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In situ and laboratory investigation of dynamic performance of a cement-stabilised Chalk trial embankment

Etude in situ et en laboratoire de la performance dynamique d'un remblais d'essai de craie stabilisé au ciment

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ABSTRACT: Use of stabilised soils in the construction of high-speed rail embankments is a desirable engineering solution as more site-won soils may be used locally thus reducing the volume and mass haul of imported and site-won materials. In the south of contract area C23, significant volumes of weathered structureless chalk will become available due to the construction of cuttings. However, presently there is little data available in the public domain to characterise the dynamic performance of a cement-stabilised chalk for use as high-speed rail embankment fill material. This paper presents the results of a field trial comprising in situ and laboratory testing of a large embankment constructed from three different chalk-cement mixes. By controlling pulverisation, stabilisation, and compaction procedures during construction, the observed variability of material grading, air voids, and density are presented in relation to the natural variation of the chalk, moisture content, added cement content, and stiffness of the supporting foundation. E_{V2} modulus values are shown to meet HS2 performance requirements but are highly sensitive to cement curing time. On the other hand, the Rayleigh wave characteristics are found to exceed HS2 criteria and the assumed shear value velocity for engineered fill, providing the justification for an increased value to be recommended for optimisation and efficiency.

RÉSUMÉ: L'utilisation de sols stabilisés dans la construction de remblais ferroviaires à grande vitesse est une solution d'ingénierie souhaitable pour HS2, car davantage de sols gagnés sur site peuvent être utilisés localement, réduisant ainsi le volume et le transport en masse de matériaux importés et gagnés sur site. Dans le sud de la zone contractuelle C23, d'importants volumes de craie altérée sans structure deviendront disponibles en raison de la construction de déblais. Cependant, à l'heure actuelle, il existe peu de données disponibles dans le domaine public pour caractériser les performances dynamiques d'une craie stabilisée au ciment destinée à être utilisée comme matériau de remblai de chemin de fer à grande vitesse. Cet article présente les résultats d'un essai sur le terrain comprenant des essais in situ et en laboratoire d'un grand remblai construit à partir de trois mélanges crayeux-ciment différents. En contrôlant les procédures de pulvérisation, de stabilisation et de compactage pendant la construction, la variabilité observée du classement des matériaux, des vides d'air et de la densité est présentée en fonction de la variation naturelle de la craie, de la teneur en humidité, de la teneur en ciment ajouté et de la rigidité de la fondation porteuse. Il a été démontré que les valeurs de module E_{V2} répondent aux exigences de performance HS2 mais sont très sensibles au temps de durcissement du ciment. D'autre part, les caractéristiques de l'onde de Rayleigh dépassent les critères HS2 et la vitesse de la valeur de cisaillement supposée pour le remblai technique, ce qui justifie une augmentation de la valeur recommandée pour l'optimisation et l'efficacité.

Keywords: Chalk; material stabilisation; trial embankment; high speed rail; dynamic performance.

1 INTRODUCTION

1.1 Background

The High Speed Two (HS2) project is a High-Speed Railway Line currently under construction in the UK. Phase 1 of HS2 runs between London and Birmingham across the English Midlands

The scope of the C23 contract, which has been awarded to Eiffage, Kier, Ferrovial Bam Joint Venture (EKFB), includes 45 embankments and 30 cuttings supporting HS2 C23 mainline.

As per HS2 Technical Standard for Earthworks (TS-E) (HS2, 2019), the design of these mainline earthworks shall comply with challenging static and dynamic performance criteria, reflective of the high operational speed of the rail. Compliance needs to be verified during construction with testing. Both the Technical Standard for Earthworks (HS2, 2019) and HS2 Specification for Engineering Works 600 series – Earthworks (HS2, 2022), indicate that field trials are a prerequisite element of the design and construction control validation process.

For mainline embankments, large volumes of engineered fill are expected to be used as upper and lower embankment fill (UEF & LEF) and as foundation treatment, i.e. excavate & replace backfill. In this context and considering the complex logistics associated with this aspect of the scope, opportunities to maximise the use of the site won material generated during excavation for the formation of the mainline cuttings is continuously being sought.

As a result, the field trials scope has been extended to include assessment and validation of site won material performance for use as embankment fill and replacement fill for earthwork foundations.

1.2 Scope & objectives

The main objective of the Earthworks field trials was to demonstrate suitability of proposed unstabilised/stabilised soils for High-Speed Railway embankment fill, to provide earthworks control and verification to validate the performance of the earthworks during and following construction and to review suitable improvement options for re-use of any excavated materials for embankment fills.

This paper discusses the results of the embankment trial of Cement Stabilised Chalk which was performed at Great Missenden. The embankment was constructed using structureless Chalk (Class 3B1) stabilised using cement mix to produce a Class 9M1 fill material for use as UEF, LEF and foundation treatment. The trial's aim was to control, validate, and optimise the earthworks construction method to ensure that the Class 9M1 fill derived from the class 3B1 chalk could reasonably achieve the design requirements set out in the TS-E (HS2, 2019).

2 THE SITE

2.1 Trial location

The trial embankment site is located near Great Missenden, Buckinghamshire. The nearest mainline asset to the trial site is South Heath Cutting. The completed trial embankment is presented in Figure 1. The excavated fill was generally structureless Chalk. The trial site layout plan is shown in Figure 2.

Figure 1. Completed trial embankment.

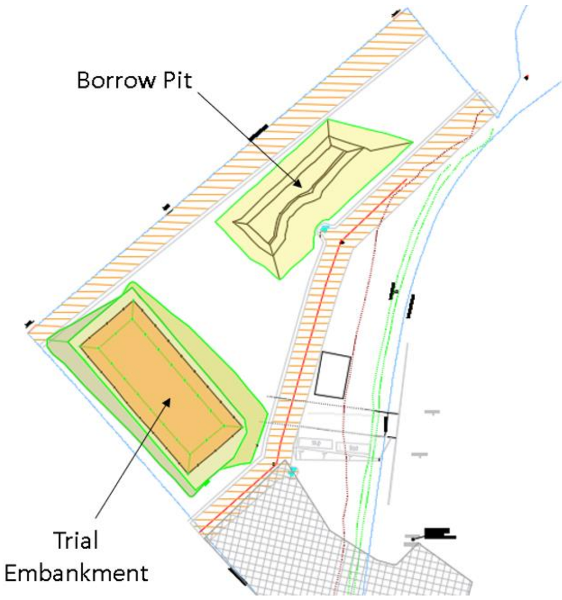

Figure 2. Trial Site Layout Plan and proposed testing locations.

2.2 Ground conditions

Based on the ground investigation at the borrow pit area, the site is characterised by structureless Chalk comprising 1m of grade Dm Chalk becoming grade Dc with depth (Figure 3). Localised zones of more structured Chalk (grades B & C) were also observed over the excavated depth.

Interpretation of available ground investigation data at the trial site indicated that the ground conditions below foundation platform level comprise grades Dm/Dc structureless Chalk over structured Chalk of Grades B/C. This is generally consistent with the ground conditions revealed at the borrow pit location.

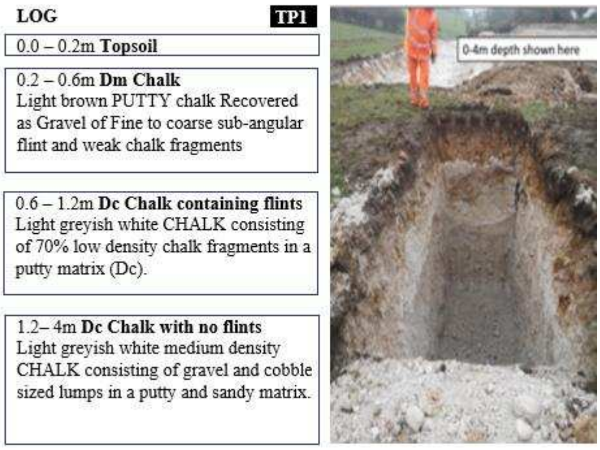

Figure 3. Photo of trial pit in the borrow pit area.

3 EMBANKMENT CONSTRUCTION

The Trial embankment was split into two areas (Area 1 and 2). Layers 1 to 3 of both Area 1 and 2 were constructed using Dm chalk mixed with 2% cement. Above layer 3, Area 1 and 2 were constructed with different binder contents, but both with Grade Dc white chalk. Area 1 used 2% cement for layers 4 to 8 and finished construction at layer 8. Area 2 used 3% cement for layers 4 to 8 and 4% cement for layers 9 to 13 and finished construction at layer 13. Individual layers were specified to achieve a compacted thickness of 250mm.

Due to variation in ground elevation, the trial location was levelled, using cut and fill within the hillside to form a basal foundation platform for the trial embankment. A 2% cement mix was used to stabilise the base.

Targeted in situ and laboratory testing were undertaken both during construction of the trial embankment and on completion to provide the necessary data for use in the assessment of the suitability of site won stabilised structureless Chalk Class 9M1 as HSR embankment fill.

4 PERFORMANCE REQUIREMENTS

4.1 Performance requirements for HSR fill

The performance requirements specified in the TS-E (HS2, 2019) are as follows:

4.1.1 Dynamic performance

The TS-E (HS2, 2019) (Table 4.2/1) specifies the performance criteria to be satisfied by the earthworks design and construction verification testing as a limiting Rayleigh wave velocity (V_R), measured at Formation Level:

$$V_R \geq 1.6 \times DS \quad (1)$$

where DS is the design speed, which for HS2 Contract C23 has been set at 360km/hr (100m/s).

This minimum V_R value is to be achieved over a frequency range of 10-50Hz.

In the beginning of the design, due to lack of information, a minimum V_S design value of 250m/s has been adopted for engineered fill forming embankments and earthwork foundation strata. This value is used for benchmarking the dynamic performance results from testing of the Class 9M1 material forming the trial embankment. The V_S design value has been revised to 300m/s at a later stage based on the evidence from field trials.

4.1.2 Static performance

TS-E specifies the minimum Deformation Modulus (E_{V2}) for Chalk when used as UEF to achieve static performance criteria:

$$(E_{V2}) \geq 45\text{MPa} \quad \text{(1m above LEF)} \quad (2)$$

$$(E_{V2}) \geq 60\text{MPa} \quad \text{(at surface of UEF)} \quad (3)$$

4.1.3 Layer thickness

The following requirements are set out in HS2 Specification, 600 series – Earthworks (2022):

- All fill materials - deposited in layers not exceeding 250mm uncompacted thickness.
- Cement stabilised materials - upper limit of 250mm may be increased depending on confirmation from field trials.

4.1.4 Testing and compaction requirements

Testing methods adopted for measuring in-situ dry density (DD) comprised: Nuclear Density Gauge (NDG), core cutter (CC), and sand replacement density (SRD). Only the NDG results were considered for assessing the material DD. The testing locations are shown in Figure 4.

Degree of compaction achieved is determined based on assessment of the DD as a proportion of maximum dry density (MDD), determined from a defined compaction test converted to a percentage. A similar method was adopted to measure the air voids (AV) in that the particle density (PD) determined from the embankment trial was used together with the moisture content (MC) and DD readings to determine the AV.

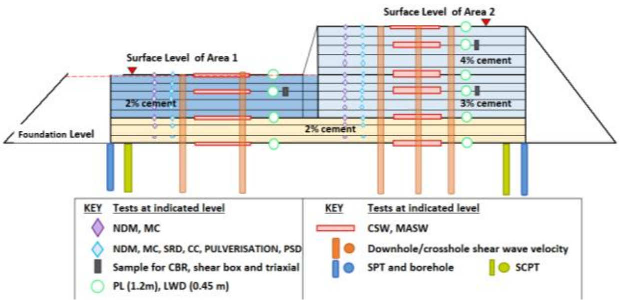

Figure 4. Testing locations and schedule for trial embankment.

Degree of compaction achieved is to be assessed against compaction data from either a standard (2.5kg) or modified (4kg) Proctor tests completed on sample of Chalk fill prior to construction. The Proctor test method used as a benchmark for the trial is determined based on the DD data obtained during compaction optimisation trials.

5 TESTING, RESULTS AND ANALYSIS

5.1 Design performance

5.1.1 Dynamic performance

Surface wave tests, comprising of Continuous Surface Wave (CSW) and Multi-channel Analysis of Surface Wave (MASW), were undertaken at foundation level and at different layers, as shown in Figure 4.

Additionally, Downhole and Crosshole seismic testing was conducted through the embankment fill and foundation strata to compare with the inverted values of Vs from MASW/CSW surveys.

The results are summarised in Table 1.

Table 1. Summary of Shear wave velocities obtained from Geophysical testing performed in Class M91 fill.

CSW (m/s)	MASW (m/s)	Downhole (m/s)	Crosshole (m/s)
400-500	500-600	400-600*	500-700

*Note - *Lower bound value is influenced by the averaging methodology considering the less stiff foundation material below the trial embankment.*

Surface wave geophysical methods are indirect ways of measuring Vshv, and therefore the VS derived from indirect methods (CSW and MASW) were benchmarked against direct methods (downhole and crosshole geophysics). Where surface wave geophysical methods were used, MASW results were considered superior in quality compared to CSW as lower variability was observed.

Benchmarking the testing results obtained from the four test types against the designed assumption of Vshv ≥ 250m/s showed mixed results throughout Areas 1 and 2 of the trial embankment. Nonetheless, all data obtained from all four test types demonstrated that the trial embankment formed of Class 9M1 fill with 2-4% cement contents exceeded the assumed Vshv value of 250m/s. A V_S of 570m/s was considered representative of 3% cement compared to 470m/s for 2% cement. A 2% cement content was considered sufficient to satisfy the dynamic requirement for the reuse of stabilised structureless Chalk Class 9M1 as embankment fill.

5.1.2 Static performance

To account for the depth of influence for a 600mm plate test (AFNOR, 2000), E_{V2} tests were performed within Layers 8 and 13. Also, to ensure that reliable and consistent results are obtained, only E_{V2} tests completed within 24hrs of compaction were assessed for each cement mix. The refined dataset, the results, the average value and percentage exceeding the Upper LEF and UEF requirements for Class 9M1 fill with 2%, 3% and 4% cement are presented in Table 2.

Table 2. Summary of E_{V2} testing results for different cement mix for Class 9M1 fill.

Fill Type	Range E_{V2} (MPa)	%Passing UEF Criteria (base)*	%Passing UEF Criteria (surface)
Class 9M1 (2% cement)	65-205	100%	100%
Class 9M1 (3% cement)	107-375	100%	100%
Class 9M1 (4% cement)	115-450	100%	100%

*Note - *: result represents tests at 1m above the top of the LEF.*

The testing results demonstrated that the static performance criteria for the use of Class 9M1 as UEF fill are met for all binder contents. Also, although E_{V2} values increased with higher cement contents, a 2% cement mix should be considered sufficient for the stabilised structureless Chalk to meet the static performance criteria when used as embankment fill.

5.2 Compaction assessment

5.2.1 Compaction optimisation

Compaction optimisation trials were performed to determine a suitable number of passes on layers 1, 2 and 3, with 9 No. NDG recordings taken after:

- 4, 6 and 8 passes on layer 1;
- 6, 8 and 10 passes on layer 2; and
- 8 and 10 passes on layer 3.

Variable MC were measured for each layer, ranging from 21% in layer 1 to about 22% in layer 2 and 25.5% in Layer 3. Therefore, compaction between layers could not be assessed collectively as MC skewed the degree of compaction and AV achieved. It was also noted that the material below 23% MC showed a reduced performance in AV, and therefore layers 1 and 2 were discounted from the compaction optimisation assessment.

From a review of the compaction optimisation trial results on Layer 3, presented as Figure 5, an increase in compaction was observed between 8 and 10 passes. Based on this, 10 passes using a 19t smooth drum roller traveling at <4kmph were adopted for the remaining duration of the trial.

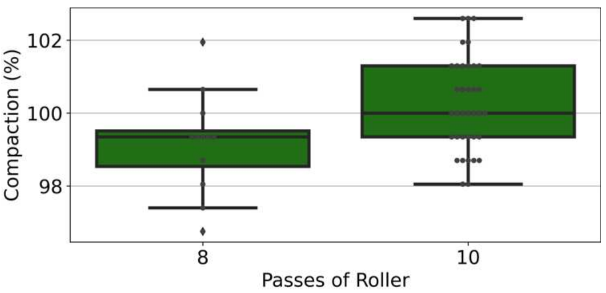

Figure 5. Trial Compaction Optimisation Results

5.2.2 Degree of Compaction and Air Voids

Based on the comparison between DD values achieved during compaction optimisation trials and laboratory Proctor tests, it was determined that the field dry density for the trial embankment compared closely to the standard (2.5kg) Proctor tests completed on 2% cement stabilised 9M1 material prior to construction. Therefore, compaction was benchmarked against MDD determined from standard Proctor tests.

Based on a comparative review of the Proctor tests, it was identified that Grade Dm chalk often produced a higher MDD than Dc Chalk by approximately 0.04Mg/m3. Based on the trial Proctor test data, MDD of 1.54Mg/m3 and 1.50Mg/m3 were determined for Dm and Dc Chalk, respectively, as Shown on Figure 6.

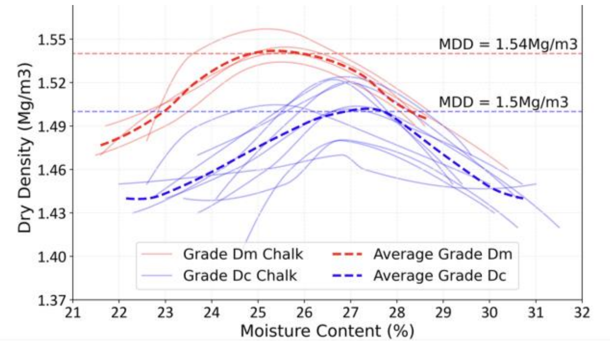

Figure 6. Trial Proctor Test Results

The degree of compaction of Dm and Dc chalk has been calculated against these respective MDD values. It is advised that compaction assessment for embankment fill during construction will need to be compared using locally determined MDD from asset specific Proctor tests for both Dm and Dc chalks used to produce Class 9M1 fill.

Optimum MC (OMC) was determined to be 25% for Grade Dm Chalk and 27% for Grade Dc Chalk. Based on average MC readings on each layer, 50% of the embankment layers (Layers 2,4,7 and 8) were dry.

Compaction data was screened to remove the following:

- Data points where cement content did not equate to 2%;
- Data points on layers where the number of passes of the roller did not equate to 10;
- Data points below an MC of 23% as the majority of this data did not achieve an AV<5%;
- Data points where NDG recordings were not recorded at 200mm depth.

When assessing the refined dataset for the trial embankment, 90% of the data exceeded a degree of compaction of 98.7% at the trial embankment, as shown on Figure 7.

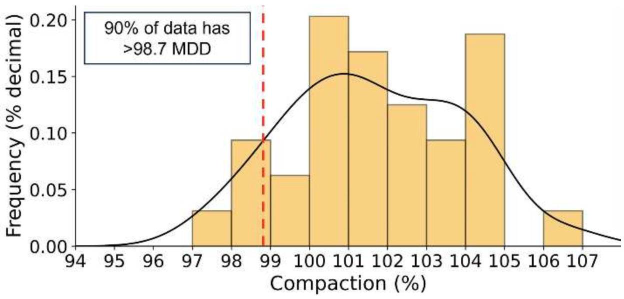

Figure 7. Histogram showing the distribution of degree of compaction for Class 9M1 fill.

The AV data from the revised dataset established showed that 90% of the data had an AV<6.1% as shown on Figure 8.

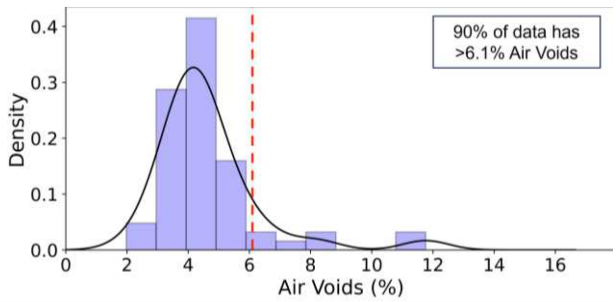

Figure 8. Histogram showing the distribution of air voids (AV) for Class 9M1 fill.

5.2.3 Pulverisation

Based on the trial data, the degree of pulverisation (DoP) ranged from 39% to 90% after the second pulverisation stage when cement was added. The three lowest values were considered outliers and, therefore, were excluded from the assessment. Based on the remaining dataset, a DoP of 60% was recommended after the second stage of pulverisation when adding cement.

5.3 Impact of layer thickness

The layer thickness during construction of the trial embankment ranged from 134-287mm, with six of the layers exceeding 250mm compacted thickness.

Compaction recordings were divided by the overall average compaction to normalise the data. From this, the average compaction of each layer was determined and plotted against the layer thickness.

The comparative review indicated that with increasing layer thickness, the normalised compaction tended to slightly decrease (albeit by less than 1% over a range of compacted layer thickness from 200-250mm). In light of the evidence from the trial, it is considered that layer thickness has a smaller impact on the degree of compaction compared to other variables (e.g. MC).

6 CONCLUSIONS

Based on the response of the structureless Chalk (Class 3B1) during trial embankment construction, pulverisation and testing, the following were identified as key requirements to ensure that the stabilised Chalk Class 9M1 fill meets the suitability criteria in terms the static and dynamic performance criteria:

- Class 3B1 Chalk should not be stockpiled due to drying effects reducing the materials ability to achieve the AV acceptability criteria (TRL, 1992).
- On classifying the chalk as either a grade Dm or grade Dc chalk, local Proctor testing should be undertaken to identify an appropriate compaction curve and MDD so that relative compaction can be assessed accurately for the asset specific embankment.
- The use of 2-4% cement during the trials have shown to not compromise static and dynamic performance requirements set in the TS-E. It is advised that the best percentage (by weight) of cement is 2%, as it has been shown to achieve the design performance criteria, whilst being the most sustainable percentage of cement to add.

The field trial results at Great Missenden have demonstrated that the site won structureless Chalk Class 3B1 can be improved to a Class 9M1, using controlled cement mix. They also demonstrated that the stabilised Chalk Class 9M1 met the static and dynamic performance criteria set by the TS-E (HS2, 2019) for use as HSR embankment fill subject to target construction requirements and trial compaction testing to determine an appropriate site specific maximum relative density.

Moreover, and based on a comparative review of results from various geophysical testing techniques, the dynamic performance in terms of Rayleigh wave velocity (V_R) was found to exceed the minimum assumed in design. An equivalent Vs design value of 300m/s is recommended for the Class 9M1 material.

ACKNOWLEDGEMENTS

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