment structure to a stiff concrete bridge deck. The design would encompass the spatial location of the polymer, for example a tailored lower level stabilisation leading up to the bridge, in combination with desired changes in polymer properties. By varying the overall stabilised ballast properties changes in ballast shear wave and track velocities can be achieved to modify track dynamics. The purpose of the transition zone is to help reduce problems like "train-bounce", which arise from sudden changes in track stiffness. The complex interference patterns generated when train approach solid structures, due to track ground waves, can increase ballast maintenance. A designed based ballast stabilisation treatment can reduce maintenance requirements in these areas. An example of a tailored lead-in and lead-off ballast stabilised concrete bridge deck is shown in FIG. 12. In this design example the polymer stiffness and spatial location increase as the railway track approaches the bridge deck (and vice versa for the bridge) to allow a smoother transition from the embankment to the bridge. On the bridge deck the polymer stiffness is reduced and its damping properties increased to reduce vibration problems (and ballast attrition). In these designs it maybe desirable to introduce rubber pads, or other types of energy absorbing systems, below the tie to allow a more flexible tie foundation base if considered appropriate. The bridge deck 35 is covered by a full depth layer of stabilised ballast 36, which is sloped at each side of the deck, whilst a partial layer of stabilised ballast 37 is provided to either side of the bridge leading to and from the sloped end of layers 36.

[0061] The transition zones maybe form d by either increasing the slope of stabilised ballast, as in FIG. 12, or by using a stepped arrangement. An example of the application of the method illustrated by the flowchart of FIG. 10 is the stabilisation of a set of points over which axle loads of 25 T at 110 mph regularly pass. This section of the line is rated at 35 Million Gross Tonnes (MGT) and the points are used to divert freight trains onto a turn-out to a marshalling yard. Lateral movement of the rail at the points (situated on ballasted track), measured by on-line train instrumentation, is in the order of 15-25 mm depending on the actual axle weight and speed at the instant of loading. Maintenance of the points is usually performed at 6-8 monthly intervals (often the points are re-aligned). Site investigations reveal that the ballast is of a dolerite basalt type with a type Ds of 28 mm. The ballast depth is between 300-400 mm, with a subballast layer between 120-150 mm overlaid a silty-clay subgrade, within a slight depression. CBR readings and cone-penetrometer readings of the subgrade indicate stiffness values of 100-120 MPa. Poisson’s ratio for this type of material is 0.4 with shear strength coefficients of c=4 kPa and \( \phi' = 29^\circ \). In situ density readings indicated bulk unit weights around 18 kN/m^2. The surface subsurface layering is known and so ground penetrating radar is not considered necessary.

[0062] The subgrade shear-wave velocity is calculated to be around 150 m/s. At 110 mph the maximum train speed is 49 m/s. The development of a transverse seismic state is therefore not expected at current train speeds (the train speed is less than 60% of the ground shearwave velocity). Track critical velocities are also outside current train speed limits. Therefore, this example primarily concentrates on the static analysis of the track.

[0063] The ballast and subballast stiffness values are around 200 MPa and 120 MPa, with purely frictional strengths of \( \phi' = 46^\circ \) and \( \phi' = 38^\circ \) respectively. The void ratio of the ballast is around 0.72 with a unit weight of 16 kN/m^2). The rail (E=210 Gpa, \( \rho=7850 \) kg/m^3) and rail pads (E=200 MN/m) are standard UK main line with bolt plate fasteners onto wooden ties of 2.6 m in length, 0.14 m in depth and 0.26 m in width. The average distance between the ties is 0.38m. No signs of mud-pumping is evident, wet-spot formation at this particular site is not considered to be significant. This is confirmed by observed well maintenance track drainage. Ballast contamination, due to over-pressed ballast, is evident. This has resulted from the development of large lateral forces as freight trains are diverted onto the turn-out. Calculation of the expected vertical and lateral
train forces (using standard procedures, for example the procedures laid out in UK and American Railway Engineering Association (AREA) guidelines) suggest dynamic amplification factors of 1.5–2× the static axle loads vertically at 100–110 mph and 1.2× the static axle loads horizontally at the turn-out at 15 mph. These values are used in combination with the site investigation material parameters as input to a static mathematical, model, based on the finite element method.

[0064] The static mathematical model used is the DIANA finite element program, which is generally available and represents the current state of the art in terms of commercially available finite element programs. The 3-dimensional finite element mesh comprises 2100 elements of the following types, 3-noded Class III Beam elements and 20-noded isoparametric brick element. A full integration scheme is used and boundary conditions are smooth in the appropriate vertical directions and fixed at the base. The mesh is split into several layers to simulate the different ballast, subballast and subgrade depths. Modifying the ballast material properties as appropriate to their spatial location simulates variations in the ballast densities. The rails, fasteners and ties are assumed to behave elastically. The ballast, subballast and subgrade are assumed to behave non-linearly and are modelled using an elasto-plastics Mohr-Coulomb constitutive soil model using a non associative plastic flow material. Material dilation for the ballast and sub-ballast are assumed, based on the critical state friction angles for the two materials.

[0065] Locomotive configurations for the determination of train loading cases include, CLASS 87 (for example, wheel diameter=1.150 m, wheel to wheel centres 3.28 m, bogie distance=0.97 m, axle weight=202 T×2 T unsprung), CLASS 86/4 and CLASS 253/254 HST. Freight loading cases include 100 tonne GLW Tank Wagon Class B (for example, wheel diameter=0.95 m, wheel to wheel centres=2.0 m, bogie distance=13 m, axle weight=25 T). An additional multiplication factor of 1.5 is used to simulate increases in the dynamic load factor for wheel flats.

[0066] The mathematical model is first used to verify the current lateral displacement values (between 10–25 mm lateral deflection depending on applied lateral force). Once the measured displacement values are simulated the finite element model is considered calibrated and various designs are investigated and analysed to determine the optimum design for the added polymer composite. To determine properties of the required designed polymer an iterative process is used in combination with the new engineered track design. The required performance is set at 5 mm lateral deflection under lateral train loading.

[0067] The actual design used for this site stabilisation is a tie back design (several designs are investigated and their performance assessed with respect to the performance assessed with respect to the performance target set). In this particular case, a composite edge beam is tied-back into the cribs using the polymer composite (the tie-backs are below the tie base). The polymer stiffness was used is E=500 MPa and the ballast loading was 10% by ballast mass. This design shows that a significant increase in lateral stability is achieved, when compared to an ordinary edge beam type stabilisation. The simulated modelling shows increases in lateral stability for this case particular case, of approximately 6 times greater than the ordinary unstabilised ballast and 4 times greater than edge beam only type of stabilisation under train loading conditions imposed. The results of the mathematical model are closely studied in terms of stresses, strains, displacements etc. to ensure that these quantities are within the acceptable fatigue limits for the composite/polymer chosen. The mathematical model is also used to investigate areas of possible plastic deformation, giving raise to permanent plastic movement, and to enable the design to be modified if necessary and factors of safety calculated.

[0068] To obtain the optimum polymer loading for the designed stiffness and cyclic properties of the composite laboratory tests were performed. The results of these laboratory tests are used to estimate the designed life span of the treated site by applying a similar deviatoric stress state as computed by the mathematical model. The tests include, direct shear box testing, triaxial compression testing (monotonic and cyclic) and cyclic boundary value tests, i.e. three-dimensional box tests. The results of the direct-shear testing (dimensions of 300 mm×300 mm) indicated that the unreinforced (unstabilised) ballast for particular case of polymer loading has shear strength coefficients of $c_{\text{u}}=0$ kPa and $\phi'=46^\circ$. Addition of the polymer at 10% loading (by ballast mass) to the ballast increases the shear strength coefficients to $c_{\text{u}}=0$ kPa and $\phi'=46^\circ$, showing a considerable increase in strength. These values were confirmed by the unconfined triaxial compression tests. The cyclic properties of the reinforced ballast were also tested. In the first of these tests a reinforced unconfined cyclic triaxial compression test at the simulated peak computer simulated deviatoric stress state was tested. The results showed an accumulated plastic strain of 0.4% at a peak cyclic deviatoric stress state of 384 kPa (as computed by the mathematical program) after 20,000 load cycles. A second sample was cyclic at a peak load of 768 kPa (factor of safety of 2× on internal stress-state). Again around 0.4% accumulated plastic strains were recorded.

[0069] In a simulated boundary value test (traditional three dimensional box-type of test for railway ballast) 2.66 million cycles at design loading conditions were applied to the surface of stabilised ballast (through loading cap) to obtain the required MGT value for 10 years loading on the WCML. The stabilised ballast experienced around 1.0 mm plastic deformation. Typical results for unreinforced cyclic ballast tests at this level of loading are generally available in the literature and indicate values of accumulated displacement between 3040 mm. The behaviour of the designed reinforced ballast is therefore far superior to the unreinforced ballast in both strength and cyclic properties. No evidence of ballast attrition was observed.

[0070] Based on the results of the laboratory tests and the mathematical modelling a modification to the design is made to reduce stress concentrations at the tie ends. The design is therefore an iterative process, taking into account the results of the of the mathematical modelling and laboratory tests, in combination with the expected loading conditions and required performance criteria, to arrive at an optimum design for this set of points to ensure all the design criteria (displacements, strains and stresses etc.) are within tolerable limits. The final composite design therefore satisfies the overall designed life-span performance criteria for lateral displacements limit of 5 mm for 10 years on the West Coast Main Line. This process therefore gives a complete design procedure and predictive capability for modified polymer stabilised railway track. To date, post-treatment performance monitoring by the local maintenance contractor has shown that the treated site has performed as per the design.
In this example a complete dynamic analysis is not necessary as subgrade and track critical velocities are significantly higher than the current train speeds. However, if the subgrade stiffness is lower (or any other special track circumstances/conditions are observed, for example significant track irregularities leading to large dynamic track forces) an additional design step to the above example is necessary. To enable a full dynamic design and analysis of railway track, and subsequently treated polymer railway track, a three-dimensional dynamic finite element program is used. The program allows the user to examine the change in the track behaviour with polymer application and represents a sophisticated design tool for track engineers. Examples of suitable MCS compositions are set out below. The exact proportions of ingredients, and even the disiocyanates and polyols in polyurethane used may be varied along with the physical properties such as viscosity, as determined by the results of the analysis process set out above.

**EXAMPLE 1**

**Application to Railway Track**

**[0072]** A ballast layer comprises an aggregate of crushed limestone of mean dimension 40 mm, and this is bound to a depth of 300 mm between the ties and rails of the track.

**[0073]** The MCS comprises for example a polyurethane having the following composition mixed using a Graco Hyrocot (Trade Mark) based machine, and is poured onto the ballast which is pre-laid to a depth of 300 mm. The foundation for this 300 mm layer of ballast is a sand carpet. The design may require an excess of polymer seeping through the ballast to create a barrier against upward movement of the sand or subgrade layer.

**[0074]** The polyurethane comprises the following two components, which are maintained separate prior to pouring, then mixed and poured together.

**[0075]** **Component A (Polyol)**

<table>
<thead>
<tr>
<th>Component</th>
<th>Weight Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Castor oil</td>
<td>49.25%</td>
</tr>
<tr>
<td>Sorbitol based polyether</td>
<td>28%</td>
</tr>
<tr>
<td>Polyether Diol</td>
<td>4%</td>
</tr>
<tr>
<td>Methyl Naphthalene (VYCEL U (TM))</td>
<td>12%</td>
</tr>
<tr>
<td>Tri (2-Chloro-2-propyl) phosphate</td>
<td>5%</td>
</tr>
<tr>
<td>Sodium Aluminum Silicate (Zeolite (TM))</td>
<td>1%</td>
</tr>
<tr>
<td>Phenyl mercuric fatty acid ester (Thorcat 535 (TM))</td>
<td>0.5%</td>
</tr>
<tr>
<td>Dialkyl tin mercaptide (Fomrez UL22 (TM))</td>
<td>0.3%</td>
</tr>
</tbody>
</table>

**[0076]** **Component B (isocyanate)**

<table>
<thead>
<tr>
<th>Component</th>
<th>Weight Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polymeric dimethylene diphenyl diisocyanate (MDI)</td>
<td>100%</td>
</tr>
</tbody>
</table>

The mix ratio of the two components is:

Component A - 100 parts
Component B - 50 parts

**[0077]** The composition, including ballast at 5% level gives the following mechanical properties:

**[0078]** Bulk density—1.55 g/cc

**[0079]** Compressive modulus—100-800

**EXAMPLE 2**

**Application to a Railway Track**

**[0080]** A 10%, loaded rail ballast is prepared using a polyurethane/bitumen composition. The isocyanate terminated pre-polymer is added to a cationic bitumen in the following preparations:

<table>
<thead>
<tr>
<th>Components</th>
<th>Weight Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyether based FR emulifiable pre-polymer</td>
<td>20 ppw</td>
</tr>
<tr>
<td>60% Cationic bitumen emulsion</td>
<td>100 ppw</td>
</tr>
<tr>
<td>The pre-polymer is based on the following:</td>
<td></td>
</tr>
<tr>
<td>PPG diol 2000 m.w.</td>
<td>100 ppw</td>
</tr>
<tr>
<td>EID 9086</td>
<td>35 ppw</td>
</tr>
<tr>
<td>Amgard TMCP (TM)</td>
<td>30 ppw</td>
</tr>
<tr>
<td>Vycel-U</td>
<td>5 ppw</td>
</tr>
</tbody>
</table>

**[0081]** The pre-polymer/bitumen composition is sprayed onto the ballast at a rate to ensure 10% loading.

**[0082]** The composition cures in two hours, and provides an elastic solid whose compressive strength at 10% yield is 50 MPa at 15° C.

**[0083]** Other curing systems for polyurethane prepolymer include the use of alkaline agents such as sodium silicate solution, calcium hydroxide and magnesium hydroxide and magnesium hydroxide slurries as well as other organic polymer emulsions. These mixtures can be used similarly to bind a particulate material such as ballast to produce a strong supporting composite. The pressure, composition and amount and location to be sprayed or otherwise applied to the ballast layer is determined by mathematical modelling of the stress effects from different trains speeds and loading to determine the polymer-ballast composite required to yield a predicted lifetime of acceptable performance. Clearly, traffic comprising a high incidence of heavy locomotives with loaded mineral trains will exert different stresses to relatively light but fast HST units, or infrequent slower and lighter multiple passenger units.

**[0084]** The polymer formulation enables the ballast to be wetted out and subsequently allowed to set a tough composite in place on the track bed, which provides long term load and vibration management of the track.

1. A method of stabilising particulates at a site comprising the steps of:
   a) surveying conditions at the site, including surface and substructure of the site, using sensing apparatus;
   b) analysing results so obtained to determine:
      I) where a multi-component system (MCS) composition is to be applied;
      II) quantities of the MCS composition to be used;
      III) properties of the MCS composition required; and
   c) carrying out selective applications of the MCS composition to the particulates at the site as determined in step (b) above.

2. A method according to claim 1 comprising the further steps of:
   a) analysing load characteristics required at the site; and
   b) analysing a structure of particulates at the site.
3. A method according to claim 2 comprising the further step of selecting a suitable MCS coating material.

4. A method according to claim 1 wherein the MCS composition is selectively applied to a ballast in a railway installation to provide a structure of stabilised ballast, whereby parts of the ballast are stabilised and other parts thereof are left untreated by the MCS composition.

5. A method according to claim 2 wherein the MCS composition is selectively applied to a ballast in a railway installation to provide a structure of stabilised ballast, whereby parts of the ballast are stabilised and other parts thereof are left untreated by the MCS composition.

6. A method according to claim 3 wherein the MCS coating material is selectively applied to a ballast in a railway installation to provide a structure of stabilised ballast, whereby parts of the ballast are stabilised and other parts are left untreated by the MCS coating material.

7. A method according to claim 4 wherein the MCS composition comprises a polyurethane based resin system which is used to bond and thereby stabilise stones in a bed of railway ballast.

8. A method according to claim 5 wherein the MCS composition comprises a polyurethane based resin system which is used to bond and thereby stabilise stones in a bed of railway ballast.

9. A method according to claim 6 wherein the MCS coating material comprises a polyurethane based resin system which is used to bond and thereby stabilise stones in a bed of railway ballast.

10. A structure comprising a ballast bed in a railway track wherein a ballast is selectively treated with a multi-component system to stabilise parts of the ballast and leave other parts untreated, so that stabilised parts of the ballast constitute reinforcing elements for the ballast bed.

11. A structure according to claim 10 wherein said stabilised parts of the ballast comprise elements extending longitudinally of the track, outside of ties, and further elements extending transversely of the track, below and between the ties.

12. A structure according to claim 10 wherein the multi-component system comprises a single component organic polymer or polymer precursor which can be poured onto the ballast and cured by reaction with atmosphere moisture or oxygen, by evaporation, by post application of a curing agent treatment with irradiation, or by application as a provider and melting onto the ballast.

13. A structure according to claim 11 wherein the multi-component system comprises a single component organic polymer or polymer precursor which can be poured onto the ballast and cured by reaction with atmosphere moisture or oxygen, by evaporation, by post application of a curing agent treatment with irradiation, or by application as a provider and melting onto the ballast.

14. A structure according to claim 12 wherein the multi-component system comprises two or more components which are pre-blended prior to pouring into the ballast.

15. A structure according to claim 13 wherein the multi-component system comprises two or more components which are pre-blended prior to pouring into the ballast.

16. A structure according to claim 12 wherein the polymer is mixed with the ballast before placing on the ballast bed and curing of the polymer.

17. A structure according to claim 13 wherein the polymer is mixed with the ballast before placing on the ballast bed and curing of the polymer.

18. A structure according to claim 14 wherein the polymer is mixed with the ballast before placing on the ballast bed and curing of the polymer.

19. A structure according to claim 15 wherein the polymer is mixed with the ballast before placing on the ballast bed and curing of the polymer.

20. A structure according to claim 10 wherein the structure is provided by the method of claim 1.

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