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A strategic and novel field trial to investigate the dynamic performance of cement-stabilised chalk as embankment fill for high-speed rail earthworks

Ouarda Boumendjel-Game[1#], Harry Saroglou[2], Matthew Fleetwood[2], Mike Black[3]

Article

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Static stiffness modulus
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Abstract

Significant quantities of site won fill material are generated from the High Speed Two (HS2) C23 main works civil engineering contract, during the excavation for the formation of cuttings and construction of tunnels. This study investigates the suitability of weathered structureless Chalk, stabilised with cement, for use as engineered embankment fill for high-speed rail earthworks. Given the dynamic loading conditions imposed by high-speed high frequency rail operations, the performance of stabilised chalk requires thorough evaluation. A strategic field trial embankment was constructed to assess the suitability of this material. The results demonstrate that the static stiffness modulus (E_{V2}) of the stabilised chalk meets HS2's minimum performance requirements, though it is found to be sensitive to cement curing time. Dynamic performance, evaluated through shear wave velocity (V_s) derived from Rayleigh wave characteristics, exceeded the minimum V_s assumed for engineered fill during detailed design, confirming compliance with HS2's dynamic performance criteria. Construction control measures, including optimal chalk grade, binder mix, moisture content, and compaction control are recommended to ensure consistent performance. These findings validate the use of cement-stabilised chalk fill for high-speed rail earthworks, enabling the development of sustainable earthwork solutions through material optimisation, waste reduction, and enhanced environmental efficiency.

1. Introduction

1.1 Background

The High Speed Two (HS2) project is a new High-Speed Railway Line currently under construction in the UK. It is a 230 km long new high-speed rail (HSR) that runs between London and Birmingham across the English Midlands.

Distinct system and performance characteristics of the HS2 project are described in the HS2 Technical Standard - Earthworks (TS-E) (HS2, 2019). The most notable are:

- The selected track slab system
- The high operating speed of 360 km/h
- The 120 years design life
- The stringent static and dynamic performance criteria to be achieved
- The strict construction verification and validation testing requirements of the end product

These performance requirements have specifically been set to ensure the safety, resilience and stability of the high-speed rail track.

1.2 The C23 Contract

HS2 Ltd (HS2) has awarded the C23 Contract for the design and construction of the civil infrastructure works to EKFB, a Joint Venture consisting of renowned international civil engineering construction contractors Eiffage, Kier, Ferrovial Construction and Bam Nuttal. In turn, EKFB has appointed Arcadis, Setec, and COWI Design Joint Venture (ASC) to provide design services and construction support for the civil infrastructure works.

[#]Corresponding author. E-mail address: ggobg@bristol.ac.uk
[1]University of Bristol, Bristol, United Kingdom.
[2]EKFB, London, United Kingdom.
[3]COWI, London, United Kingdom.

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The C23 Contract encompasses an 80 km long open route section that connects the Chiltern Tunnel to Long Itchington Wood, located within the Central region between Wendover in Buckinghamshire and Southam in Warwickshire. The earthworks scope includes the design and construction of 30 mainline cuttings, 45 mainline embankments, and 7 km of green tunnels. Given the extensive scope of the project, a significant volume of earth moving and associated mass haul logistics are expected. The route and extent of the C23 Contract is presented as Figure 1.

The C23 contract is considered to be the largest single geotechnical contract currently being delivered in the UK.

1.3 Technical challenges

Major technical challenges were identified at the early stage of the design development process, requiring an effective strategy to be planned and meticulously executed to overcome these challenges and deliver sustainable solutions that would ensure the safety, stability, resilience and longevity of the railway track. One such challenge was the selection of a slab-track form to limit long-term maintenance requirements. However, this track system cannot accommodate large movements, meaning that any displacement of the supporting platform must be kept within specific limits to maintain safe operations of the railway. To achieve this, key static and dynamic performance requirement together with very stringent long-term heave and settlement criteria were specified in the HS2 TS-E (HS2, 2019).

Another significant challenge was the ground conditions beneath the C23 route (Figure 2), which comprise over-consolidated high plasticity Clays, weak mudrocks, and Chalk.

These geological units are known for their unfavorable response to loading and unloading conditions. These ground risks have further exacerbated the challenge already presented by the strict post track installation heave and settlement criteria.

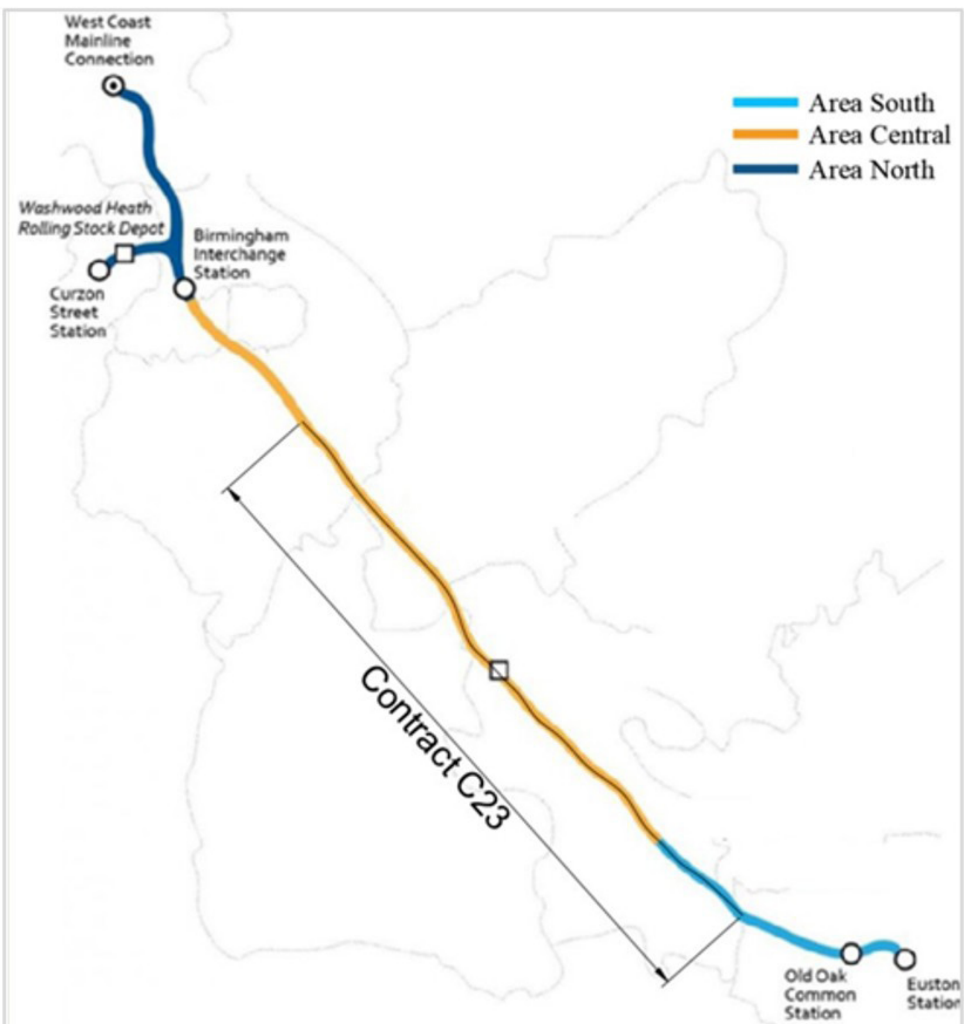

Figure 1. HS2 C23 Contract section route map.

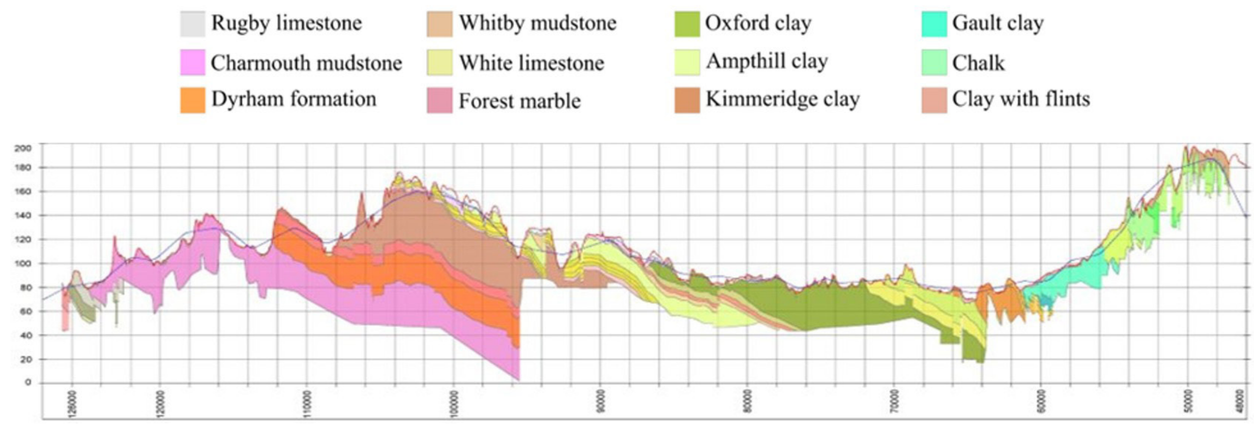

Figure 2. Ground conditions beneath the HSR C23 route.

Based on detailed evaluation of these challenges, uncertainties relating to predicting long-term earthworks heave and settlement, and dynamic amplification due to repeated transient loading, were identified as the main risks that would need to be adequately understood, assessed, and mitigated during the design and construction phases. Following collaborative discussions and risk reduction workshops, an innovative earthworks strategy was developed and executed to overcome these critical challenges. The scope comprised the construction and monitoring of three novel large scale instrumented field trials (two embankments and one cutting) to obtain better understanding of the characteristics and behaviour of the in-situ high plasticity foundation strata (Katsigiannis, 2024).

An additional significant challenge was the shortage of high-quality site-won granular fill material along the C23 route. This constraint added further complexities to mass haul logistics, including impact on costs and construction schedule. To address this challenge, the field trial programme was extended to include large scale material field trial embankments to ascertain the feasibility of treating the unsuitable site-won fills with the aim of rendering them suitable for re-use in mainline earthworks, transitions to structures, and for foundation treatment. This approach enables the development of sustainable solutions that will not only minimise the need for imported engineered granular fill but also reduce costs, shorten the construction schedule, and reduce the carbon footprint.

The suitability of re-using these site-won fill materials as earthworks fills was thoroughly evaluated by following a comprehensive selection and testing process. This included assessing their performance and demonstrating that they comply with HS2 technical ttandards when used as HSR embankment fill and as replacement material for foundation treatment. Both stabilised and unstabilised fills were investigated. In addition, laboratory testing trials were conducted to supplement the field trials and provide other essential material characteristics required for design and construction, using these site-won fill materials.

1.4 Scope and objectives

According to HS2 technical standards, the design of mainline earthworks, earthwork transitions and in-situ foundation strata must adhere to stringent static and dynamic performance criteria that are reflective of the high operational speed of the railway. These criteria ensure the safety and stability of the high-speed rail infrastructure.

Furthermore, the TS-E (HS2, 2019) and HS2 Specification for Civil Engineering Works (SCEW) (HS2, 2022) emphasise the importance of compliance testing during construction. This testing is crucial for verifying and validating the performance of the end product. Moreover, both the TS-E and SCEW highlight the significance of the field trials as an essential element of the design and construction control validation process. Field trials provide invaluable data for assessing material properties and behaviour under controlled conditions, enabling refinement and optimisation of the design and construction processes that will ensure the end product meets the stringent performance requirements.

This paper outlines the field trial embankment constructed at the trial site in the Great Missenden area, near section C2 of the C23 route, focusing on the use of cement stabilised chalk fill. The objectives of this trial were to:

- Assess the suitability of the cement stabilised chalk fill as HSR embankment fill in lieu of the engineered granular fill.
- Determine the minimum material acceptance criteria to be targeted during construction to demonstrate compliance with the static and dynamic performance requirements.
- Optimise the construction method for earthworks to ensure that the stabilised chalk fill meets the minimum static and dynamic performance requirements specified in the TS-E (HS2, 2019).

2. HSR earthwork embankment configuration

The TS-E (HS2, 2019) provides configuration and terminologies for the different mainline earthwork assets. Earthwork embankments are formed of two main parts, namely: the trackbed and the earthwork structure. The earthwork structure, in turn, comprises an upper embankment fill layer (UEF) and a lower embankment fill layer (LEF) below the prepared subgrade layer (PS). The configuration and terminologies for mainline earthwork embankments are presented as Figure 3.

As part of the project's environmental sustainability pledge, optimised and efficient solutions to reduce the carbon footprint were continuously sought during the detailed design process. For mainline earthworks, the re-use of the significant quantities of chalk fill to be generated on site for embankment construction was identified as an opportunity for optimising imported engineered granular fill.

3. Earthworks performance requirements

3.1 Earthworks design approach

HS2 requires that the design solution for embankments delivers a stable fill platform having consistent stiffness at formation level. The selected design solution is, therefore, expected to ascertain the following as a minimum:

- A stable foundation for the embankment structure.
- Suitable fill for use as UEF and LEF.
- Compaction targets that will achieve the prescribed minimum material stiffness.

3.2 Fill material acceptability and performance

According to HS2 TS-E (HS2, 2019), field trial earthworks shall be undertaken to demonstrate that the Designer's proposals will provide the required performance requirements.

For stabilised fills, the same standard states that: "*Treatment using lime, cement or other additives may be proposed to achieve the acceptability or performance limits required. These treatments may be by modification or stabilisation. The Designer shall confirm, with justification, that long-term performance will be maintained throughout the design life of the Earth Structure and that any proposed treatments will not be adversely affected by chemical properties of the ground or other agents.*"

Accordingly, the field trial was conducted to gather construction and testing data necessary to assess the suitability of the proposed cement stabilised structureless Chalk as HSR embankment fill. The trial also aimed to determine the minimum acceptable material properties to be targeted during construction, ensuring the chalk fill is sourced, placed, pulverised, compacted, and tested in a manner that achieves the static and dynamic performance requirements specified in HS2 technical standards.

3.3 Performance requirements

HS2 requires that the embankment structures after placement and compaction achieve the minimum performance criteria defined below.

3.3.1 Dynamic performance requirements

The dynamic performance is determined from the assessment of the dynamic stiffness exhibited by the earthwork structures when subject to dynamic loading. This is the Dynamic Railway loading applied over a very short term (instantaneous) (Arup, 2017; HS2, 2019; HS2, 2022). The TS-E (HS2, 2019) defines the earthworks dynamic stiffness as the "*transient stiffness of the earthwork at any defined level in response to dynamic loading*" and 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 in the frequency range 10-50 Hz:

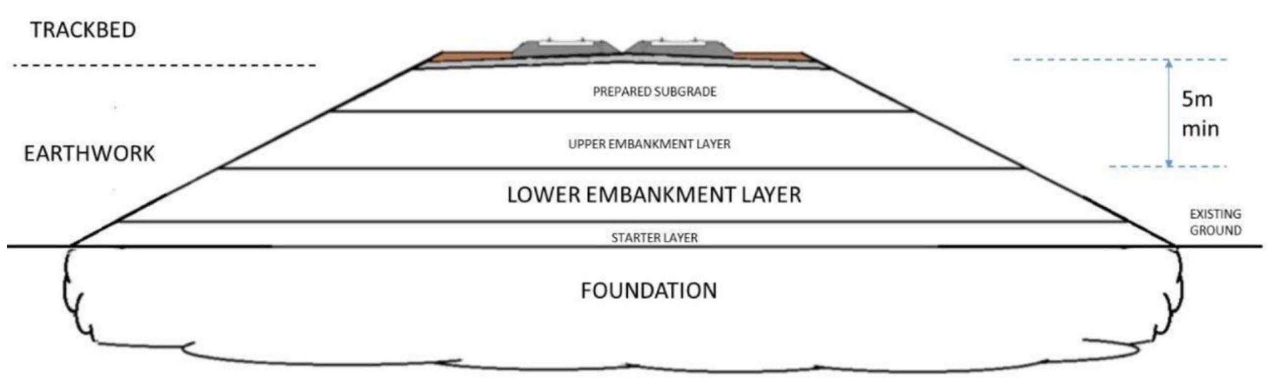

Figure 3. Typical HSR earthwork embankment configuration.

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

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

V_R is determined from the simplified direct relationship with the shear wave velocity (V_s) proposed by Richart Junior et al. (1970).

In the absence of trial testing information for embankment fill at the start of the design process, a minimum V_s of 250 m/s has been assumed for engineered fill forming the HSR embankments and the excavate and replace fill (E&R) for foundations treatment. This design value was revised to 300 m/s to reflect the high results recorded during field testing performed at various stages during the field trials (Hope et al., 2024; Saroglou et al., 2025).

3.3.2 Static performance requirements

The static performance is determined from assessment of the static stiffness of the embankment fill under static loading conditions. The TS-E (HS2, 2019) defines the earthworks static stiffness as the "*stiffness of the earthwork at any defined level under the application of a sustained load*". The same TS-E specifies the performance criteria to be satisfied by the earthworks design and construction verification testing as a limiting vertical deformation modulus (E_{V2}), measured at Formation Level. The E_{V2} limits and compaction acceptability criteria for embankments are summarized in Table 1.

The HS2 TS-E requires that the static performance is demonstrated by design and validated by construction verification testing of the end product.

4. Chalk fill characteristics

Chalk is present at the C2 section of the C23 route (Figure 2). According to the BGS Lexicon (BGS, 2021b) and the ground investigation (GI) undertaken by HS2 during scheme design (HS2, 2016), the Chalk deposits in this area comprise the White Chalk Subgroup, which in turn consists of the following:

- Lewes Nodular Chalk Formation - weak to moderately strong nodular medium to high density chalk and hardgrounds with interbedded 'soft to medium hard' chalks (some of which are grainy), marls and some interbedded chalks. The softer chalk is more abundant towards the top. The nodular chalks are present as regular seams.
- New Pit Chalk Formation – principally blocky, white firm to moderately hard chalk with numerous marl seams, including named marker horizons and 'wispy marls'. Flint occurs sporadically in the upper part of the formation, described in the BGS as 'firm to moderately hard' (BGS, 2021a).
- Holywell Nodular Chalk Formation - generally a hard nodular chalk, weathering typically to silt rather than clay, with thin interbedded marls and significant shell debris.
- Zig Zag Chalk Formation - mostly firm, pale greenish grey to off-white blocky chalk, with the lower part characteristically more 'marly'. Typically flint poor.
- West Melbury Marly Chalk Formation - typically, buff, grey and off-white soft, marly chalk. Typically flint poor. Noted in the BGS as hard grey limestones.

Based on the definition in CIRIA C574 (Lord et al., 2002), weathering determined from recovered cores ranged from fully weathered clast or matrix supported (grade Dc or Dm) to intact high strength (grade A). The Dm grade is defined in the CIRIA C574 as low-density Chalk that behaves as a cohesive, fine soil, where the comminuted matrix dominates. The grade Dc, on the other hand, is defined as low to medium density Chalk that behaves as a granular, coarse soil, where the clasts (intact Chalk lumps) dominate.

An extensive literature review of previous case studies was undertaken to obtain some understanding on the suitability, long-term behaviour, and performance of stabilised weathered chalk fill (Barker et al., 2018; Britpave, 2017; Judd, 1976; Lord et al., 2002; Phear et al., 2018a, b; Warren et al., 2003). Very limited data was available and was mainly related to other infrastructure projects. Key learning outcomes are as follows:

- Site specific characterisation of the weathered Chalk is needed for adequate assessment of its suitability for re-use.
- Intact dry density (*IDD*) is the most reliable parameter for characterisation of weathered chalk fill.
- *IDD* and moisture content (*MC*) are two characteristics that generally control the acceptability and level of treatment of weathered chalk fill.
- Setting reliable degree of pulverization (*DoP*) is critical to achieving uniform cement mixing distribution.

Table 1. E_{V2} limit and compaction performance requirements for embankments (HS2, 2019).

Earthwork layer	Material	E_{V2} (MPa)	Min. Compaction acceptability criteria (Modified Proctor)
UEF	Stabilised	≥ 60 at surface ≥ 45 at base (1 m above LEF)	*DC* ≥ 98% *MDD* *AV* ≤ 5%
LEF	Stabilised	-	To be determined from relationship testing

No E_{V2} limiting criteria are specified for LEF in HS2 TS-E.

The HS2 SCEW (HS2, 2022) classifies structured Chalk fill as Class 3 and stabilised soils as Class 9. The project specification labels the structureless Chalk grade Dm/Dc as Class 3B1 and the cement stabilised chalk fill as Class 9M fill. These terminologies are used throughout this paper. Testing found the structureless Chalk grade Dm/Dc (Class 3B1) to be low density chalk with an *IDD* < 1.55 mg/m^3.

5. The embankment field trial

5.1 Trial location

The location plan of the field trial in relation to the HSR line is shown in Figure 4.

The trial site slopes gently from an elevation of about +140mAOD to an elevation of 138mAOD.

The structureless Chalk for the trial embankment construction has been sourced from a temporary excavation situated adjacent to the trial site. Figure 5 shows a layout plan of the trial site and the temporary excavation area.

The Chalk was excavated, transported and directly placed for the embankment trial construction without stockpiling.

5.2 Ground conditions at the temporary excavation area and the trial location

A review of the available GI information (HS2, 2016) in conjunction with the BGS Lexicon (BGS, 2021b) indicated that the trial site and the designated temporary excavation area sourcing the chalk fill were expected to be underlain by the undifferentiated Holywell Nodular Chalk and the New Pit Chalk formations. The New Pit Chalk at the top is described as consisting of principally blocky, white firm to moderate hard Chalk with numerous marls or pair marl seams. Structureless Chalk was anticipated to be locally present near surface and be predominantly of grade Dc, meaning that it behaves as granular coarse soil where the clasts (intact Chalk) dominate (Lord et al., 2002).

A supplementary GI was undertaken during the field trial to verify and validate the anticipated Chalk formation at the trial site. It comprised the excavation of 5 trial pits to a maximum depth of 4.0 m below ground level. Three of these were dug within the temporary excavation area and 2 at the embankment trial site.

For the temporary excavation, the interpretation focused on the assessment of the depth and extent of the structureless Chalk (Class 3B1), as it is the main constituent needed for preparing the cement-stabilised chalk fill Class 9M required for the embankment trial. The log and view of TP1, dug as part of the supplementary GI, are presented in Figure 6 as an example.

Interpretation of the factual data revealed the ground conditions at the temporary excavation area to comprise weathered structureless Chalk, consisting of 1 m of grade Dm Chalk becoming grade Dc with depth. Localised zones of more Structured Chalk (grades B & C) were also observed over the excavated depth. This confirmed the Chalk profile interpreted from previous investigations, using the grading proposed by Lord et al. (2002).

Similar ground conditions were encountered at the trial embankment site. These are generally consistent with the ground conditions revealed by the previous GI data. A longitudinal section depicting the interpreted ground profile at both areas is illustrated as Figure 7.

Figure 4. Great Missenden field trial location.

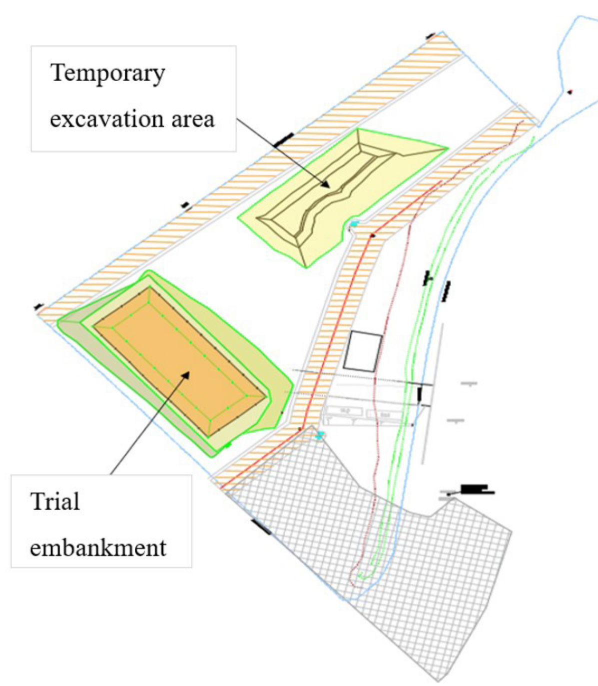

Figure 5. Layout plan of field trial site.

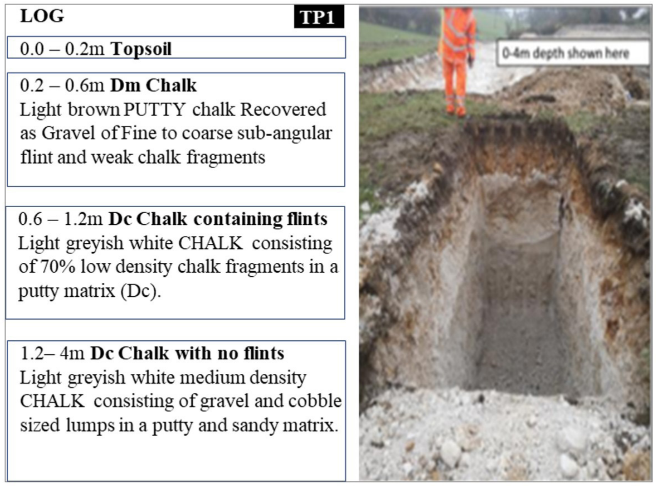

Figure 6. Ground conditions at temporary excavation area.

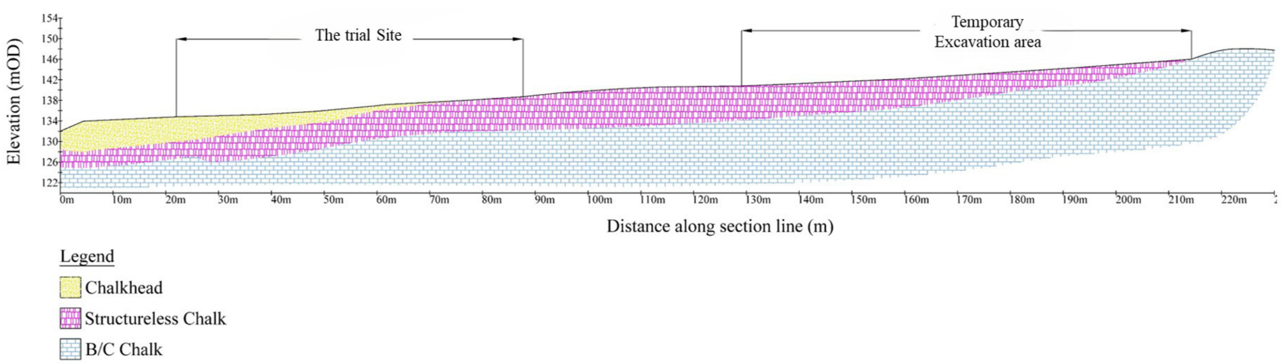

Figure 7. A longitudinal section showing the ground profile at the temporary excavation area and the trial site.

5.3 Trial embankment construction

5.3.1 Site preparation works

Due to variation in topography, the trial location was levelled, using cut and fill within the hillside to form a basal foundation platform for the trial embankment. The fill from the cutting comprised gravelly Clay with flint and Chalk. The foundation platform fill was improved using up to 5% lime stabilisation over the top 300 mm depth to provide a competent base for the trial embankment. Prior to construction of the fill platform, all topsoil at the trial location was stripped and the formation cleared in preparation for the embankment trial construction.

5.3.2 Trial embankment geometry and construction process

The trial embankment area was 61 m long and 20 m wide. The targeted maximum height was specified as 3.1 m, to be reached by placing 13 layers of Class 9M chalk fill. The side slopes were specified as 1v:2h.

The trial embankment was split into two testing areas, namely testing Area 1 and testing Area 2, each 30 m long and 20 m wide. Due to shortage of structureless Chalk Class 3B1, the height of Area 1 was revised to be 2 m and constructed, using up to 8 layers of Class 9M fill material.

The sequence adopted for the trial embankment construction is shown as a construction process in Figure 8. It includes material hauling, pulverisation, cement mixing, compaction and trimming of each fill layer. Plant and equipment used for construction are also shown on Figure 8.

The process followed for constructing the trial embankment is described below:

- For both Areas 1 and 2, fill layers 1 to 3 were constructed using grade Dm chalk mixed with 2% cement.
- For Area 1, fill layers 4 to 8 were constructed using grade Dc chalk mixed with 2% cement. Construction of testing Area 1 finished at layer 8.
- For Area 2, fill layers 4 to 8 were constructed using grade Dc chalk mixed with 3% cement, whilst layers 9 to 13 had 4% cement. Construction of testing Area 2 finished at layer 13.

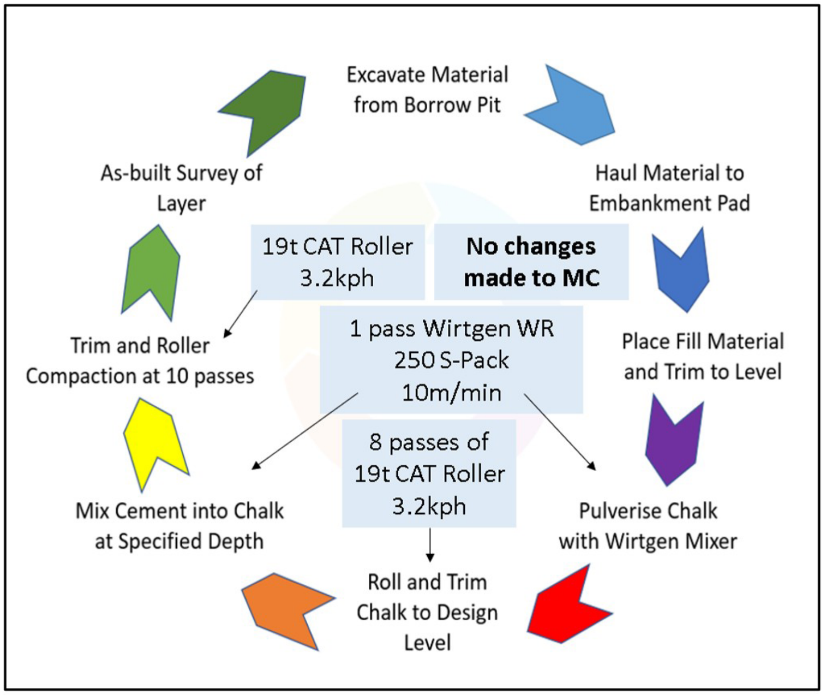

Figure 8. Construction process.

- Individual layers were specified to typically achieve a compacted thickness of 250 mm.

The completed trial embankment is presented in Figures 9a, 9b and 9c. Testing Areas 1 and 2 are apparent on Figure 9c.

Samples were obtained at targeted locations and depth during construction of each testing area, as well as at finished levels upon completion, for laboratory testing.

5.3.3 Testing schedule and locations

In situ and laboratory testing were performed during the trial. The specified in-situ tests and their locations, together with the sampling locations for laboratory testing, are shown on Figure 10. The individual fill layers in each testing area, along with the cement binder mix applied to each are also shown on Figure 10.

Key in-situ testing comprised:

- Geophysical surveys to provide V_s profiles of the engineered fill and the foundation strata, for interpretation of the dynamic performance.
- Plate load tests (PLT) at the specific locations to provide a continuous stiffness profile, E_{V2} within the embankment fill, taking in consideration the depth of influence of 1.2 m.
- Nuclear density gauge (NDG), core cutter (CC) and sand replacement density (SRD) to measure field *MC*, air voids (*AV*) and *DD* needed for the assessment of compaction acceptance criteria.

Key laboratory testing included:

- Proctor test to determine the optimum moisture content (*OMC*).
- Strength tests to determine the strength and stiffness after stabilisation.
- Particle size distribution (*PSD*) to determine the grading of the chalk fill before cement mixing and after for assessment of the potential effects of pulverisation on the mix.

The testing methods used for the respective tests were specified in the trial specification (ASC, 2022).

5.3.4 Pulverisation

A pulverisation trial was performed at the temporary excavation area to test the effectiveness of the selected pulverisation method intended for the trial embankment construction. The method involved a two-stage pulverisation process. In the first stage, the chalk layer underwent a single pass of rotavation without the addition of cement. This initial step was carried out to break up and loosen the material.

In the second stage, a single rotavation pass was also performed but with cement added to the chalk fill. The rotavation was carefully controlled, maintaining a fixed machine speed and ensuring an overlap equal to the width of the machine's wheel to achieve consistent coverage. The percentage target cement addition rate was verified using tray checks prior to the machine being used for embankment construction. Additionally, the mixing depth was checked before commencing construction of the trial embankment.

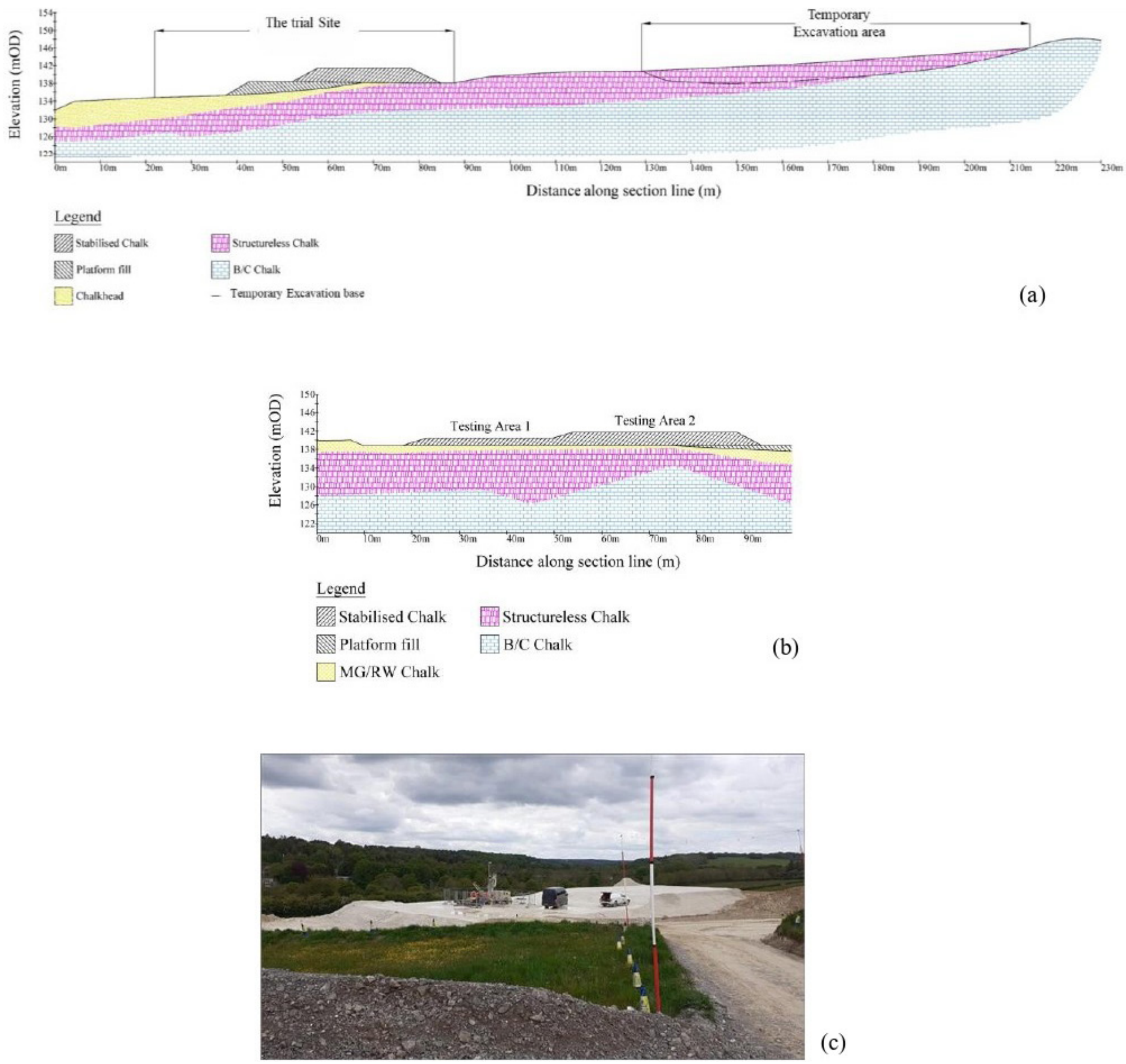

Figure 9. As-built trial embankment sections: (a) Long section showing temporary excavation area and trial site; (b) Long section showing testing Areas 1 & 2; (c) Photo showing completed trial embankment.

6. Analysis and results

6.1 Dynamic performance

Direct (downhole, crosshole) and indirect (continuous surface wave, multi-channel analysis surface wave) geophysical surveys were performed to measure the V_s of the embankment fill and the foundation strata to denote their dynamic stiffness. Downhole (DH) and crosshole (CH) surveys were performed at finished level of layer 8 for Area 1 and layer 13 for Area 2 on completion of the trial embankment construction. Continuous surface wave (CSW) and multi-channel surface wave (MASW) were performed at foundation level and at various layers, as shown in Figure 9.

The recorded V_s results from the different methods are summarised as V_{shv} in Table 2.

The V_{shv} results obtained from the direct and indirect geophysical surveys are also shown as V_s profiles in Figures 11 and 12 for testing Areas 1 and 2, respectively.

The results obtained from the different geophysical testing methods demonstrate that the Class 9M fill consistently exceeded the minimum V_s of 300 m/s, assumed for the embankment fill during design. In addition, based on a detailed analysis of the results, V_s of 470 m/s and 570 m/s are found to reliably represent the dynamic stiffness of the Class 9M fill with 2% and 3% cement content, respectively. These values highlight the significant improvement in dynamic properties achieved by the addition of cement. Thus, they demonstrate the acceptability of the Class 9M fill as a viable material for HSR embankment construction.

Table 2. Summary of V_{shv} obtained from geophysical testing.

CSW (m/s)	MASW (m/s)	DH (m/s)	CH (m/s)
400-500	500-600	400-600*	500-700

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

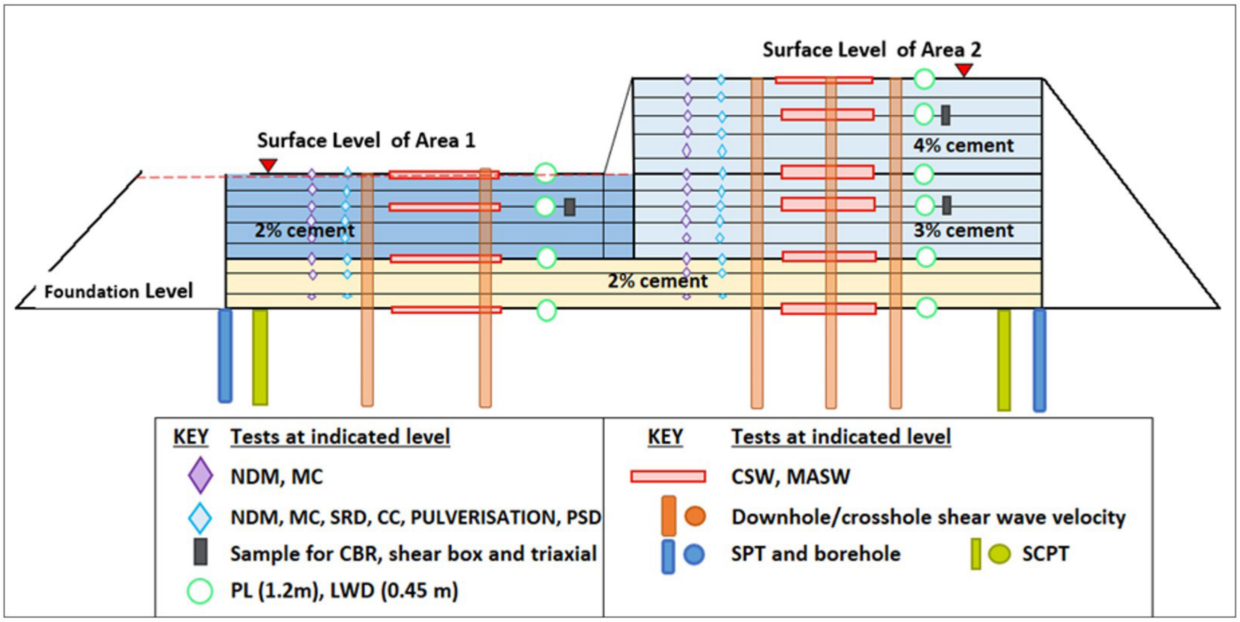

Figure 10. Testing locations and schedule for trial embankment.

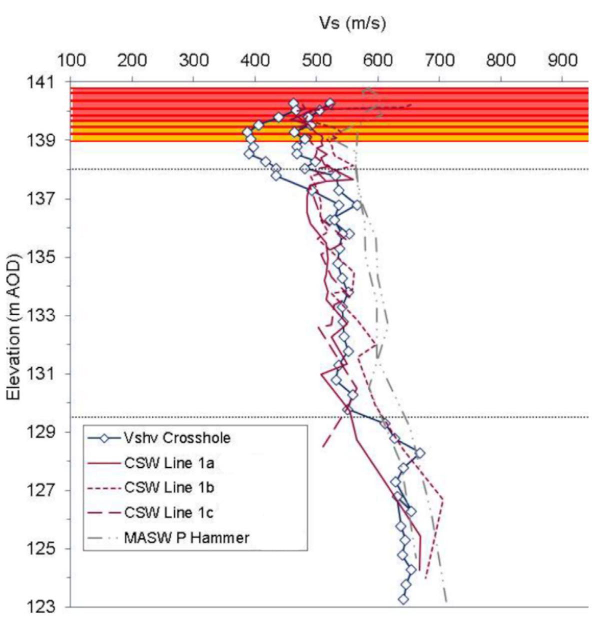

Figure 11. Summary inverted V_s profiles at testing Area 1.

In summary, the testing results confirmed that the structureless Chalk Class 3B1 improved using a minimum of 2% cement mix is acceptable for re-use as HSR embankment fill, since it satisfies the required dynamic performance criteria, characterised by a minimum V_R value, measured as an equivalent dynamic material stiffness V_s.

6.2 Static performance

The PLT is considered a reliable method to determine the static stiffness of soils. Considering the depth of influence of 1.2 m for a 600 mm plate used for the testing (AFNOR, 2000), the test locations were carefully selected to ensure that reliable data is obtained for each cement mix. In testing Area 1, seven PLT tests were performed from the finished level of layer 8. In testing Area 2, a total of 14 PLT tests were carried out. Of these, seven tests were undertaken during construction from the finished level of layer 8 and the remaining seven were performed from the finished level of layer 13.

PLT tests were performed 24 hours after completion of fill placement and compaction. Testing was also undertaken between days 18 and 21 after completion of the embankment trial construction to study the potential effect of curing time on the long-term stiffness of the Class 9M fill. The results are presented as a range for each cement mix in Table 3.

Table 3. Summary of E_{V2} results for different cement mix for Class 9M fill.

Cement	E_{V2}^{+}	E_{V2}^{+}	E_{V2}^{++}	E_{V2}^{++}
mix	Range	Mean	Range	Mean
(%)	(MPa)	(MPa)	(MPa)	(MPa)
Dc + 2	65-409	136	65-409	136
Dc + 3	107-375	188	107-375	188
Dc + 4	115-450	244	115-4500	>>500

$^{+}$Measured after 24hrs; $^{++}$Measured between 18 and 21 days.

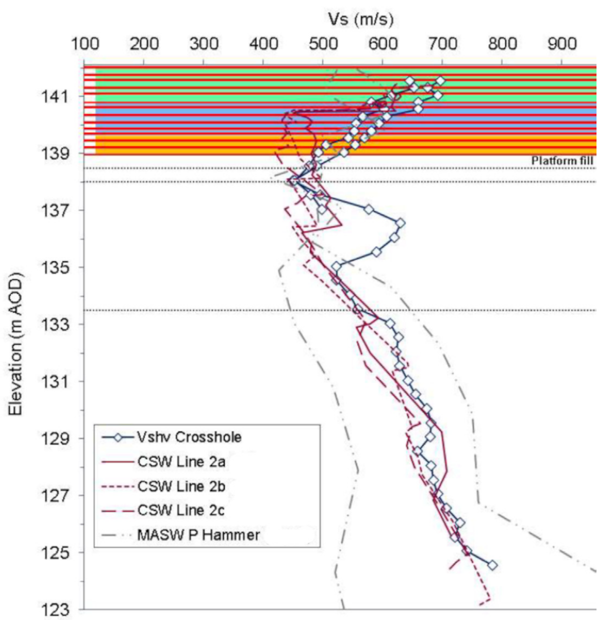

Figure 12. Summary inverted V_s profiles at testing Area 2.

The analysis highlights the performance and behaviour of Class 9M fill formed of Dc grade Chalk in relation to static stiffness and the influencing factors of cement content, time, and foundation strata. The findings indicate that the Class 9M fill achieved E_{V2} results exceeding the minimum limiting static stiffness criteria, confirming its suitability as an HSR embankment fill material. A clear trend emerged, showing that the static stiffness of the Class 9M fill improved with higher cement content. However, the rate and extent of improvement were governed by the cement content.

For Class 9M fill with 4% cement, an increase in stiffness was observed over time, suggesting an ongoing stabilization process. In contrast, the 2% and 3% cement mixes demonstrated significant early improvement, with stiffness levels appearing to plateau after 24 hours. This indicates that lower cement content accelerates the stabilisation process, achieving its full effect within a shorter timeframe, while higher cement content results in continued strength gain, and ultimately higher stiffness, over a longer curing period.

Another key observation was the relationship between stiffness and the depth of influence during testing. The stiffness of the Class 9M fill was greater when the tested depth was entirely within the fill, pointing to the potential impact of the foundation strata on the overall performance of the embankment fill mass. This is further supported by the lower E_{V2} results recorded for the stabilized chalk fill with 2% cement mix, placed on the levelling fill platform. These lower results confirmed the influence of the foundation on the long-term performance of the HSR embankment fill mass.

In summary, based on the testing results, structureless Chalk grade Dc, stabilised with 2 to 3% cement, is considered suitable for use as both UEF and LEF in HSR embankments. Structureless Chalk grade Dm, stabilised with 2% cement, could potentially be used as LEF. However, its suitability would need to be assessed on a case-by-case basis, taking into consideration the embankment height and the specific characteristics of the underlying foundation strata.

6.3 Compaction requirements

6.3.1 Compaction optimisation

Compaction optimisation trials were performed during placement and compaction of layers 1, 2 and 3 of the testing areas to determine a suitable number of passes. Nine NDG records were taken in:

- layer 1 - after 4, 6 and 8 passes
- layer 2 - after 6, 8 and 10 passes
- layer 3 - after 8 and 10 passes

Variable *MC* was measured in each layer, ranging from an average of 21% in layer 1 to about 22% in layer 2, increasing to 25.5% in Layer 3. This indicated that compaction between layers could not be assessed collectively, as *MC* skewed the degree of compaction, and the *AV* achieved. It was also noted that material with *MC* below 23% showed a reduced performance in *AV*. Consequently, layers 1 and 2 were excluded from the compaction optimisation assessment.

From a review of the compaction optimisation trial results on layer 3, an increase in compaction was observed between 8 and 10 passes. Based on this, 10 passes using a 19 tons smooth drum roller traveling at < 4 km/h were adopted for the compaction of the remaining layers forming testing Area 1 and testing Area 2 of the trial embankment. Compaction optimisation on layer 3 is presented, as Figure 13.

6.3.2 Assessment of compaction acceptance criteria

Proctor tests were undertaken in the laboratory, using the standard 2.5 kg and the modified 4.5 kg rammer, to determine the *OMC* and maximum dry density (*MDD*). A cement-stabilised chalk fill with 2% binder content was used for the Proctor tests.

The field *DD* values achieved during compaction optimisation trials were compared to the *MDD* values obtained from laboratory Proctor tests. The field *DD* are found to closely match the *MDD* determined in the laboratory from the standard (2.5 kg) Proctor tests. As a result, the compaction of the trial embankment was benchmarked against the *MDD* values from the standard (2.5 kg) Proctor tests.

Also, from a comparative analysis of the Proctor tests, it was observed that grade Dm chalk fill consistently achieved a higher *MDD* than grade Dc chalk fill. The difference between the two grades is approximately 0.04 mg/m^3 (or 40 kg/m^3). Using the trial Proctor test data, the following *MDD* values were determined:

- For grade Dm Chalk: *MDD* = 1.54 mg/m^3
- For grade Dc Chalk: *MDD* = 1.50 mg/m^3

The trial Proctor test results are shown on Figure 14.

The degree of compaction (*DC*) of the grades Dm and Dc chalk has been calculated against these respective *MDD* values.

Using the Proctor test results in Figure 13, the *OMC* was derived as 25% for grade Dm chalk and 27% for grade Dc chalk. It should be noted that based on the average *MC* readings recorded on each layer, nearly 50% of the layers forming the trial embankment (i.e. layers 2,4,7 and 8) were dry.

A data screening process was applied during the analysis of the compaction results from the trial embankment construction and testing, filtering out the following data points:

- Datapoints where cement content did not equate to 2%.
- Datapoints on layers where the number of passes of the roller did not equate to 10 passes, as determined from the optimised compaction trial.
- Data points below an *MC* of 23%, as most of this data failed to meet the limiting criteria of *AV* ≤ 5%.
- Data points where NDG recordings were taken at a depth below the 200 mm specified as a minimum for measurement in each layer.

The resulting credible datasets from the embankment trial are presented as a histogram in Figure 15.

Analysis of the refined dataset revealed that 90% of the data points exceeded a degree of compaction (*DC*) value of 98.7%. This finding demonstrates that the *DC* required to achieve the minimum static and dynamic stiffness for Class 9M chalk as an HSR embankment fill is consistent with the minimum acceptance compaction criteria outlined in the HS2 technical standard based on the modified Proctor (refer to Table 1).

A similar screening process was followed during the interpretation of the *AV* results. The credible datasets are presented in Figure 16.

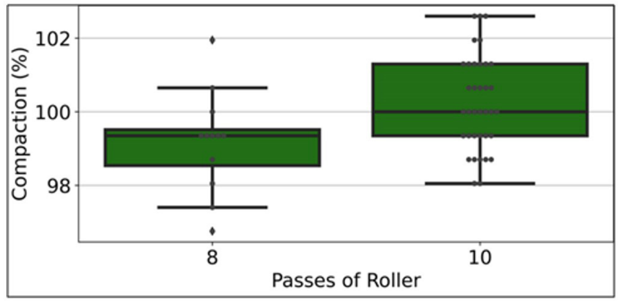

Figure 13. Trial compaction optimisation results.

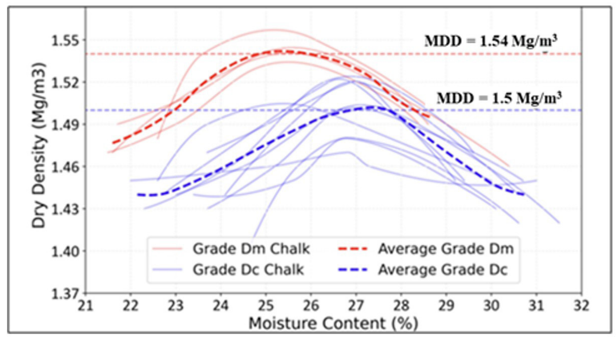

Figure 14. Trial standard Proctor test results.

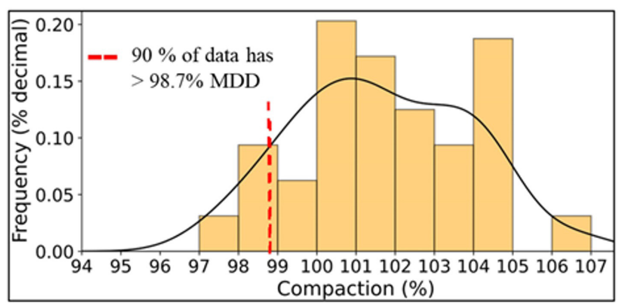

Figure 15. Histogram showing the distribution of *DC* for Class 9M fill.

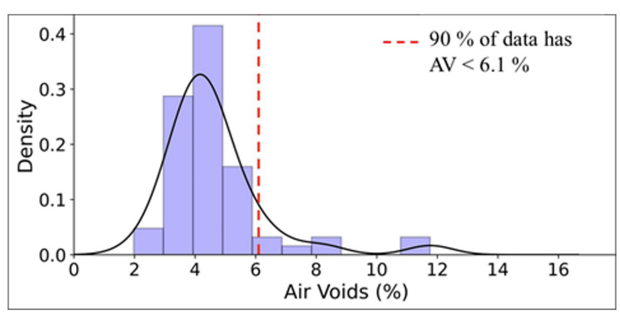

Figure 16. Histogram showing the distribution of *AV* for Class 9M fill.

Assessment of the refined dataset showed 90% have an average *AV* less than 6.1%. This is higher than the maximum 5% criteria outlined in HS2 technical standard (See Table 1).

The field trial results suggest that achieving the required minimum static and dynamic stiffnesses (E_{V2} and V_R) for a Class 9M chalk fill can be achieved with reduced compaction efforts. Specifically, the results indicate that the compaction criteria for *AV* can be relaxed by approximately 20%. This finding points to a potential opportunity to optimise the compaction process, reducing the effort and resources needed while still meeting HS2 performance requirements.

6.4 Pulverisation

The chalk pulverisation during construction of the embankment was applied into two stages. During the first stage, placement and pulverisation of the chalk fill occurred on the same day. No change in *MC* was observed, indicating that the material's moisture condition remained stable. In the second stage, cement was added to the pulverised chalk fill to produce the stabilised chalk mix. The results obtained showed that the *DoP* achieved generally ranged between 39% and 90%, with a discernible trend apparent between the 55 to 80% range.

Figure 17. Example of cement mixing of a pulverised chalk.

The analysis of the refined datasets determined that a *DoP* of 60% is an appropriate and practical target for chalk, and was subsequently recommended for HSR embankments formed using cement-stabilised Class 9M chalk fill.

An example of a pulverised chalk being subject to cement mixing is shown in Figure 17.

6.5 Impact of layer thickness

In accordance with HS2 SCEW (HS2, 2022):

- All fill materials shall be deposited in layers not exceeding 250 mm uncompacted thickness.
- For cement and/or lime-stabilised materials, the upper limit of 250 mm may be increased if field trials demonstrate that thicker layers can still achieve the performance requirements.

The thickness of each of the placed and compacted fill layers was measured during construction of the trial embankment. The thickness was found to range from 134 mm to 287 mm, with six of the 13 layers exceeding 250 mm.

To assess the potential influence of layer thickness on compaction performance, individual compaction readings were normalised by dividing each value by the overall average. This process yielded a single representative normalised compaction value for each compacted layer. These values are plotted against layer thickness, as shown on Figure 18.

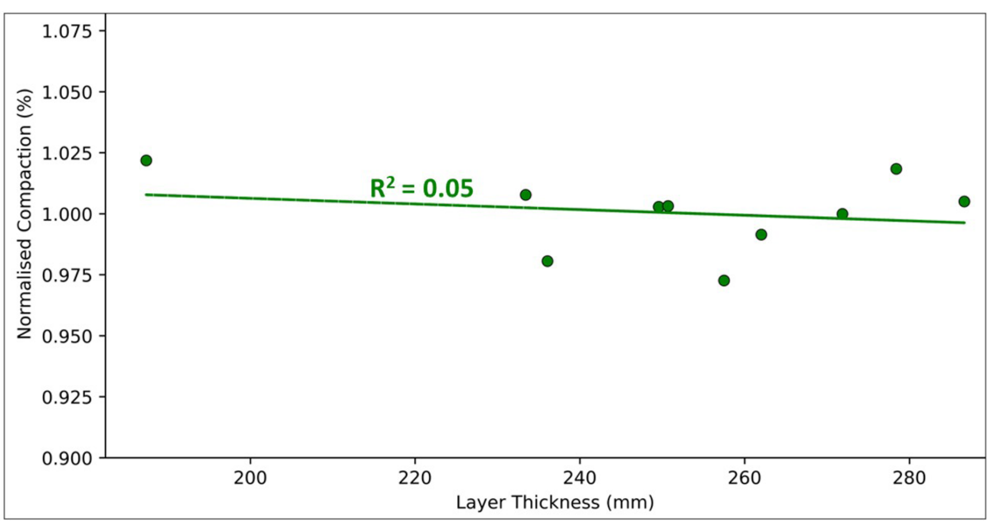

Figure 18. Normalized compaction vs layer thickness.

The results indicated a slight reduction in compaction with increasing layer thickness. However, the decrease was considered minor, as less than 1% reduction was observed across compacted layer thicknesses ranging from 200 mm to 250 mm. This suggests that layer thickness has a relatively minimal impact on compaction performance. This interpretation is supported statistically by the coefficient of determination (R^2) value of just 0.05, indicating a weak correlation between layer thickness and compaction performance. Other factors, such as *MC*, are likely to exert more significant influence on compaction performance based on evidence from the trial.

6.6 Minimum percent cement content for stabilised fill

The SCEW (HS2, 2022) requires that cement stabilised fills Class 9 must have a minimum of 2% cement content by weight, unless shown to the *"Contracts Engineering Director by field trials that a lesser percentage gives the required performance"*. It has been demonstrated during the trial that structureless Chalk Class 3B1 requires improvement using between 2 to 3% to meet the suitability criteria for re-use as HSR embankment fill.

6.7 Earthwork fills for transition to structures

A robust transition from mainline earthworks to concrete structures is needed. To achieve this, an interface earthwork zone, comprising engineered fill that creates a consistent gradual increase in dynamic response across the transition between the stiffness characteristics of the earthwork and the concrete structure, is required (HS2, 2020). The earthwork fill at the transition to structure is defined as UEF* in the same HS2 standard. As agreed with HS2 during the design development, the minimum static stiffness, E_{V2}, to be achieved for the UEF*, is the lesser of:

- +25% stiffer than UEF; and
- 120 MPa, but never less stiff than UEF.

Based on the high static performance of the Class 9M chalk fill during the trial for 3% and 4% cement content, an opportunity for further optimisation was identified. Structureless Chalk grade Dc mixed with 3 to 4% cement was found to be suitable for use as UEF* in the earthwork transitions to structures.

7. Conclusions

The material field trial embankment results performed as part of the innovative large scale earthworks strategy, developed specifically for the C23 section of HS2, demonstrated that the site-won structureless Chalk grade Dm/Dc (Class 3B1) can be effectively improved using controlled cement mix to produce a cement-stabilised Class 9M chalk fill. The trialed Class 9M fill produced with a cement content of 2 to 3% achieved both the static and dynamic performance requirements set out in the TS-E (HS2, 2019), confirming its suitability for re-use as HSR mainline embankment fill.

Based on the trial results, the following optimisations have been identified and are currently being implemented in the construction of mainline earthworks and earthworks to transitions:

- For mainline embankments (UEF and LEF), the compaction acceptance criterion for the Class 9M chalk fill, in terms of *AV*, has been relaxed from *AV* ≤ 5% (prescribed in the TS-E) to *AV* ≤ 6%, as demonstrated by the trial compaction performance.
- Class 9M chalk fill is used as LEF for mainline embankments, with a relaxed compaction acceptance criterion of *DC* ≥ 95% *MDD* based on standard Proctor.
- For earthwork transitions to structures, Class 9M chalk fill is used as UEF*, with a specified cement content of 3 to 4% to satisfy the minimum static stiffness criteria set out in HS2 standard for approach to transitions (HS2, 2020).

These optimisations have been used to establish revised compaction performance criteria for the Class 9M chalk fill, as outlined in Table 4.

Furthermore, the following key requirements were identified as needing to be observed during construction to preserve the quality of the structureless Chalk Class 3B1 when producing the cement-stabilised Class 9M chalk fill:

- Only structureless Chalk grade Dc should be used for producing a cement stabilised chalk fill Class 9M for UEF and UEF*.
- Structureless Chalk Class 3B1 should not be stockpiled due to drying effects, reducing the material's ability to achieve the *AV* acceptability criteria (TRL, 1992).

Table 4. Revised compaction acceptance criteria for class 9M fill as HSR embankment fill.

Embankment (layer)	Material	E_{V2} (MPa)	Min. compaction acceptability criteria (Modified Proctor)
UEF	Stabilised	≥ 60 at surface	*DC* ≥ 98% *MDD*
		≥ 45 at base (1m above LEF)	*AV* ≤ 6%
LEF	Stabilised	To be determined from design	*DC* ≥ 95% *MDD*
			AV ≤ 6%

- On classifying the structureless Chalk fill as either a grade Dm (LEF) or grade Dc chalk (LEF/UEF/UEF*), local Proctor testing should be undertaken to determine an appropriate compaction curve and *MDD,* ensuring adequate assessment of relative compaction for the asset-specific earthwork embankment.

The knowledge and learning insights acquired from this novel field trial are expected to be fully reflected in the new guidance being developed for earthworks using stabilised chalk fill, as part of the ongoing revision of the CIRIA C574 report. Thus, it will contribute to the building of a technical legacy for future earthworks projects in the UK and elsewhere.

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Declaration of interest

The authors have no conflicts of interest to declare. All co-authors have observed and affirmed the contents of the paper and there is no financial interest to report.

Authors' contributions

Ouarda Boumendjel-Game: methodology, data collection & curation, data analysis, data interpretation, writing – review & editing, writing – original draft. Harry Saroglou: methodology, data interpretation, review and editing. Matthew Fleetwood: methodology, investigation, data collection. Mike Black: data collection, review & editing.

Data availability

All data produced or examined in the course of the current study are included in this article.

Declaration of use of generative artificial intelligence

This work was prepared without the assistance of any generative artificial intelligence (GenAI) tools or services. All aspects of the manuscript were developed solely by the authors, who take full responsibility for the content of this publication.

List of symbols and abbreviations

AV	Air voids
CC	Core cutter
CH	Crosshole seismic test
CSW	Continuous surface wave
DC	Degree of compaction
DD	Dry density
DH	Downhole seismic test
DoP	Degree of pulverisation
DS	Design speed for HS2
E&R	Excavate and replace
E_{V2}	Vertical deformation modulus
GI	Ground investigation
HS2	High Speed 2
HSR	High-speed rail
IDD	Intact dry density
LEF	Lower embankment fill
MAS*W*	Multi-channel analysis surface wave
MC	Moisture content
MDD	Maximum dry density
NDG	Nuclear density gauge
OMC	Optimum moisture content
PLT	Plate load test
PSD	Particle size distribution
SCEW	Specification for civil engineering works – 600series earthworks
SRD	Sand replacement density
TS-E	Technical standard – earthworks
UEF	Upper embankment fill
UEF*	Upper embankment fill at transition
V_R	Rayleigh Wave Velocity
V_s	Shear wave velocity
V_{shv}	Shear wave velocity from direct and indirect field testing

References

AFNOR NF P 94-117-1. (2000). *Soils recognition and testing, part 1: module under static load to the plate (EV2).* L'Association Française de Normalisation, Saint-Denis.

Arup. (March, 2017). *Track-earthworks' interaction. Ref nº C861-ARP-GT-REP-000-000026 Rev P01.* London.

ASC. (2022). *Great missenden earthwork and stabilisation trial specification* (Document no. 1MC06-CEK-GT-SPEC-CS03_CL05-000006, Rev. P03). Amsterdam.

Barker, C.A., Phear, A.G., & O'Riordan, N.J. (2018). Design, construction and performance of chalk trackbed for High Speed One. In *Proceedings of the Conference "Engineering in Chalk"* (pp. 85-91). ICE Publishing.

British Geological Survey – BGS. (2021a). *BGS Geology 50K WMS.* Retrieved in January 31, 2025, from https://www.bgs.ac.uk/technologies/web-map-services-wms/web-map-services-geology-50k/

British Geological Survey – BGS. (2021b). *BGS Lexicon of named rock units.* Retrieved in January 31, 2025, from https://www.bgs.ac.uk/technologies/the-bgs-lexion-of-named-rock-units/

Britpave. (2017). *Soil improvement and soil stabilisation definitive industry guidance, BP/62*. Wokingham.

Hope, A., Boumendjel-Game, O., Wood, H., Saroglou, H., Katsigiannis, G., Butler, S., & Dudfield, J. (2024). Management of the dynamic performance of earthworks for High-Speed Rail. In *Proceedings of the XVIII ECSMGE 2024. Geotechnical Engineering Challenges to Meet Current and Emerging Needs of Society.* CRC Press. http://doi.org/10.1201/9781003431749-446.

HS2. (2022). *Specification for Civil Engineering Works (SCEW), 600 Series – Earthworks* (Doc. HS2-HS2-CV-SPEC-000-010600 Rev P06). London: High Speed 2 Ltd.

HS2. (2016). *Scheme design ground investigation report* (Doc. No.: 1MC06-CEK-GT-REP-002-000046). London: High Speed 2 Ltd.

HS2. (2019). *Technical Standard - Earthworks (TS-E)* (Doc. HS2-HS2-GT-STD-000-000001 Rev P08). London: High Speed 2 Ltd.

HS2. (2020). *HS2 Approach to Earthwork Transitions* (Doc. No. HS2-HS2-GT-REP-000-000046, Rev P02). London: High Speed 2 Ltd.

Judd, H. (1976). *Stabilization of chalk for road making purposes* [M. Phil thesis]. University of Surrey, UK.

Katsigiannis, G. (2024). High-speed rail earthworks design developments and innovative trials – building Britain's technical legacy. State of the-art report. In *Proceedings of the XVIII ECSMGE 2024. Geotechnical Engineering Challenges to Meet Current and Emerging Needs of Society.* CRC Press. http://doi.org/10.1201/9781003431749-8.

Lord, J.A., Clayton, C.R.I., & Mortimore, R.N. (2002). *Engineering in chalk (CIRIA C574).* London: CIRIA.

Phear, A.G., Barker, C.A., & O'Riordan, N.J. (2018a). Andrew Lord Memorial Paper: design and specification of chalk earthworks for High Speed One. In *Proceedings of the Conference "Engineering in Chalk"* (pp. 77-83). ICE Publishing. http://doi.org/10.1680/eiccf.64072.077.

Phear, A.G., Barker, C.A., & Riordan, N.J. (2018b). Construction and performance of chalk earthworks for High Speed One. In *Proceedings of the Conference "Engineering in Chalk"* (pp. 90-99). ICE Publishing.

Richart Junior, F.E., Hall Junior, J.R., & Woods, R.D. (1970). *Vibration of soils and foundations.* New Jersey: Prentice-Hall.

Saroglou, H., Vowles, M., Dimitriadi, M., Black, M., Boumendjel-Game, O., Fleetwood, M., & Bejarano, L. (2025). Dynamic performance of earthwork fills: experience from C23 field trials in HS2. In *Proceedings of the Conference "Earthworks 25".* London: British Geotechnical Association.

Transport and Research Laboratory – TRL. (1992). *Stabilised capping layers using either lime, or cement, or lime and cement* (Report TRL, No. 151). TRL.

Warren, C.D., Phear, A., Schultheis, T., & Gregg, I. (2003). Treatment and placement of chalk spoil from the CTRL thames tunnel. In *Proceedings of the Conference "Underground Construction"*, London.