BRITPAVE SOIL STABILISATION TASK GROUP

RESEARCH REPORT:

THE LEACHABILITY OF STABILISED SOILS

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The British Cementitious Paving Association

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The British Cementitious Paving Association

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INTRODUCTION

The stabilisation of weak natural soils using binders such as lime and/or cement is a sustainable method to enable re-use of otherwise unsuitable fill material in civil engineering projects. This improvement technique avoids landfill of poor materials and the import of quarried aggregates and is a sustainable and cost-effective method which has been extensively used in the UK since the 1980's.

Notwithstanding the strong positives of soil stabilisation, concerns are sometimes raised over the leaching potential of certain chemistries from lime or cement stabilised soils. While the Britpave Soil Stabilisation Task Group (SSTG) expert members generally understand and advise these pollution risks to be low relative to the volume of treatment undertaken, there have been a small number of specific cases where high pH water has been discharged from sites where soil stabilisation was used. Of these two instances it is considered by Britpave that the likely reason pollution occurred was due to the type of land drainage causing rainwater to flow through the treated material, elevating the leachate pH before discharge. Britpave consider this type of drainage as unsuitable to be placed into stabilised fill. To alleviate concerns and promote the safe use of soil stabilisation, Britpave commissioned a research project to assess properties of stabilised soils and associated leaching behaviour to provide advice and inform control methods.

This project investigated the leaching potential of UK soils stabilised by different dosages of lime and cement following extended leaching test methods in accordance with BS EN 15863:2015. Britpave member Balfour Beatty worked with Nottingham Trent University (NTU) to deliver this programme of work. Balfour Beatty obtained, characterised and prepared soil samples for NTU to test. Leaching tests were undertaken at NTU's Maudslay Civil Engineering Laboratory with chemical testing of the leachate undertaken by colleagues in the Chemistry Department at Clifton Campus. This publication provides the findings of the project with interpretation and recommendations.

PRACTICE AND LITERATURE PERSPECTIVES ON LEACHING RISKS

PRACTICE PERSPECTIVE

With regards to the potential for significant quantities of leachate emanating from lime and/or cement treated earthworks to cause pollution, BS EN 16907-4 (BSI, 2018; annex M) states:

"The possibility of binder leachate is unlikely as far as currently known, because they are effectively consumed within the improved layer to form a cemented material with cementitious gels."

And further notes *"the potential for quicklime to migrate through clay soils have found that migration is negligible, i.e., less than 50 mm"*.

Britpave members concur their usual experience strongly aligns with the above statements. Where they are aware of very rare problems with high pH leachate, they were in the member's opinion limited to specific situations of poorly designed permanent drainage causing surface water to infiltrate and flow through stabilised material before discharging to a watercourse.

There is no direct knowledge of Cr(VI) issues directly sourced from adding cement for stabilisation to natural fill sources. Members experience is the opposite, as cement stabilisation of contaminated land is typically validated with tank testing and substantial reduction in potentially toxic leachates, Cr(VI) being one such routinely monitored parameter, is the normal and expected outcome.

WHY BINDERS ARE POSSIBLE LEACHATE SOURCES

As stabilised soils increase in strength due to pozzolanic reactions and / or cement hydration, there are several phases common to both lime / cement stabilised soil which could leach lime e.g. Calcium Hydroxide ($Ca[OH]_2$); Calcium Silicate Hydrate (C-S-H); Calcium Aluminate Hydrate (C-A-H) and Calcium Alumino-Sulphate Hydrates (such as ettringite and mono-sulphate).

Most prevalent is the $Ca(OH)_2$ which rapidly forms when both lime and cement powders are hydrated in the soil mixing process. In its unbound / unreacted state, $Ca(OH)_2$ is preferentially leached, although it's very low solubility of $Ca(OH)_2$ e.g. 1.73grams/litre in 20°C water, means static water soon becomes saturated and significant dissolution could only occur with regular fresh water replacement (Maltais et al., 2004). $Ca(OH)_2$ dissolution is through dissociation into Ca^{2+} and hydroxyls, with the latter increasing the solution pH to a maximum pH12.4. As Portland cement also contains significant hydroxides of potassium and sodium, which are very strong bases, the alkalinity of these solutions may initially be higher i.e. pH13-14 (Baston et al., 2012).

While cement hydration products e.g. C-S-H, C-A-H; form relatively rapidly (hours) they remain metastable for months. For lime stabilisation the pozzolanic reactions are much slower to develop substantially (weeks, months and possibly years) the added and unreacted Ca(OH)2 would slowly be consumed:

i. as pozzolanic reactions between silicate and aluminate from clay minerals combine with calcium hydroxide to form cementing gels

ii. with time for diffusion of the Ca^{2+} and hydroxyls through the pore water, allowing pozzolanic reactions to penetrate pervasively and deep into the clods of soil.

Laboratory studies indicate leaching of cementitious systems can continue after all unreacted $Ca(OH)_2$ has been removed albeit at a diminished rate. $Ca(OH)_2$ would then be removed from the substantially less soluble C-S-H (Maltais et al., 2004) and may also be leached from other hydrates e.g. some C-A-H phases (Ekström,2001).

Chromium (Cr) is a naturally occurring element in typical near surface concentrations of 35mg/kg, but up to 2300mg/kg in ultrabasic igneous rocks and most natural sources of Cr occur in the harmless / insoluble reduced oxidation state of Cr(III) (Rawlins et al, 2012). However, human industrial process, in particular those which elevate pH higher than 9, may cause oxidation to the soluble Cr(VI) state which in elevated concentrations may be carcinogenic (Unceta, 2010). While, cement manufacturing environments can promote Cr oxidation, since the early 2000's UK manufacturers have added reducing agents, e.g. Ferrous sulphate, to ensure hydrated cements have <2mg/kg soluble Cr(VI) (Taylor, 2015). While it seems unlikely that use of cement in a soil stabilisation application would diminish the reducing properties of such agents, the authors are not aware of any literature to this effect and hence this experimental work has directly investigated Cr leaching.

PERMEABILITY

Permeability is of fundamental importance in consideration of any leachate scenario as water is essential to cause dissolution and then transport the solute. Cohesive fills are composed of individual clods and permeability is principally controlled by the large pore space (or macro-porosity) around these, so that a loose structure will have high permeability through open channels (Figure 1a). Whereas a dense structure will force water through the intact structure clods (Elsbury et al 1990).

Factors such as moisture content, clod size, and compactive effort significantly affect interclod porosity and permeability in both untreated and lime treated soils (Benson and Daniels, 1990; Cuisinier et al, 2011). For instance, increased moisture content or higher compaction effort reduce macropore spaces, thereby substantially lowering permeability. Beetham et al. (2015) noted that preparation techniques, such as longer mellowing periods, especially with higher lime percentages enhance clod strength, promoting low ductility clods and a structure prone to high interclod porosity after compaction.

It is well known that the immediate lime-clay reactions promote flocculation of the clay particle structure and literature conclusions are typically that this enhanced porosity increases permeability from untreated (e.g. Bell, 1998; Townsend and Klym, 1966; McCallister and Petry, 1992). However, it must be considered that small scale laboratory studies use fine particles of clay homogenously mixed with lime which effectively isolate the micro-pore structure influence. This preparation potentially obfuscates the field scale process where clod flow has primary influence. In this regard Cuisinier et al. (2011) quantified that while lime treatment substantially increased the volume of smaller pore classes, their influence on permeability was minimal to conclude permeability of lime treated soil is dominated by the macropores as visualised in Figure 1.

Over time, permeability generally decreases as pore-blocking occurs due to the crystallization of calcium aluminate hydrate (C-A-H) and calcium silicate hydrate (C-S-H) gels, consistent with findings by El-Rawi et al. (1981) and Wild et al. (1987). Long-term data suggest that stabilized soils eventually achieve permeability levels comparable to natural clay (Gutschick, 1978).

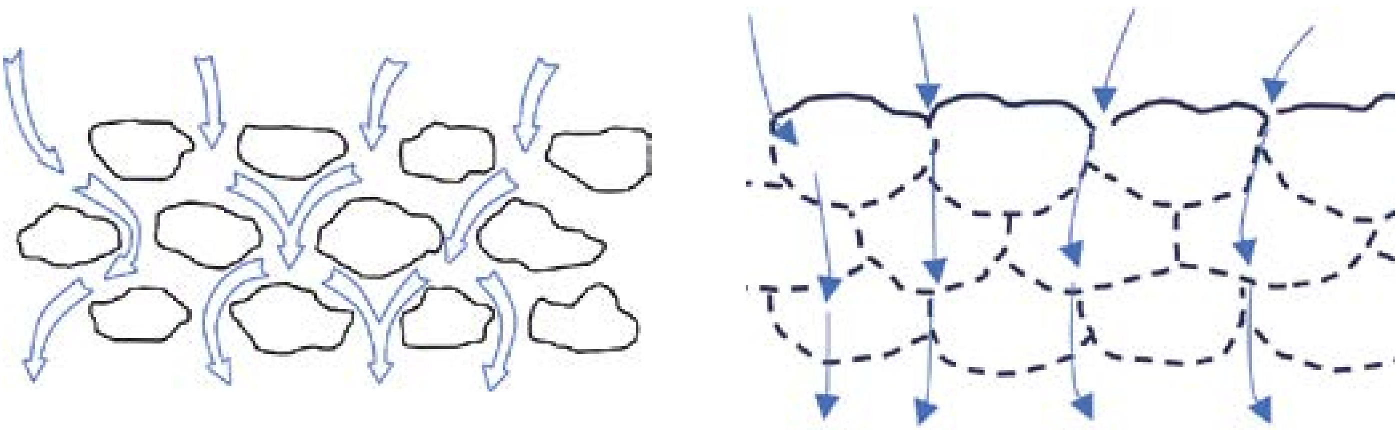

Figure 1 - (after Elsbury et al, 1990) Influence of soil clods on the permeability of compacted clay. a, (left) shows a loose structure and high permeability from flow around clods. b, (right) shows a dense structure and low permeability controlled by through clod flow

LEACHATE STUDIES

Literature contains a limited number of studies on stabilised soil leaching typically tracking both pH and Ca^{2+} concentrations by taking eluates (leachate extracted in a controlled test). While differences in test set up, eluate timing and overall duration will prevent direct comparison to the British Standard tank testing procedure used in this study (described later), it provides a basis for consideration. Notable findings across key studies by McAllister and Petry (1992), De Bel et al. (2005), Deneele et al. (2016) are:

- For all except the lowest lime binder doses of 1% which ranged pH9.5-10.5, eluate alkalinity was typically >pH11 and up to the maximum pH12.4. The initially high pH values typically decreased steadily as leaching cycles progressed. Similar trends are seen in studies using cement although initial values up to pH13 were noted.
- Ca^{2+} ions were also greatest in high lime doses and within the initial eluates but generally reduced over time. Specimens prepared dry of Optimum Moisture Content (OMC) had the highest Ca^{2+} concentrations, whereas specimens wet of OMC (WMC) would have significantly less.
- Where studies undertook parallel strength testing, they associate reduction in eluate pH over time with progressive decalcification of C-S-H and considerably reduced specimen strength. However, longer curing before soaking and a higher lime dose (3% instead of 1%) substantially reduced the extent of strength loss.

SCOPE OF WORKS

The experimental testing evaluated the leaching potential of stabilised soils using tank testing BS EN 15863:2015. This method is commonly used in practice to assess the efficacy of soil stabilisation in remediation projects.

U100 (200 mm h, 100 mm dia.) specimens used for the tank test had binder contents of 1.5%, 3% and 4.5% lime and 1% lime / 2% cement and 1% lime / 4% cement to represent the range of binder dosage typically adopted in the UK. Cement stabilised specimens were included in the scope to particularly assess the release of chromium and other heavy metals. Specimen preparation is detailed underneath. In total, 78 individual U100 specimens were compacted for the trials and around 800 individual eluate samples were taken and analysed.

In addition to the U100 specimens and wanting to demonstrate relevance to field practice, two 300 mm x 340 mm x 340 mm blocks of material stabilised with 1.5% lime in Summer 2020 were carefully extracted from a 3m high trial embankment and sealed to prevent moisture loss then put into storage. The blocks were characterised as sample quality class 1 undisturbed samples in accordance with BS5930 2020 and had the following in situ properties:

Block A:	Block B:
Dry density – 1.706Mg/m^3	Dry density – 1.810 Mg/m^3
Moisture content – 20.5%	Moisture content – 13.0%
Air voids – 1.4%	Air voids – 8.9%

Block A was left whole (Figure 2) but Block B was sectioned into 5 specimens roughly equal in volume to the U100 specimens. This allowed direct comparisons of long-term field stabilised material with lab prepared material as well the effect of surface area on the leachability of stabilised material i.e. does a larger specimen (e.g. stabilised embankment) leach less per unit volume. Additionally, a comparison could be made between material with different air voids percentages and whether higher air voids would create a pathway to increase leachability. The relative dimensional data for each size of specimens can be seen in Table 1.

Specimen Type	Surface Area (m^2)	Volume (m^3)
U100	0.0785	0.00157
Small Field Block	0.0794	0.00152
Large Field Block	0.615	0.0347

Table 1 - Comparison of geometry for different specimen types

Figure 2 - Left – Sampling the block during field trial in 2020. Centre - Field block specimen extracted from its storage casing after more than 3 years of curing. Right – Block specimen in its soaking container

SAMPLE PREPARATION

A standard laboratory method was used to produce a uniform blended stock of two host soils (Merica Mustone;MMG and Glacial Till;GT which are characterised below), moisture-conditioned to a consistent pre-binder moisture content. Lime was then mixed in by hand, followed by a two-hour mellowing period before further water and cement additions, as applicable. This process produced a degree of pulverisation comparable to the field block material.

The U100 cylindrical specimens were compacted using two different compaction efforts described below.

1. The main approach for both MMG and GT materials used 2.5kg rammer (normal proctor; 25 blows in 5 layers) and included OMC and WMC (10% wet of OMC) sub batches.
2. To assist comparisons with the field block which field records indicated had a field compactive effort that equated to approximately 1.64MJ/m^3 and had been cured for approximately 3.5 years extra U100 batches were created for the MMG which all used 1.64MJ/m^3 compaction effort (5 layers, 25 blows, 4.5 kg rammer). These specimens, were all prepared at the same moisture content as the above noted WMC 2.5kg specimens and sub batches were air cured at 28 days and 90 days before soaking.

Air voids in all U100's were <5% and the average deviation from target moisture content was minimal at 0.2% for MMG and 0.4% for GT. Minimum relative compaction (compared to 2.5 kg rammer maximum dry density) was 96% for MMG and 95% for GT, both occurring in WMC prepared specimens as expected.

Following compaction, specimens were wrapped in cling film and placed in a close fitting, sealed bag for air-cured for 28 days at 20°C (except the above noted exceptions cured for 90 days) before tank soaking (Figure 3).

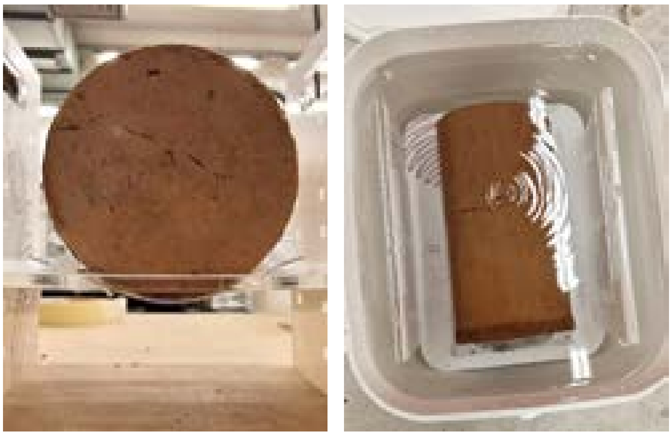

Figure 3 - Photographs of soaking set up for leachate testing. Left – Frame holding specimen to allow access to entire specimen. Right – Specimen and frame positioned in the soaking water

LEACHATE TESTING

The stabilised soils were soaked in pure laboratory grade water as per the set up in Figure 3 and in accordance with BS EN 15863:2015, the eluates were taken and the demineralised, pH neutral water replaced after 0.25, 1, 2.25, 4, 9, 16, 36, 64 days. The tank testing was extended to 128 and 256 days for select batches days i.e. 60% of the U100's and all the field blocks. For each of the sampled eluates and a cumulative specimen (a 50ml sample comprising of 5ml of each of the 10 eluates) for each batch, the pH and conductivity were measured and elemental quantification carried out using Inductive Couple Plasma (ICP) at NTU's chemistry department.

To add robustness from repeatability, every U100 sub batch had 3 specimens so that every leachate result is the average of 3 measurements. While there was only 1 large block A, 3 eluate samples were taken representing each third as the tank emptied. The Block B was cut into 5 blocks so results are the average of 5 specimens.

UNCONSOLIDATED UNDRAINED (UU) TRIAXIAL / PERMEABILITY

When the tank testing was complete, a single U100 from each batch was tested for permeability in accordance with BS EN ISO 17892-11 using cell pressure of 10kPa and specimen pressure differential of 10kPa. Immediately after permeability testing, unconsolidated undrained triaxial testing in accordance with BS EN ISO 17892-8 was undertaken to determine undrained shear strength at a 50kPa confining stress.

THE TEST SOILS

Noting that composition and mineralogy may influence leaching characteristics, natural soil with no evidence of contamination were sourced from three different geological formations commonly encountered in UK construction were targeted. These were; Sidmouth Formation (weathering grade IV) of the Mercia Mudstone Group (**MMG**) from the Midlands, Glacial Till (**GT**) from Oxfordshire and a weathered (brown) London Clay (**LC**) from the Chilterns (classification data in Table 2). These sources were identified for their differences in plasticity with the MMG being low plasticity, the GT being intermediate plasticity and the LC being high plasticity.

Due to suspected sulphate swell (total potential sulphate (TPS)>1.1%) issues causing, the LC specimens disintegrate upon water immersion and so were discarded from the trial.

Geology	Particle Size Distribution (Percent passing)							Atterberg Limits			Chemical Testing		
	20 (mm)	10 (mm)	5 (mm)	2 (mm)	0.6 (mm)	0.425 (mm)	0.063 (mm)	LL (%)	PL (%)	PI (%)	pH	TPS (%)	Organic matter content (%)
MMG	100	99	96	90	85	84	77	34	17	17	8.7	0.1	0.2
GT	100	98	96	94	92	91	74	42	18	24	8.4	0.2	0.6

Table 2 - Characterisation data for host material sources. Results an average of minimum 3 tests

As the investigation included quantifying heavy metals leaching from stabilised soil specimens, leachates from dried powders of the untreated soils were evaluated for the same metals using ICP after two separate extraction methods conducted by the NTU chemistry department:

1. In accordance with BS EN 12457-2 the soil was mixed in a solid to pure water ratio of 1:10, agitated with an end over end tumbler procedure, with the resulting eluate centrifuged to remove suspended solids.
2. An alkali digest of the soil by boiling for 1 hour in a 0.5M NaOH solution (of pH13.52) at a 1:10 solid to liquid ratio. The eluate was centrifuged to remove suspended solids.

Table 3 shows that the alkali digest typically led to much higher determinations of most heavy metals than the lab water method. Principally, this demonstrates that a very high pH may increase the solubility of some metals in the natural soil, most notably As and V in the NaOH digest being two orders of magnitude higher than the lab water equivalent. While the host materials are thought to be a clean naturally occurring sources, this shows that there are potentially heavy metals present in the soil which can become more mobile in high pH environments. The outputs from these aggressive test methods will be compared with those from the tank tests.

	MMG				GT			
	1:10 NaOH Digest		1:10 water		1:10 NaOH Digest		1:10 water	
	Min	Max	Min	Max	Min	Max	Min	Max
Sb	Tr.	10	Tr.	Tr.	Tr.	20	Tr.	Tr.
As	45080	50290	260	354	25170	28040	Tr.	Tr.
Be	Tr.	Tr.	Tr.	Tr.	Tr.	Tr.	Tr.	Tr.
Cd	Tr.	20	Tr.	Tr.	Tr.	30	Tr.	Tr.
Cr	430	960	57	101	430	490	Tr.	5
Cu	590	850	58	116	6430	8430	Tr.	21
Pb	240	270	11	25	150	190	Tr.	Tr.
Hg	40	50	Tr.	Tr.	100	160	Tr.	5
Ni	30	100	38	58	110	230	Tr.	Tr.
Zn	940	1730	255	1083	600	1120	Tr.	98
V	34110	38010	238	271	12250	12930	Tr.	8
Se	Tr.	Tr.	7	21	Tr.	Tr.	16	33

Table 3 - Maximum and minimum leachate values (from 3 sub samples of the untreated soil) for heavy metals normalised to micrograms per kilogram µg/kg. Tr. – Trace, below limit of detection <5 parts per billion.

RESULTS

LEACHATE – OBSERVATIONS

All the stabilised specimens remained intact and the solutions visually clear with absence of any obvious suspended solids. This contrasted with untreated control U100s which almost immediately started to discolour the water and within hours were disintegrated to a soft and plastic sludge in turbid water. While colourless, the eluates had significant electrical conductivity (ranging 52-648mS/m), which closely trended with the calcium content and a corresponding high pH to indicate that, as expected, $Ca(OH)_2$ was the primary dissolving substance. These are discussed in further detail below.

An unexpected observation across the results was that there was little discernible difference between the leaching trends (EC, pH and elemental) between the OMC and WMC moisture conditions. Accordingly, no attempt is made to distinguish difference between OMC and WMC results and the WMC results are primarily described as the dataset is larger (additional E9-10 eluates). Similarly, the MMG_28d specimens of 1.64MJ/m^3 compactive effort were closely comparable to the 2.5kg specimens with examples shown for the Ca trend in Figure 6.

LEACHATE – HEAVY METALS

Across all batches the determinations of **heavy metals from stabilised soil eluates were all very low and often below the limit of detection**. The cumulative eluate specimen (average across the eluates) determinations are shown for the highest binder dosages (worst case) in Table 4. Of particular note is that none of the stabilised eluates (both individual and cumulative) had concentrations which exceeded the World Health Organisation (WHO) drinking water thresholds. Results from tank tests (which force leaching) are not usually directly compared with water quality standards as a pass / fail criteria but is done simply to show how low the concentrations are i.e. considered safe to drink. It can be seen the values leached from the stabilised specimens remain below the values leached from the natural soils using both the water and the aggressive NaOH digest method (Table 3). The elution method clearly has a substantial influence, demonstrating the potential for some lab tests to portray a much more negative version than methods evaluating more field relevant release mechanisms. Particularly it highlights how slow diffusive release was from these stabilised soil specimens.

As the study has a particular focus on Cr, the elemental Cr in each eluate from selected tank test specimens is also plotted in Figure 4. As expected, the 4% cement stabilised specimens had the highest values across the study period and GT samples were notably higher than the MMG equivalent. Notwithstanding and even after 256 days, a period exceeding the usual cycle of 64 days by 4 fold, the highest Cr value recorded was 37µg/l. For comparison the WHO drinking water standard limit for Cr is 50ug/l. Figure 5 helps quantify how the extremely low Cr diffusion rates further reduced on an inversely proportional basis over time. Taking the worst case (GT_QL1C4_2.5kg) as an example, the initial Cr flux rate of 1.58×10^{-5} mg/m^2 per second reduced by 2 orders of magnitude to 6.69×10^{-7} mg/m^2 per second by 256 days.

	MMG		GT	
	QL4.5 Cum.	QL1+C4 Cum.	QL4.5 Cum.	QL1+C4 Cum.
Sb	Tr.	Tr.	Tr.	Tr.
As	Tr.	Tr.	Tr.	Tr.
Be	Tr.	Tr.	Tr.	Tr.
Cd	Tr.	Tr.	Tr.	Tr.
Cr	7.1	11.6	3.5	24.5
Cu	11.6	10.4	1.6	0.8
Pb	Tr.	1.1	Tr.	Tr.
Hg	0.9	0.7	Tr.	Tr.
Ni	1.6	2.3	1.4	2.9
Zn	3.1	3.2	1.6	4.4
V	3.2	5.2	1.2	3.9
Se	0.8	0.8	4.8	1.6

Table 4 - Heavy metal elemental determinations in ppb (µg/l) leached from the cumulative eluate (average of E1-E10). Only the highest (maximum) and worst case values from triplicate testing are shown

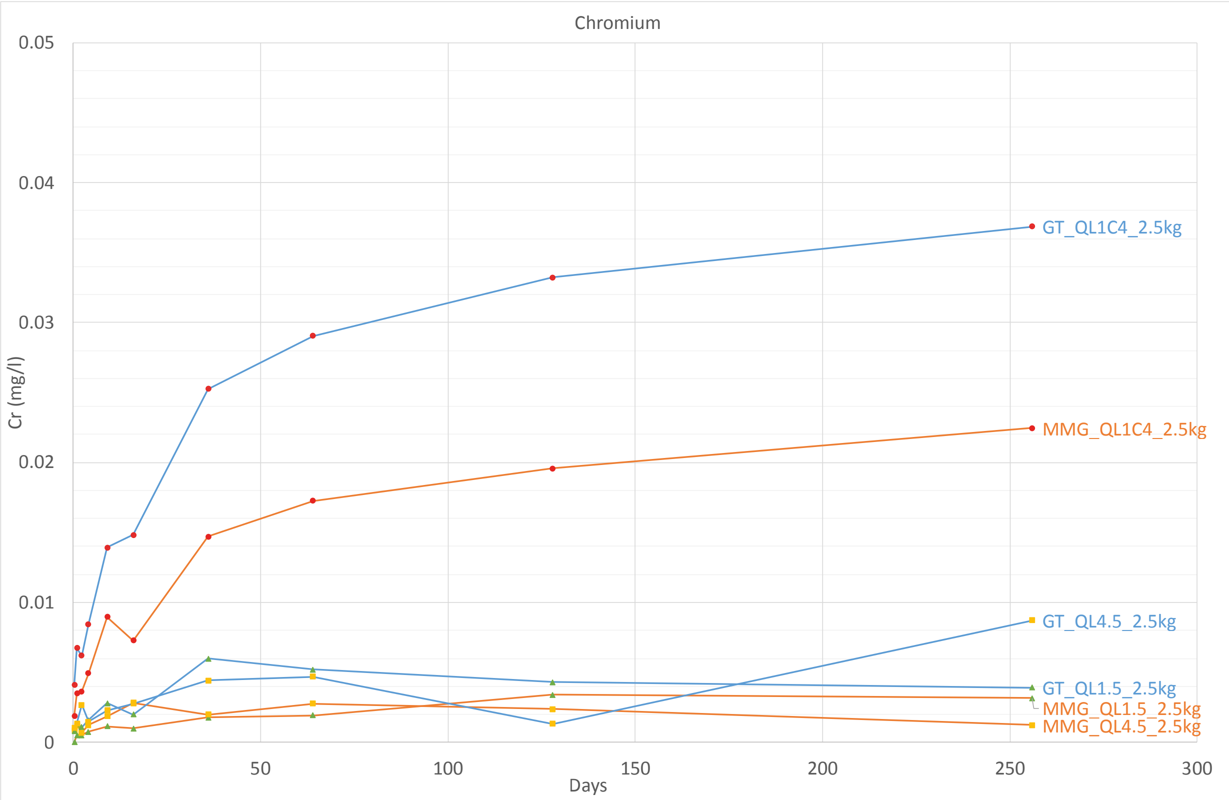

Figure 4 - Chromium leachate values for E1-E10. All values are the average of 3 specimens

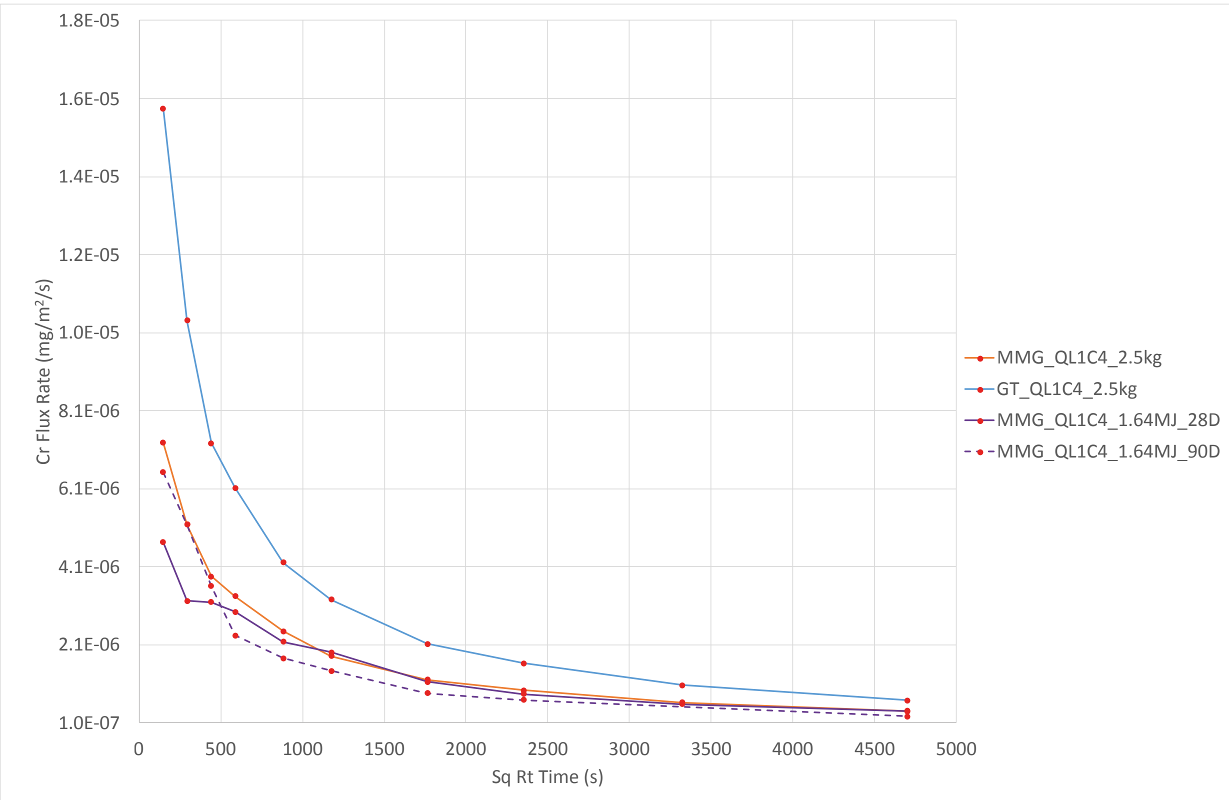

Figure 5 - Flux rate of chromium for E1-E10. All values are the average of 3 specimens

LEACHATE – $Ca(OH)_2$

$Ca(OH)_2$ dissolution is first described in terms of changes to calcium concentration and the corresponding changes to pH are considered below. Calcium was dissolved from the specimens via a diffusive process and Figure 6 shows the decreasing trend of cumulative calcium leached from the specimens in each batch. This data is normalised to mg/m^2 to remove difference in specimen surface area and allow direct comparisons.

Key observations are:

- The higher lime dosages have proportionally higher cumulative Ca, which is expected for diffusion along a higher concentration gradient.
- The flux and thus total calcium leached from the field blocks is much less than the lab prepared specimens. The total amount of calcium removed from the large block was minimal. While the flux from the small field blocks was a little higher, it was still much lower than the 1.5% lime lab specimens.
- For the MMG lab specimens the increased compactive effort has little influence on the flux rate and total calcium leached. However, the longer cure period of 90 days has a significant influence with 10th eluate cumulative Ca around 33% less than the 28 day equivalent.
- The GT specimens Ca flux and 10th eluate cumulative total is notably less than the MMG equivalents for both QL1.5 and QL4.5 dosage and this will be considered further in relation to the undrained durable strength.

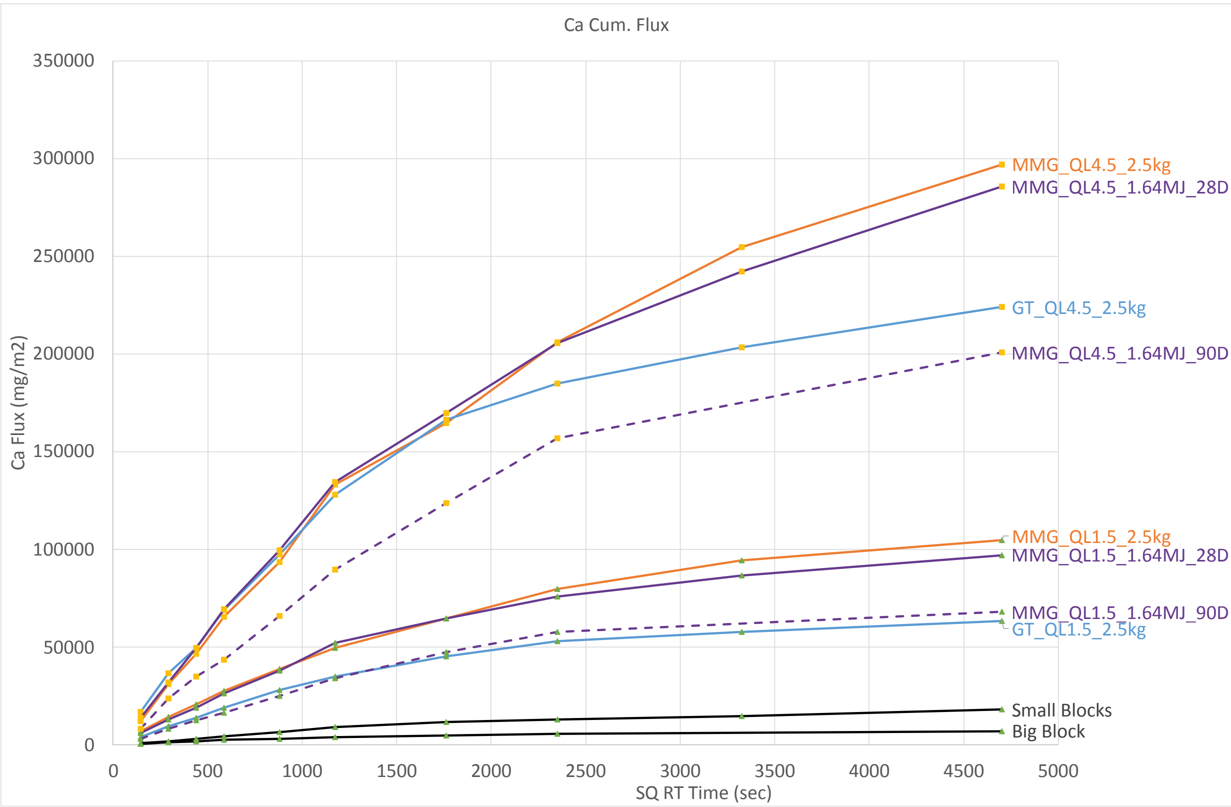

Figure 6 - Cumulative Calcium leached from each batch and normalised to mg/m² vs square root of time. Each point is the average from three specimens (or five for the small field blocks)

The eluate pH trend over time is shown below in Figure 7, which was principally similar for both GT and MMG soil types, but to aid clarity from overlapping trends, selected trends covering the range of MMG data are shown instead of all.

Key observations are:

- After 6 hours (E1), all lab prepared specimens had increased eluate pH to similar values ranging 11.3 to 11.5. Thereafter leachate alkalinity typically increase over time with QL4.5 specimens reaching pH12.4 by 64days. The QL1.5 and QL1C4 specimens increase at a lesser rate with maximum values of pH11.9-11.98 but 256 days. This matches the slow but continuous diffusive release of Ca seen above (Figure 6)
- In comparison to the U100 QL1.5 equivalents the field specimens have a substantially lower pH trend, again this is consistent with the Ca data. Noting that pH is a logarithmic scale and with a pH10.4 large field block E10 has approximately 32 fold less hydroxyl activity than E10 of MMG_QL1.5_2.5

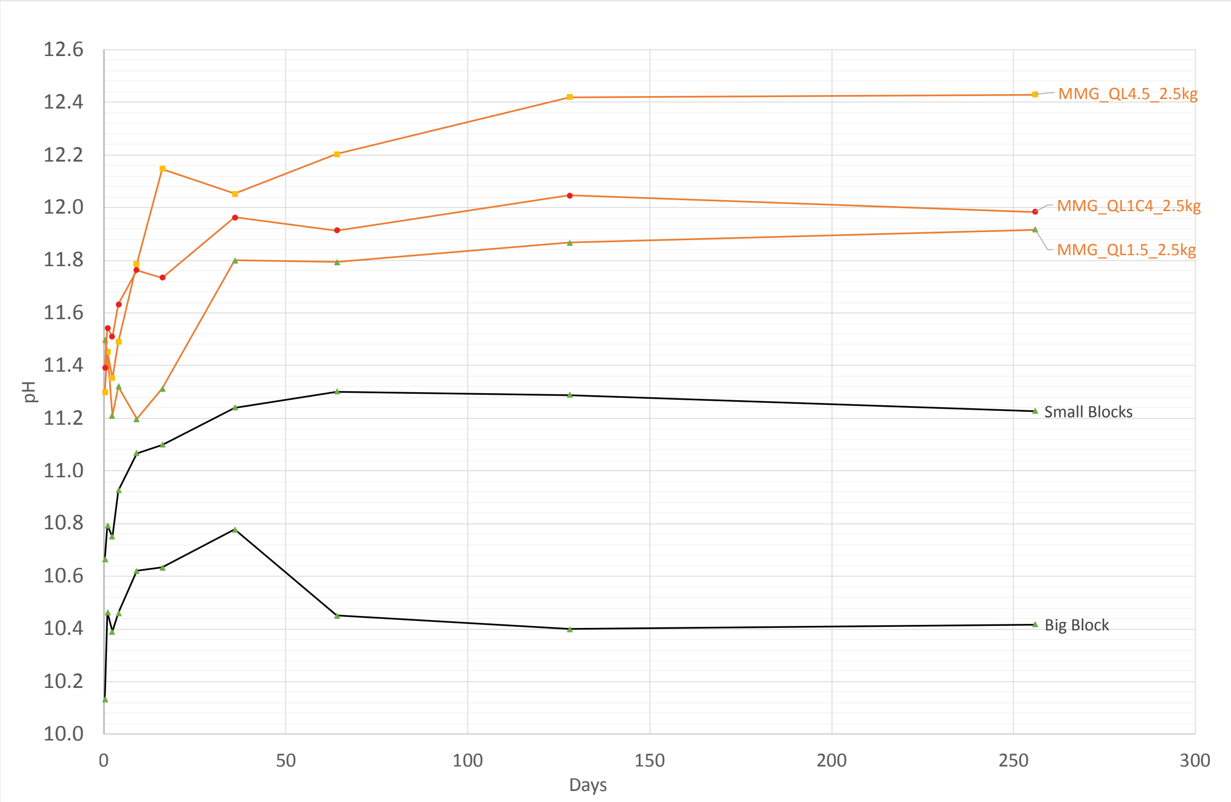

Figure 7 - Eluate pH trend from each eluate for the MMG 2.5kg and field block specimens. The 1.64MJ/m3 data is omitted to aid clarity. All values are the average of three specimens

Table 5 summarises permeability and Figure 8 displays the undrained shear strength for the specimens after soaking. The permeability results were all in the range $3.0x10^{-9}$ to $3.6x10^{-8}$ m/s with the exception of the 4.5% lime and 1% lime/4% cement $1.64MJ/m^3$ compactive effort specimens which were $6.2x10^{-7}$ and $5.4x10^{-10}$ respectively and as such are considered anomalous. Based on the definitions in CIRIA C750 (Preene et al, 2016), this would class the material as "very low" permeability.
As expected, the undrained shear strength results in all material types increased with the increase in binder. With regards to the shear strengths, the following trends are observed:

- The GT specimens exhibited higher strengths than their MMG counterparts with the lime only specimens appearing more sensitive to lime dosage
- With the higher $1.64MJ/m^3$ compactive effort, the strengths at all binder dosages are higher than the comparative 2.5kg specimen.

Sample Reference	Permeability (m/s)
MMG_QL1.5_2.5kg	$3.6x10^{-8}$
MMG_QL3_2.5kg	$1.1x10^{-8}$
MMG_QL4.5_2.5kg	$1.6x10^{-8}$
MMG_QL1C2_2.5kg	$9.2x10^{-9}$
MMG_QL1C4_2.5kg	$1.6x10^{-8}$
MMG_QL1.5_1.64MJ_28	$6.9x10^{-9}$
MMG_QL4.5_1.64MJ_28	$6.2x10^{-7}$
MMG_QL1C4_1.64MJ_28	$5.4x10^{-10}$
GT_QL1.5_2.5kg	$3.0x10^{-9}$
GT _QL3_2.5kg	$7.9x10^{-9}$
GT _QL4.5_2.5kg	$2.7x10^{-8}$
GT _QL1C2_2.5kg	$3.8x10^{-9}$
GT _QL1C4_2.5kg	$2.6x10^{-8}$

Table 5 - Permeability data for wet of optimum specimens tested after 256 days (single specimen only)

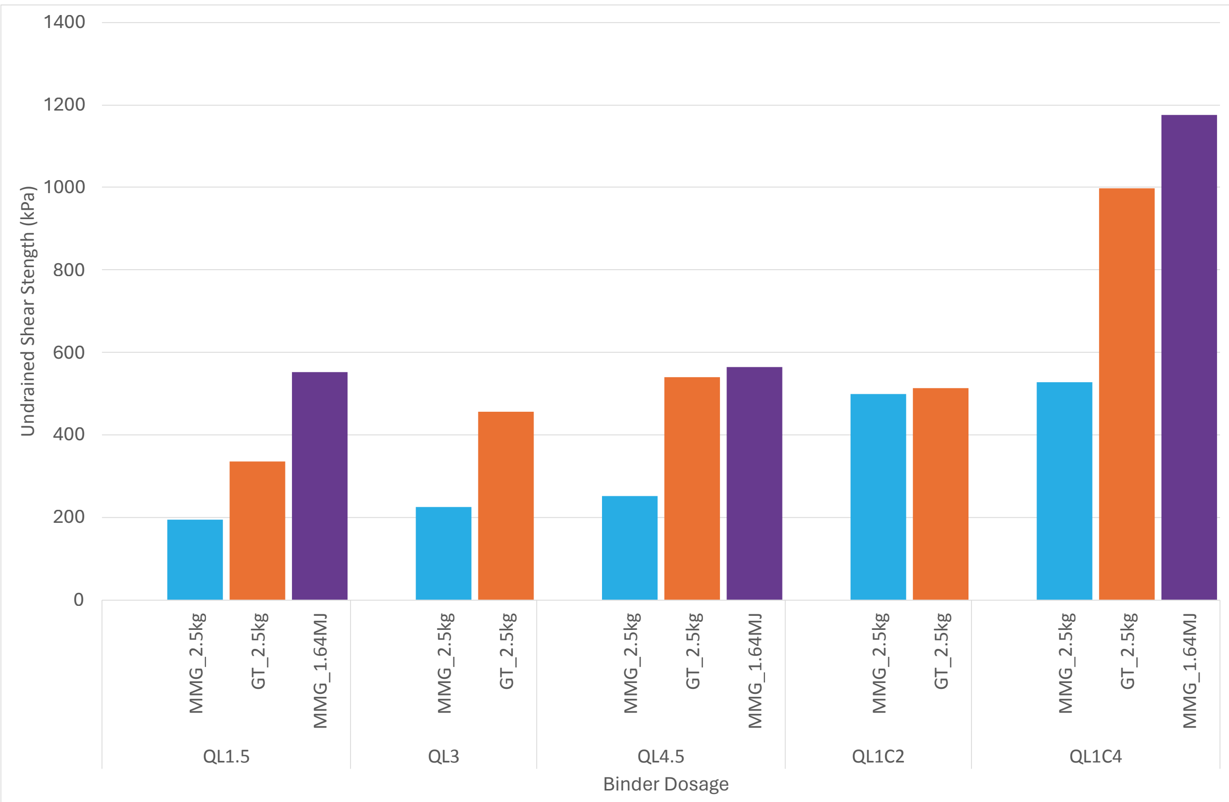

Figure 8 - Undrained Shear Strength of the wet of optimum Specimens tested after 256 days (single test @50kPa confining stress)

ANALYSIS AND DISCUSSION

Table 6 indicates the amount of residual CaO % remaining in lime treated specimens after 256 days of leaching (the method to calculate residual CaO % is summarised in the table caption). This highlights the minimal leaching of field blocks to retain 96-99% of their original lime. This is notably much greater resilience to lime leaching than the lab prepared specimens. As the field blocks had cured for approximately 3 and half years before tank testing it is considered the primary influence on leaching seen in this study is cure time before tanking. More curing time to permit pervasive pozzolanic reactions to effectively consume the $Ca(OH)_2$ into reaction products of C-S-H/C-A-H etc. and/or convert to calcite, so there is minimal unbound lime available to remove and this resounds with the findings of Deneele et al. (2016). The influence of cure duration is particularly striking considering the dry OMC and relatively high air voids of 8.9% of the small block specimens. McCallister and Petry (1992) associated a greater degree of lime leaching from the higher permeability of dry OMC specimens, yet the 3.5-year cure of the blocks in this study appears to have more influence to result in minimal leaching despite the imperfect moisture condition.

Another notable trend seen in Table 6 is the amount of lime removed by leaching is directly proportional to the amount added so the more binder added, the more there is to remove and cause leaching. However, the benefit of additional curing is also consistent in the MMG U100's with both 1.5% and 4.5% 90 day cured specimens retaining 82-83% of their dose after 256 days leaching, as compared to the 75-75% CaO retention seen in the 28 day cure equivalents.

Sample Reference	Original CaO Dose (%)	Residual CaO (%)	Proportion of CaO dose remaining (%)
MMG_QL1.5_2.5kg	1.5	1.07	71
MMG_QL4.5_2.5kg	4.5	3.19	71
GT_QL1.5_2.5kg	1.5	1.24	83
GT_QL4.5_2.5kg	4.5	3.51	78
MMG_QL1.5_1.64MJ_28D	1.5	1.14	76
MMG_QL4.5_1.64MJ_28D	4.5	3.39	75
MMG_QL1.5_1.64MJ_90D	1.5	1.25	83
MMG_QL4.5_1.64MJ_90D	4.5	3.71	82
Large Block	1.5	1.49	99
Small Blocks	1.5	1.43	96

Table 6 - Residual CaO for lime only specimens after 256 days of soaking, average of three specimens. The residual CaO in each specimen was calculated by: i) Multiplying the cumulative Ca (mg/l) removed after 256 days by the 6.5 litres the specimen was soaked. Report the total Ca removed in grams. ii) Multiplying the total Ca removed by 0.7147 to obtain the equivalent mass of CaO leached. iii) Use the CaO mass leached with the original specimen volume, particle density and moisture content to determine the equivalent percentage of lime removed. Subtract from the original dosage to obtain the residual lime %.

While only very small amounts of CaO are required to increase pH significantly e.g. 1g CaO in a litre of water equates to an approx. pH of 12.45, you can only generate a substantial amount of high pH water if there is sustained water flow into, through and out of the treated material. In this regard, the study has demonstrated that even after 256 days of aggressive elution forced by the tank test set up, the permeability of the stabilised specimens was very low. As an example, using the higher end of the typical permeability range of $3.6x10^{-8}$ m/s - $3.0x10^{-9}$ m/s, this would only amount to water being able to penetrate 3.1mm into a stabilised fill after 24 hours. This fundamentally mitigates the risk of significant flushing of high pH eluate from the material. While permeability values were determined from specimens prepared slightly wet of OMC (which is the recommended working practice; see Britpave BP62 and BP75), as leaching trends from OMC specimens mirrored those of the wet OMC, under the conditions tested this slightly drier condition had no significant influence on the diffusion driven leaching processes.

Therefore, the results support the long-standing practice perspective stated in BS EN 16907:4 (2018) that *"the possibility of binder leachate is unlikely as far as currently known"*. The only reasonably foreseeable ways for significant binder leachate to develop would be from:

- Poor soil stabilisation working practices such as poor mixing; inadequate pulverisation; excessively dry fill; insufficient compaction to a low density.
- Directly introducing a pathway into the stabilised material that promoted a high surface area in contact with flowing water.

That Britpave members experience of high pH water discharge is limited to specific situations where infiltration drainage was known to have been installed into stabilised material. This should be avoided as such approaches would contradict longstanding industry guidance, with some below key documents quoted:

BS EN 16907:1 (2018, p49) 'Earthworks Part 1: Principles and general rules'

> *"The earthworks designer should identify the likely pathways for significant water inflow that may have an adverse effect on the earthwork (Figure 8), either during or after construction; and identify appropriate temporary and permanent drainage measures. Each case requires a specific design which should consider issues such as flow capacity, outfalls, and maintenance requirements during construction."*

BS 6031 2009; corrigendum 1 'Code of Practice for earthworks' (BSI, 2019; p51):

> *"the attention of the earthworks designer should be drawn to the potentially deleterious effects that poorly planned SUDS can have on either pre-existing or newly designed earthworks" and "consider the potential impact of SUDs on earthworks stability, i.e. aim for infiltration areas away from at risk areas to gain the benefit of SUDS and avoid additional risk."*

The CIRIA SUDs Manual (Ballard et al, 2015) makes specific reference to soil stabilisation.

> *"The existing subgrade materials may also be improved by the addition of lime and/or cement to give an acceptable long-term CBR value if the areas with a low CBR are extensive. This will only be possible with Type C pavements (no infiltration). The impact of water on the stabilised materials should be very carefully considered."*

Note – the term *"no infiltration"* used in the above SUDs Manual refers to avoiding installation of a drainage pathway through the stabilised layer(s), with water shedding from the surface of the treated layer illustrated as acceptable.

CONCLUSIONS

Under the conditions tested this study concludes:

Stabilised Soils Exhibit Minimal Leaching Risk

The study confirms that leaching from lime and cement-stabilised soils is minimal, even under aggressive laboratory conditions. The low levels of leachate detected align well with industry experience and expectations from previous research.

Ongoing Curing Further Reduces Leaching Potential

Longer curing times significantly reduce the availability of unreacted lime for leaching. Field samples, which had cured for over three years, showed negligible lime loss. This highlights that risk of leachate progressively reduces for typical applications where prolonged infiltration of water into and through treated is avoided.

Good Working Practices Promoting Low Permeability Limits Leachate

The stabilised soils demonstrated very low permeability, restricting water movement and further minimising the potential for leaching. In practice, earthworks should be maintained with surface water and ground water flow managed to avoid the earthworks being in a saturated or submerged condition for extended periods of time.

Tank Immersed Conditions are more onerous than Field Conditions

The tank testing methodology represents an extreme case, where stabilised soils are fully immersed to directly encourage leaching. In practical applications, such conditions are unlikely unless poor drainage design directs water flow through stabilised materials.

No Evidence of Significant Chromium Leaching

Chromium present within the stabilised soil eluates was well below WHO drinking water standards for total Chromium. The very low rate of leaching by diffusion reduced significantly over time further mitigating this risk. The study also showed reduced heavy metal mobilisation in the stabilised soils compared to the untreated natural soils.

Durable strength

Even after prolonged water immersion in an unconfined condition the stabilised soils retained their substantial strength, whereas untreated soil disintegrated immediately. This underscores their durability and long-term performance in civil engineering applications.

Drainage Design is Essential

The rare instances of high pH water discharge identified in past projects were linked to poor drainage design. Ensuring that water does not infiltrate into and /or flow through stabilised material is key to preventing leachate issues.

Findings Reinforce Existing Industry Best Practices

The study supports existing guidelines, such as BS EN 16907-4 (2018), confirming that properly designed and executed soil stabilisation presents negligible environmental risk.

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The British Cementitious Paving Association

Britpave, the British Cementitious Paving Association, was formed in 1991. It is active in all areas of transport infrastructure including roads, airfields, light and heavy rail, guided bus, safety barriers and drainage channels, soil stabilisation and recycling.

The Association has a broad corporate membership base that includes contractors, consulting engineers and designers, suppliers of plant, equipment and materials, academics and clients both in the UK and internationally.

Britpave provides members and clients alike with networking opportunities. The Association aims to develop technical excellence and best practice in key cement and concrete markets through its publications, seminars and website.

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