Reframing lime treatment carbon calculations

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Abstract

The ability for low dosages of lime to improve wet-of-optimum cohesive fill to an optimum moisture content for compaction is well known. Increasingly, lime is also used to attain improved long term performance criteria, maximising opportunities for on-site soil retention. The costs of landfill tax and aggregate levies mean the economic case for lime treatment versus granular import is strongly understood, particularly where material performance is key. However, the high embodied carbon content of lime can dampen the overall strong positive contribution lime treatment has on climate neutrality compared to granular fill import.

This paper will review and build on the work of others in the calculation of embodied carbon of lime treatment considering:

1. updated understanding on the role of carbon sequestration in lime treated structures;
2. recent work that has shown BS EN 16907:4 (2018) 'stabilised soil' definition can be met with quicklime dosages as low as 1.5% providing the opportunity to replace the need to import structural fill classes (class 6/7 type fill);
3. other environmental considerations such as haulage, construction techniques and waste generation (recent UK government figures report soil waste accounts for 57% of all the 45 million tonnes sent to landfill).

The paper will review the revised carbon impact of lime stabilised site-won fill against imported fill through an High Speed Two (HS2) case study to demonstrate that low-dosage lime treatment presents a viable low-carbon option to support the adoption of a circular economy, low carbon approach in construction.

Keywords: Earthworks design, lime stabilisation, material reuse, carbon, burrow pit, sustainability.

1. Introduction

Since its inception as a ground improvement technique in the 1970's, the addition of lime has become one of the 'go-to' options to enable the reuse of otherwise unsuitable cohesive fill on earthwork schemes. However, it may perform poorly in some carbon calculator generated assessments due to the high embodied carbon of the lime binder (as compared to untreated site won fill or imported aggregate). This can lead to diminished opinion of this otherwise sustainable approach to soil upcycling, if long term carbon sequestration and other carbon neutrality benefits (such as reduced landfill and usage of finite natural resources) are not balanced. Using a case study on High Speed Two (HS2) Midlands this paper will outline how the adoption of lime stabilised fill as part of a wider, integrated mass haul approach is not only a sustainable option but often the lowest carbon option, particularly where there is limited granular site won material available. This is before other sustainability benefits such as the reduction of waste sent to landfill and reduction in haulage on public roads are considered.

Dr Paul Beetham (Nottingham Trent University) provides peer review and advice to HS2 on the approach to lime stabilisation of scheme embankments. Balfour Beatty VINCI (BBV) are HS2's main works contractor for the West Midlands who are constructing 90km of HS2 between Long Itchington in Warwickshire to the centre of Birmingham and on to Staffordshire. They are supported by Mott MacDonald SYSTRA Design Joint Venture (DJV) and together form an Integrated Project Team (IPT).

2.Background

2.1 State of literature on embodied carbon in UK lime stabilisation earthworks

Research on carbon emissions from UK lime-stabilised earthworks is limited, with Hughes et al. (2011) being a notable source. Their study concluded that lime treatment could increase earthworks' carbon footprint by up to 90% and labelled it 'carbon-perverse' despite acknowledging benefits to cost, programme, and waste reduction. However, this characterisation may be misleading, as their carbon estimates assumed availability of a nearby granular fill borrow pit as an alternative to lime-treated cohesive fill.

While such scenarios may favour granular fill in carbon terms, Life Cycle Assessment (LCA) extends beyond embodied carbon alone. In geology-constrained projects, such as HS2 Midland's route through the Mercia Mudstone Group, carbon comparisons differ substantially, as discussed below.

2.2 Recent perspectives on lime stabilisation sustainability

Modern sustainability assessments adopt a climate neutrality perspective, extending beyond carbon footprint to include raw material preservation and waste reduction which are key benefits of soil stabilisation. Effective ground engineering could virtually eliminate the 26 million tonnes of soil waste sent to UK landfill annually (DEFRA, 2024).

Often overlooked sustainability gains include; On-site material reuse, reducing road haulage and its impacts (road wear, accidents, traffic, and air pollution); Design optimisations enabled by lime stabilisation (see Neville et al., 2025), enhancing climate resilience and long-term durability by improving resistance to water immersion.

These core benefits should be integral to LCA. However, this paper primarily focuses on recent research advancements in carbon quantification, including 1) The role of lime-stabilised earthworks in carbon sequestration; 2) Evidence that effective stabilisation requires less lime than previously assumed.

2.2.1 Carbon sequestration

Quicklime (CaO) is produced by decarbonation from heating $CaCO_3$ (limestone/chalk) to approximately 900°C, resulting in a high embodied carbon value of 0.78 tCO_2e/kg (MPA, 2024; Jones & Hammond, 2024). However, this does not account for CO_2 reabsorption when lime carbonates back to $CaCO_3$.

While carbonation in lime-treated soils has long been recognised (Diamond & Kinter, 1965), recent research has further quantified its extent, enabling carbon offset calculations. The European Lime Association (2023) reports an average in-service carbonation of 33% across industrial lime applications, including stabilisation. A review by Grosso et al. (2020) found carbonation levels in lime-stabilised soils ranging from 30–80% in lab and field studies. Field studies on various soil types with 2.5–4% lime, aged 4–40 years, report consistent carbonation levels of approximately 37% (Eades et al., 1962; Haas & Ritter, 2018; Akula et al., 2020). Lab results from Kleib et al. (2024) show carbonation depends on lime content, with 59%, 44%, and 34% carbonation for 1%, 2%, and 4% lime, respectively, achieved within 4 hours under field conditions. The European Lime Association (2023) also notes 95% of the total carbonation occurs within the first year of earthworks placement, meaning rapid carbon 'payback'. While research in this area is evolving, a conservative estimate suggests at least 33% of embodied CO_2 can be offset in Life Cycle Assessments. However, for lower lime dosages, the higher carbonation rates reported by Kleib et al. (2024) will also be considered as a 'state of the art' comparison in the below sequestration assessment.

2.2.2 Lower lime dosage for stabilisation

Historically, UK specifications like the *Specification for Highway Works* (Series 600) have mandated a minimum lime dosage of 2.5%. In contrast, BS EN 16907:2018 defines performance requirements rather than prescribing a minimum. Phipps and Wayles (2024) demonstrated through lab and field trials that durable stabilisation can be achieved with just 1.5% lime, reducing the carbon footprint of lime-stabilised material by up to 40%.

3. Reframing Carbon Calculations - Case Study on HS2 Midlands Sublot Delta Borrow Pits

Construction of HS2 Midlands requires a 22 million m^3 placement exercise and the mainline embankments include 8 million m^3 of High-Speed Rail (HSR) lime stabilised (class 9) fill. In line with good practice LCA noted above, the general approach used extensive ground investigation and trials to inform an optimised earthworks mass balance, maximising material reuse and minimising shortfall.

This case study, focused on the Sublot Delta (central section of HS2 Midlands to the east of Birmingham), demonstrates the benefits of reframing carbon calculations using recent research. The central section required high embankments to connect a series of viaducts, prompting a value engineering exercise to address an initial shortfall of **800,000m³** of fill suitable for lime stabilisation (Class 7 fill). This also involved balancing the landscaping design to accommodate arisings from the nearby Bromford Tunnel.

While the tunnel arisings were a similar volume (approx. **800,000m³**), the gypsum bearing Mercia Mudstone alongside additives from the tunnelling process gave uncertainty on long term fill performance. This case study compares the carbon impact of three material sourcing scenarios (Figure 1) for SLDelta embankments while facilitating the **on-site reuse** of tunnel arisings.

Scenario 1 – the initial approach
The original plan sourced 800,000m³ of Grade III/IV Mercia Mudstone class 7 fill (for lime stabilisation) from Mainline North (MLN) cuttings, requiring 2.5% lime stabilisation to achieve Class 9 fill. Tunnel arisings were used for landscaping near MLN, resulting in:

- **20km public road** haulage of 800,000m³ Class 7 fill via rigid HGV from MLN to SLDelta.
- **20km public road** haulage of 800,000m³ tunnel arisings via rigid HGV from Bromford Tunnel to MLN.
- 115km public road haulage of **36,000t** lime via articulated tanker HGV from Buxton to SLDelta.

Scenario 2 – Optimised approach including value engineering
Following HS2 funded research into lime stabilisation efficiency (see Neville et al., 2025), a reduced **1.5% lime dose** was proven effective. Instead of the MLN cuttings, Class 7 fill was sourced from SLDelta borrow pits, which were then backfilled with the tunnel arisings—minimising haul and reducing emissions. This required:

- **1km internal haul** of 800,000m³ Class 7 fill via articulated dump truck (ADT) from borrow pits to embankments.
- **2km internal haul** of 800,000m³ tunnel arisings via ADT from Bromford Tunnel to borrow pits.
- 115km public road haulage of **21,600t lime** via articulated tanker HGV from Buxton to SLDelta.

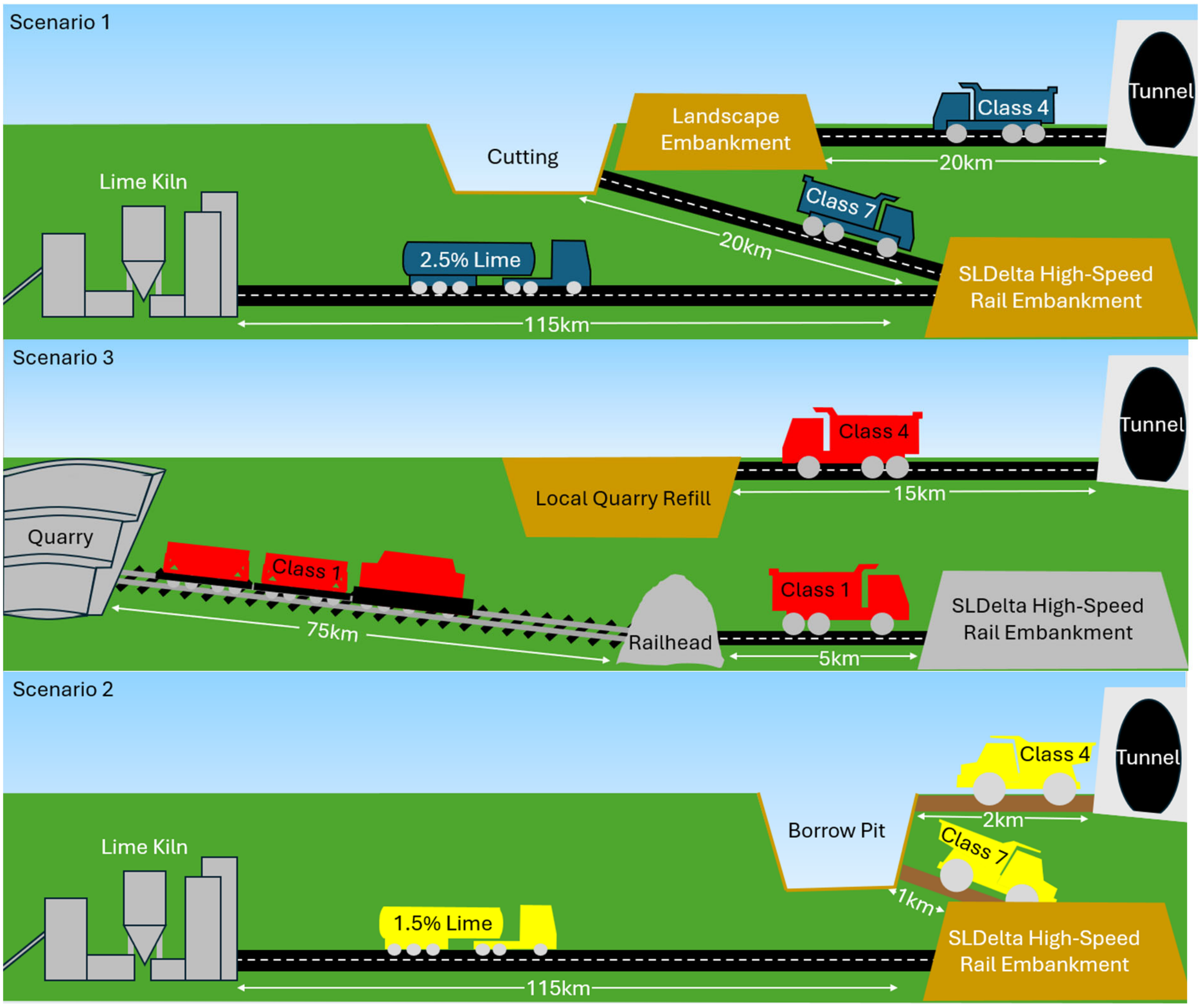

Figure 1 - Schematics of the three scenarios compared in this case study

Scenario 3 – No Lime stabilisation
Without lime stabilisation and no alternative granular fill source, 800,000m³ of Class 1 (granular full suitable for HSR) would need to be sourced from quarries. However, given nationwide quarry demand, this would be **logistically impractical and prohibitively expensive**. If somehow feasible, it would utilise the highest capacity peak district quarries needing:

- **Rail freight** of 800,000m³ Class 1 fill from Peak District quarries to a Midlands railhead.
- **5km** public road haulage of 800,000m³ via rigid HGV from railhead to SLDelta.
- **15km** public road haulage of 800,000m³ tunnel arisings for quarry restoration.

3.1 Carbon calculation – step one: CO_2 emissions

The first step focuses on quantifying the CO_2 emitted from two sources which vary substantially across the three scenarios i.e. CO_2 from the freight haulage and CO_2 embodied within the materials (particularly lime). It is noted the work would necessitate other activities to place and compact fill (with / without lime treatment) would increase the total amount of CO_2 emission, however, relative to the aforenoted, these would be only moderately different across the scenarios. Accordingly full CO_2 quantification is not done due to the limited scope of this paper, however, the recommendations will conclude it would be a useful follow-on exercise. The carbon emissions generated form transport and embodied within the products is summarised in Table 1 and the basis for making these calculations is summarised below.

Table 1 - Calculations for carbon emissions from transport and materials

	Scenario	Return Journey Description	Vehicle	Laden or Unladen	Distance (km)	Number of Trips	tCO_2e
Transport	1	Class 7 from MLN to SLDelta	Rigid	Laden	20	88,421	3,973
				Unladen	20	88,421	1,326
		Tunnel arisings from SLDelta to MLN	Rigid	Laden	20	88,421	3,973
				Unladen	20	88,421	1,326
		2.5% Lime dose delivered to site	Artic	Laden	115	1,286	280
				Unladen	115	1,286	91
						Transport Subtotal	10,969
	2	Class 7 from borrow pit to site	ADT	Laden	1	42,000	234
				Unladen	1	42,000	37
		Tunnel arisings to borrow pit	ADT	Laden	2	42,000	469
				Unladen	2	42,000	74
		1.5% Lime dose delivered to site	Artic	Laden	115	771	168
				Unladen	115	771	55
						Transport Subtotal tCO_2e)	1,037
	3	Quarry to railhead	Rail	Laden	75	1227	3,835
				Unladen	75	1227	3,836
		Railhead to site	Rigid	Laden	5	96,842	1,088
				Unladen	5	96,842	363
		Tunnel Arisings to local quarry restoration	Rigid	Laden	15	88,421	2,980
				Unladen	15	88,421	995
						Transport Subtotal tCO_2e	13,097

	Scenario	Material	Addition Rate (%)	Mass Required (t)	Embodied Carbon Factor (tCO_2e/t)	tCO_2e
Material	1	Lime	2.5	36000	0.78	28,080
	2	Lime	1.5	21600	0.78	16,848
	3	Aggregate	N/A	1840000	0.004928	9,067

Calculation Methods: Transport: Number of trips = volume x wet density / payload Unladen tCO_2e = 0% laden factor x trip distance x number of trips Laden tCO_2e = 100% laden factor x trip distance x payload x number of trips Materials: Mass lime required = volume x dry density x binder addition rate Mass aggregate required = volume x bulk density Total embodied tCO_2e = Mass lime/aggregate required x embodied carbon factor	Scenario	Total tCO_2e
	1	39,049
	2	17,885
	3	22,558

Transport. Baseline density and transport factors (from DESNZ, 2024) used to determine CO_2 from freight of materials are summarised in Table 2 and the lower portion of Table 1 shows how they were applied to the scenarios. For HGV delivery the approach separates a 100% laden delivery journey from an empty return journey, which is realistic for the separate/ongoing processes. No figures were available for ADTs and for this limited scope paper the $kgCO_2e/t.km$ used for the Rigid HGVs were increased by 18% to account for the authors best estimate of their lesser efficiency on the internal route. DESNZ (2024) provides only one CO_2 per km figure for train freight so it was applied for both delivery directions.

Materials. The embodied carbon from the cradle to gate manufacture. Values for both lime and aggregate were taken from the Inventory of Carbon and Energy V4.0 (Jones & Hammond, 2024)

Table 1 demonstrates that even before the benefits of carbon sequestration are applied, the optimised lime stabilisation approach of scenario 2 would comprise the lowest carbon footprint approach as it has 20% less combined transport/product CO_2 than the quarried import option. The benefits of the value engineering and research programme to justify a 1.5% lime dose is clear as the optimal scenario has 55% less calculated CO_2 than the initial approach.

Table 2 - Assumed information used for the calculations in Table 1

Assumed Density of Class 7/Tunnel Arisings	Dry Density	1.8 t/m^3
	Bulk Density	2.1 t/m^3
Assumed Density of Granular Fill	Bulk Density	2.3 t/m^3

Method of Transport	0% Laden Factor ($kgCO_2e/km$)	100% Laden Factor ($kgCO_2e/t.km$)	Assumed Payload (t)
Rigid Bodied HGV (Rigid)	0.74987	0.11824	19
40t ADT	0.8848466	0.139523	40
Articulated Tanker (Artic)	0.61558	0.06763	28
Rail	0.02779	0.02779	1500

3.2 Carbon Calculation – Step 2: towards LCA accounting for sequestration

Table 3 calculates the degree of carbonation to cause CO_2 sequestration within the lime treated earthwork for scenario's 1 and 2. As discussed above the approach compares both the conservative 33% and Kleib et al. (2024) degree of carbonation values, the latter is used to reflect current state of science demonstrating higher degrees of carbonation associate with lower doses. These sequestration values have been used to revise the embodied carbon in the lime and LCA CO_2 as shown in Table 3

Table 3 - Embodied carbon and LCA of lime used in scenario 1 and 2 based on Kleib et al. (2024) carbon sequestration % and a conservative baseline for comparison.

Scenario	Lime Addition (%)	Embodied tCO_2e (from The carbon emissions generated form transport and embodied within the products is summarised in Table 1 and the	% CO_2 Sequestration	LCA lime tCO_2e

		basis for making these calculations is summarised below. Table)			
1	2.5	28080	Conservative	33	22576
			Kleib et al.*	39	20555
2	1.5	16848	Conservative	33	11288
			Kleib et al.*	51.5	8171

* values were interpolated from the 1, 2, 4% lime factors in Kleib et al (2024)

3.3 Case study LCA considerations and cost

With the carbon sequestration and a step towards LCA applied, both lime stabilised scenarios 1 and 2 have much reduced transport and materials CO_2. The optimised scenario 2 now has 59% (Kleib et al, 2024) or 45% (conservative) less CO_2 than the quarried import scenario 3. Other LCA benefits to the lime stabilisation option would be the avoidance of using 1.84 million tonnes of finite quarried stone, which could be preserved for other uses. While cost considerations were not a primary focus of this paper, an outline cost comparison of the material / haul costs has been presented in Table 4 to highlight how lime stabilisation was the only viable option and how the optimised approach saved approximately £10million.

Table 4 - Additional cost and transport considerations for each scenario

Scenario	Total tCO_2e (accounting for LCA)		Cost*			Number of road movements
			Transport	Materials	Total	
1	Conservative	33,480	£12 million	£5.4 million (Lime)	£17.4 million	356,256
	Kleib et al.	31,458				
2	Conservative	**12,322**	£4 million	£3.2 million (Lime)	**£7.2 million**	**1,542**
	Kleib et al.	**9,205**				
3	22,558		£12 million	£55.2 million (Quarried Aggregate)	£67.2 million	370,526

*Assumptions - a) cost of road haul using rigid body tipper lorries based on £15 per cubic meter b) Cost of site haul using ADT at £5 per cubic meter c) lime at £150 per tonne (including transport) d) quarried aggregate at £30 per tonne

4. Conclusions

This paper has taken a step towards LCA for lime stabilisation earthworks by including the benefits of carbon sequestration in carbon calculations. A best practice and more complete LCA approach should quantify this sequestration alongside other environmental benefits such as waste reduction and preservation of finite resources.

A case study based around a large earthworks operation (1.6million m^3) for HS2 Midlands embankments has demonstrated best practice approaches to minimising haulage and material CO_2 means lime stabilisation was the most favourable carbon option by a twofold factor. It was also the most cost-effective approach by a 9-fold factor. This was achieved by:

1. Value engineer the cut and fill balance to minimise haul distances;
2. Use targeted research into lime stabilisation efficiency to justify 40% reductions to lime dose; and
3. Applying carbonation effects using both conservative (33% carbonation) and state of the art considerations

The time and effort to identify, explore and obtain approval for the use borrow pits must be recognised. Collaboration between contractor, designer, client and environmental approval bodies (e.g. Environmental Agency) is also crucial to success. It is also important to allow sufficient time for lab and field trials to support the application of the research to the project.

It is acknowledged that where a local source of suitable granular fill source is available this will likely still be the best option in any LCA, as noted by Hughes *et al* (2011). However, this study shows where that is not an option lime stabilisation should be considered the optimum. As the lime industry advances towards Net Zero (as targeted for 2040) then case for lime use will be further strengthened. It is recognised that not all embodied carbon was considered in the scenarios presented but any additional carbon was deemed insignificant enough to not impact the overall magnitudes presented to enable comparison. It is recommended that there is further research following paper that quantifies other LCA benefits.

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