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Lime stabilisation for earthworks: a UK perspective

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Lime stabilisation is a versatile technique applied during earthworks operations. Modern soil recycling units are much more efficient at pulverising fill material and intermixing the added binder/water than machinery available 20 years ago. While supplier innovation adds flexibility to the site working method, specifications have not been sufficiently updated to permit optimal application. This review paper details the physico-chemical changes instigated through the lime–clay soil reaction, updating previous reviews. It aims to assist scientific debate, current practitioners and future specification changes. For example, the application of the minimum 24 h mellowing periods (mandatory to UK specifications) with high reactivity, quicklime powders is concluded to cause increased air voids in the compacted fill. Increased air voids are associated with reduced long-term strength and potential volume change from water ingress, which is of particular concern for sulfate swelling. Shorter mellowing periods and/or use of hydrated lime may lesson this issue; however, a 'one size fits all' approach is discouraged in preference to site-specific methodologies refined to suit the fill material and project requirements. The discussion also summarises working methods which may lower the risk of sulfate swell and defines areas requiring further practical research.

1. Introduction

The improvement of engineering properties of clay fills through the addition of a small percentage of lime binder has been a popular ground improvement technique in the UK since the 1970s (Notman, 2011). Following the introduction of this technique, industry and academic efforts have been applied to better understand the mechanisms behind the observed ameliorative effects. This combined effort has advanced the state of knowledge and practice to identify three fundamental effects caused by the reaction of lime with clay minerals, namely moisture conditioning, cation exchange and pozzolanic reaction (Sherwood, 1993). These processes generally realise a favourable outcome. However, heterogeneous soil chemistry and mineralogy may result in important changes to the nature of reactions between lime and soil. Practically, this prevents a 'one size fits all' approach to lime stabilisation and highlights the importance of a detailed understanding of the science underlying the lime–clay soil reactions for those involved in the practical application

of this process. With this understanding, field processes can be changed according to the soil's chemistry and mineralogy to ensure the desired outcome, namely an engineered material with a suite of appropriate characteristics that meet project requirements.

As sustainability drivers increase pressures to minimise landfill and reuse materials, research into the potential for incorporating waste-derived pozzolans is increasing. For example, laboratory work has identified potential in incorporating wastepaper sludge ash (Rahmat and Kinuthia, 2011) and red gypsum (Hughes et al., 2011) into binder mix designs. These 'new pozzolans' add different types and ranges of chemistry/mineralogy. This imposes further layers of complexity on an already challenging topic and although the results are promising for the specific clay materials tested under laboratory conditions, the implications of soil heterogeneity relevant to site applications are less well understood.

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It is timely, therefore, to summarise the state of science and practice, focusing on a simple case of lime stabilisation. Compiling this information into one point of reference provides substantial benefit for organisations engaged in soil stabilisation projects and also provides a point of comparison for any future work with new pozzolans. This paper reviews literature and applies experience of site practice to interpret the key aspects relevant to achieving the desired performance in field applications of lime stabilisation. As this experience is predominantly from UK practice, comments relating to specification are based upon the Highways Agency specifications and guidance notes (Highways Agency, 1995, 2007, 2009). However, although specifications may vary, the reasoning presented is relevant globally.

The paper is structured to first introduce the context of lime stabilisation and principles underlying lime–clay reactions (Section 2) before factors important in applying these principles at the field scale are described (Section 3). A discussion of how these concepts may promote a strong, durable and volumetrically stable fill material, including consideration of sulfur swell follows (Section 4). Discrepancies between theory and practice are then summarised and suggestions where enhanced knowledge would add value to practical applications are made (Section 5).

2. Context of lime stabilisation

Lime is typically applied to clay soils that, in an untreated condition, provide problems for construction. In particular, shrink/swell of the substrate may damage engineering structures. Clay soils with a liquid limit (W_L) greater than 90% or a plasticity index (I_P) greater than 65% are thus classified as unsuitable for use as an earthworks fill material, unless treated (e.g. with lime; Highways Agency (2009)).

Rapid improvements to the soil's engineering properties are commonly referred to as 'lime improvement' (separating it from 'lime stabilisation'; Table 1) and have two facets. The first relates to conditioning of the fill to the optimum moisture content (OMC) for compaction. The second relates to chemical alterations at the surface of the clay particles which decreases the volume change potential of the clay minerals.

With greater additions of lime binder (i.e. in excess of the initial consumption of lime (ICL) value, BSI (1990)) pozzolanic reactions between lime and clay can result in substantial long-term enhancement of engineering properties, including high strength, durability and frost resistance (Eades and Grim, 1966). The added benefits from the pozzolanic reactions are experienced

Treatment intent	Physico-chemical process	Common terminology	Indicative lime requirements	Typical time required[a]
Lower the moisture content of a wet/low-strength soil towards OMC. Either for compaction as a general fill, or to enhance trafficability.	Removal of free moisture by reaction with quicklime. Cation exchange/clay mineral aggregation effectively increasing the OMC (see Sections 2.4.1 to 2.4.3 for details).	Lime improvement	Low, e.g. 0·5–4 (initial moisture content/ clay content dependent)	1. Immediate 2. Rapid (0–72 h)
Reduced plasticity/potential for volume change.	Cation exchange/clay aggregation reduces clay mineral effective surface area and affinity for water. Early pozzolanic reactions restrict subsequent dispersion of aggregations (see Section 2.4.3 for detail).	Lime improvement		Rapid (0–72 h)
Substantially improved engineering properties, i.e. strength, stiffness and durability.	Pozzolanic reaction between lime–clay soil system (see Section 2.4.4 for detail).	Lime stabilisation	In excess of the ICL value, e.g. 2–10% (actual binder addition determined by site-specific mix design)	Ongoing improvement from 72 h continuing for months/years

Increasing
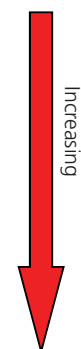
[a] Indicative times only. Actual time depends upon multiple factors detailed in later text.

Table 1. The treatment intent and the implications for lime addition and time-dependent reactions

more slowly than the rapid lime improvement reactions, and can progress over months and even years. Lime may also be used in combination with additional binders, for example Portland cement, or through combined reaction with pozzolans such as ground granulated blastfurnace slag (ggbs). Such approaches may be sought when greater strengths are required rapidly (e.g. within 7 d). It is important to note that these approaches alter the reaction product chemistry and locations where strength improvement takes place, when compared with soil treatments involving lime only (Wilkinson *et al.*, 2010).

2.1 Volume stability

The volume stability and durability of a lime-treated fill is of paramount importance. Although the majority of soil stabilisation works result in the desired performance (Petry and Little, 2002), occasionally problems occur. Following high-profile failures in the United Kingdom (M40 motorway, Oxfordshire; Snedker (1996)) and United States (Las Vegas; Hunter (1988)), the potentially deleterious reaction between sulfur and a lime–clay soil system has received substantial attention. There is a considerable body of work supporting the notion that this combination of reactants may lead to the precipitation of ettringite and/or thaumasite (Little *et al.*, 2005). The formation of ettringite, in particular, may be accompanied by substantial expansion with the potential to cause damage to engineering structures (Snedker, 1996).

The potential to generate problems for construction due to adverse soil chemistry is very much smaller than the potential to develop problems due to a high air voids percentage of the lime-treated soils. A major factor in addressing the latter involves the early lime–clay soil reactions in combination with the working methodologies employed and this paper addresses this in some detail below. A potential for sulfur swell may be broadly defined from the association of sulfur species with certain geological formations (see Figure 7 later). However, as sulfur swell issues from soil stabilisation are relatively rare and material from these potentially sulfur-bearing formations (see Figure 7 later) have also been successfully treated, it becomes apparent that the issue is more complex than this general association and Section 4.3 expands considerably on this point. Notwithstanding, industry experience suggests that sulfate swell potential is of specific concern with high sulfur clay soils that are also of high plasticity, with the Lias clay formation having notoriety in this regard (Holt *et al.*, 2000; Snedker, 1996).

2.2 Role of water

A particular amount of water is required to achieve an OMC that coincides with the maximum dry density (MDD). In addition, the initial moisture content dramatically influences the manner in which lime diffuses through and reacts with the clay system. A greater initial moisture content enhances the efficiency of lime diffusion (Barker *et al.*, 2007) and provides sufficient water to precipitate pozzolanic hydrates in the longer term (Bell, 1988). This illustrates the importance of understanding the intent of the lime treatment. A focus on achieving MDD for bulk fill compac-

tion does not fit well with achieving efficient development of the long-term pozollanic reactions and vice versa. Furthermore, the timing of water availability is critical in determining whether ettringite growth results in soil expansion (Little *et al.*, 2005). Therefore, the role of water management within a lime-soil system receives specific attention in this paper.

2.3 Lime types

Lime binder may refer to quicklime (CaO) or hydrated lime (Ca[OH]$_2$) and may be provided in various forms, such as pellets, flakes, powder or as particles suspended within a water slurry. Each variant of lime binder is produced to different physical/chemical criteria (e.g. as categorised in BSI (2006)) and may suit a specific soil stabilisation application better than another type/form. Lime type is considered further in Section 3.4. However, the sequence of lime–clay reaction must first be discussed before implications of lime binder type can be considered.

2.4 Lime–clay soil reactions

This initial discussion of the underlying reactions assumes the added lime is in close contact with the reacting clay component and ignores any requirement for the lime constituents to first migrate into position. The latter complication is added by field applications of lime stabilisation which process larger clods of clay and will be considered in Section 3.2. The processes are discussed in the order in which they are considered to occur in a field scenario which aids later correlations to physical effects.

2.4.1 Drying

Substantial drying is only applicable where quicklime is used as the binder, removing excess water from the soil system through the action of 'slaking' the quicklime (CaO) to calcium hydroxide (Ca[OH]$_2$). This combines 32% of the quicklime's initial mass with water molecules, causes an increase in volume (potentially providing deleterious expansive stresses if in a confined environment). The resultant exo-thermic reactions generate substantial heat. This heat causes evaporation which further reduces the moisture content (Greaves, 1996). Therefore, the influence is principally one of drying out the material.

2.4.2 Calcium hydroxide dissociation

Whether added directly, or produced through quicklime slaking, calcium hydroxides enter the soil water solution. Calcium hydroxide is relatively stable in water, although it can partially dissociate to provide calcium (Ca^{2+}) ions and hydroxyl groups, which may then react with the clay–soil system (Bergado, 1996). The hydroxyl groups also elevate the pore water pH to a maximum value of approximately 12·45. Calcium hydroxide dissociation is a prerequisite to subsequent changes that determine the engineering properties of lime–clay mixes.

2.4.3 Cation exchange and soil structure change

The modification of the clay structure mainly involves the calcium ions and is regarded as a rapid cation exchange process occurring on the surface of clay particles. Clay particles typically

exhibit surface charge imbalances and the negative charges are balanced by hydrated cations. Accordingly, individual clay particles are surrounded by adsorbed water in the diffuse double layer arrangement (Van Olphen, 1977). The thickness of the diffuse double layer is controlled by several factors (Reeves *et al.*, 2006) although the valence of the charge-balancing cations has primary influence. Incoming divalent cations exert a greater attractive force towards the clay particle surface than any monovalent cations (which are common to natural clay soils, e.g. K^+ or Na^+). This balances the clay surface charge with fewer hydrated cations and the thickness of the diffuse double layer shrinks in response (Bohn, 2002). As the diffuse double layers shrink, the electro-static charges on adjacent clay particles interact to a greater extent. Opposing negative charges of parallel aligned (face to face) clay particles are repelled and reconfigure to promote a flocculated, positive/negative charge (e.g. edge to face) arrangement (Figure 1). This causes silt-sized aggregations of clay particles to group together (Bell, 1996) and two influences on the clay soil structure are suggested: an increase in micro-porosity, *intra*-aggregate to the flocculated particles (Figure 1(c)); and a change to the meso-porosity, *inter*-aggregate to the flocculated particles (Figure 1(d)). This reduces the effective surface area of clay minerals in contact with the inter-aggregate pore water accounting for much of the immediate change in physical properties of the clay soil associated with lime improvement (Figure 2; Bell (1988))

- reduced plasticity and shrink/swell
- promotion of brittle/friable behaviour
- increased permeability.

As the described change in soil structure is dependent upon a suppressed diffuse double layer, it might be expected that the effects could be reversed through suspension within water. However, this is not evident and the aggregations persist, even when reworked during classification tests, such as particle-size distribution and Atterberg tests. This resilience is caused by the rapid growth of some pozzolanic reaction products (Diamond and Kinter, 1965). These early-formed reaction products localise around points of contact (e.g. edge/face) between clay particles within the flocculated structure (Figure 1(c)). This discrete strengthening at point of contact explains how formation of a very small quantity of reaction product provides resilience against dispersion (Diamond and Kinter, 1965).

2.4.4 Pozzolanic reactions

Pozzolanic reactions may be broadly summarised as new mineral growth, facilitated by high pH pore water (i.e. pH > 9) and involving reactants sourced from either the added lime, host clay soil, or transported in from an external source, namely solutes within the pore water (Bell, 1996; Boardman *et al.*, 2001; Diamond and Kinter, 1965; Sherwood, 1993). With the noted exception of early-formed reaction products (Diamond and
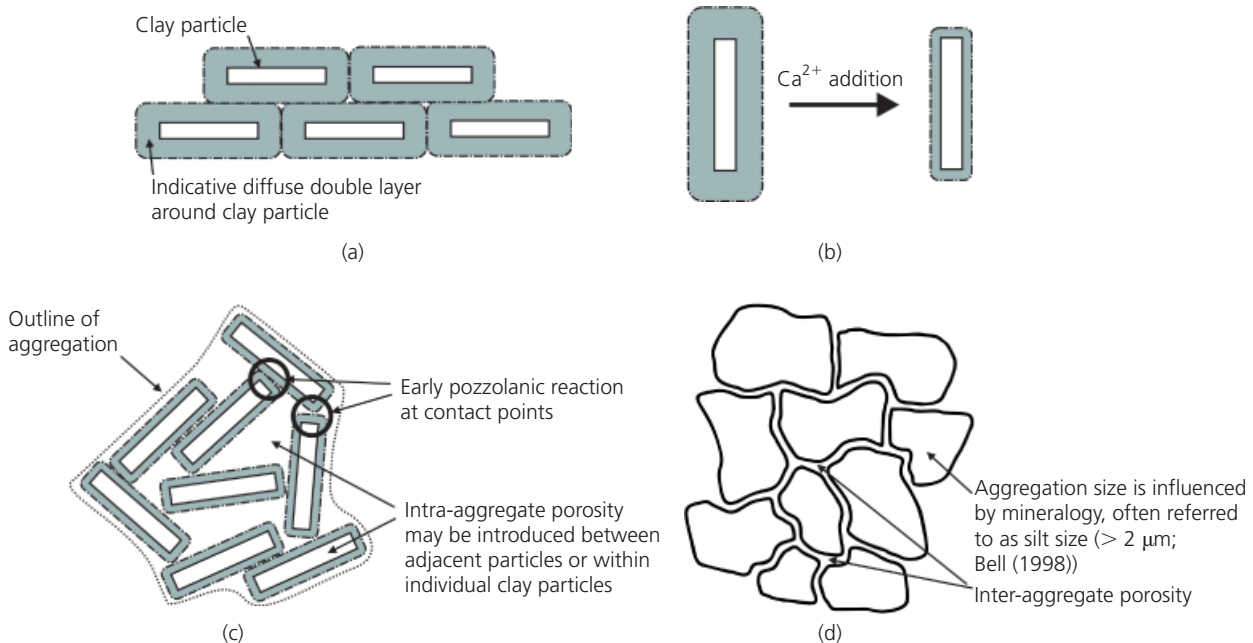

Figure 1. Sequence illustrating influence of early lime–clay reactions upon clay particle arrangements and soil structure: (a) diffuse double layer is initially deep, causing clay particles to align in a disperse arrangement; (b) substitution of Ca^{2+} cations for Na^+/K^+ cations reduces diffuse double-layer thickness; (c) aggregation of clay particles as diffuse double-layer 'buffer' reduction results in repulsion of like charges on clay particles; (d) aggregations act as larger particles with adjacent surfaces separated by inter-aggregate pore space
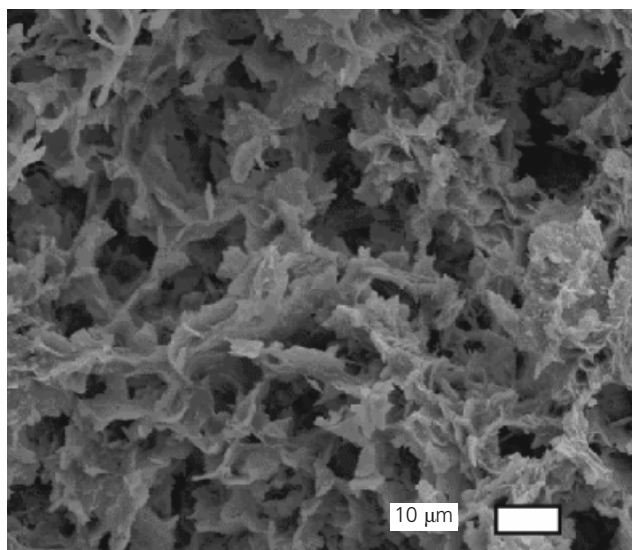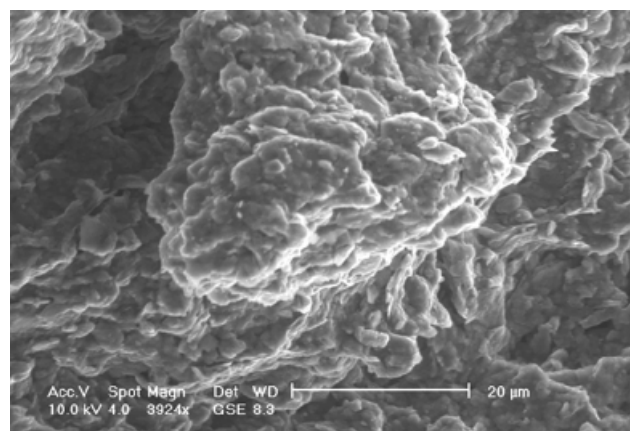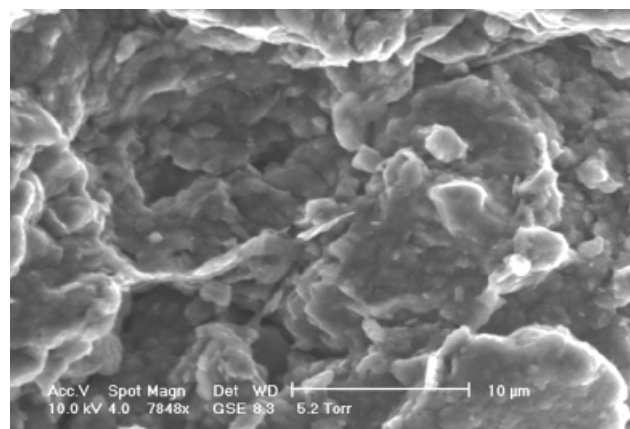
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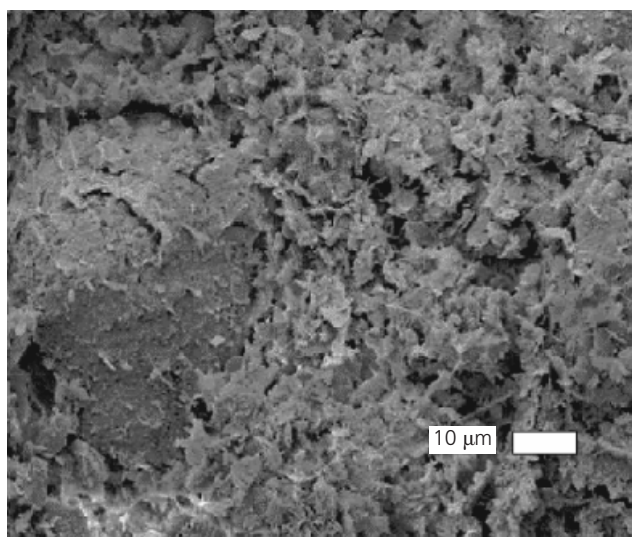
(b)

Figure 2. Scanning electron microscope images (from Wilkinson *et al.* (2010)) indicating how lime modification alters the fabric of an untreated clay soil (a) to produce silt-sized aggregations closely separated by an inter-aggregate porosity (b): (a) shows untreated clay fabric (freeze dried); (b) shows lime-treated clay fabric (freeze dried)

(a)

(b)

Figure 3. Environmental scanning electron microscope images of lime-treated clay (32 d cure) illustrating pore water/C-S-H gel connecting individual aggregations with little visible air voids: (a) lime-treated fabric at 'as cured' moisture content (reproduced with permission of the Transportation Research Board; Beetham *et al.* (2014)); (b) as part (a) with further magnification

Kinter, 1965), long curing periods (weeks and months) are required for the newly formed minerals to provide notable and ongoing benefit. The increase in strength with curing is attributed to the new minerals binding adjacent aggregations of clay (Figure 3; Bell (1996)). Wild *et al.* (1987) suggested that by infilling the inter-aggregate pore space, strength increase and permeability reduction would also occur through 'pore blocking'.

Clay soils are typically rich in alumino-silicates and reaction products similar to those produced through hydration of Portland cement form, such as calcium silicate hydrates (C-S-H), calcium aluminate hydrates (C-A-H) and calcium aluminate silicate hydrates (C-A-S-H). The composition of the reaction products formed by the lime–clay soil reaction is necessarily driven by the timing of reactant availability. The abundant early supply of an alternative chemistry, for example SO_4^{2-} ions, in lieu of silicate, may dramatically change the reaction product from an ameliorative into a potentially deleterious mineralogy. This introduces the concept of reactant timing and will receive further attention in sections on ion migration at the field scale and adverse chemistry (see Sections 3.2 and 4.3).

3. Transferring science to practice

3.1 Clay clods

Up to this point, much of the discussion involved processes operating at the microscopic scale and assuming an intimate

lime–clay mixture. This can make it difficult to relate to site processes in which the rotovating/mixing action of site machinery tends to produce clods of clay soil (which may be up to 50 mm in diameter) with lime applied to the periphery of these clods. Lime stabilisation has some aspects similar to standard earthworks – for example, the immediate strength is mostly influenced by dry density. However, the inclusion of lime binder in conjunction with the clod size adds a further strength dynamic. Upon immediate contact with lime, the clay clods go through the lime–clay reaction sequence as described above and this alters the fill properties in an ongoing manner. The lime is initially localised along the periphery of the clods and for the lime–clay reactions to extend beyond the surface of a clod, the calcium ions and hydroxyl groups must transport deep into the clod.

3.2 Lime migration

Ion transport in clay soils is primarily driven by diffusion along electro-chemical gradients where ions redistribute to regions of low concentration (Jungnickel *et al.*, 2004). Although the diffusion process dominates in soils of high plasticity, advection becomes increasingly influential with increased permeability – that is, with permeability greater than 1×10^{-9} m/s (Mitchell and Soga, 2005). Therefore, where soil plasticity is low or there is a significant granular component, advection may become the key ion transport mechanism. Although ion diffusion predominantly involves the migration of charge-balanced anion/cation pairs (Jungnickel *et al.*, 2004), in a lime-treated clay soil, the distribution of Ca^{2+} occurs more rapidly and with wider coverage than the hydroxyl groups (Davidson *et al.*, 1965). This suggests that lime does not diffuse as paired $Ca[OH]_2$ as might be anticipated in an advective system. Rogers and Glendinning (1996) attributed the difference in migration distance and rate to the high reactivity of OH^- with the surface of alumino-silicates. However, in a saturated soil condition, connected pore water enhances thermal conductivity to stimulate molecular excitement, and this substantially accelerates the rate and extent of OH^- diffusion (Barker *et al.*, 2007). Beetham *et al.* (2014) reported that when clods of clay were at a high degree of saturation before lime treatment, the elevation of pore water pH to more than 10 throughout 20 mm clay clods is achievable within several days. They also noted that the reduced surface area of clay particles, flocculated by the preceding Ca^{2+} cation exchange process, would also decrease OH^- interactions, promoting the wider migration of these hydroxyl groups.

Following movement of Ca^{2+} ions and hydroxyl groups into place, the subsequent development of pozzolanic reactions throughout the clods is given the distinction 'diffuse cementation' (Stocker, 1975). As the pozzolanic reaction mechanism relies upon the connectivity of pore water around clay aggregations, the potential for these reactions to extend over the larger, air-filled inter-clod porosity is limited. Therefore, while lime stabilisation has potential to develop substantial diffuse cementation, unless other binders are added (such as Portland cement or alkaline-activated ggbs), there is little potential for 'inter-clod

cementation'. It has not been universally accepted that diffuse cementation plays a significant role within lime stabilisation. Some authors have suggested that ion diffusion can only occur to a very limited degree (Ingles and Metcalf, 1972; Petry and Wohlgemuth, 1988). This may be due to the experimental conditions that led to these conclusions either being sub-optimal for efficient ion migration (i.e. unsaturated soil condition), or promoting another influence upon strength to occur more rapidly, thus causing diffuse cementation to appear insignificant. With the former, there are multiple influences on the rate of pozzolanic reaction to consider and this will be explained in Section 4.1.2).

3.3 Compaction

The principles of compaction for a lime-improved or -stabilised clay are similar to those influencing a standard clay soil improved by mechanical compaction. In general, MDD corresponds with the maximum shear strength (attainable immediately). However, with the addition of lime, the MDD attainable from a treated fill reduces and the OMC typically shifts towards the wet side (Figure 4; Bell (1996)). Lime treatment tends to produce a relatively flat curve when results of dry density are plotted against moisture content, which in some situations may flatten completely so that a lesser or no increase in MDD is associated with an OMC.

3.3.1 Inter-clod porosity

The reduction in MDD has been linked with the flocculation of clay particles causing an increase of porosity and a lower density (Sherwood, 1993). However, as the size of pore space imposed by clay particle flocculation is considered to be <0·3 µm (Bin *et al.*, 2007), it is unlikely that this intra-aggregate porosity could fully account for the larger reductions in dry density. In a study on compacted clods of untreated clay of high plasticity, Benson (1990) associated large reductions in dry density and increased permeability with increased void space between clay clods (i.e. an inter-clod porosity with pore sizes >100 µm); influences from changes to
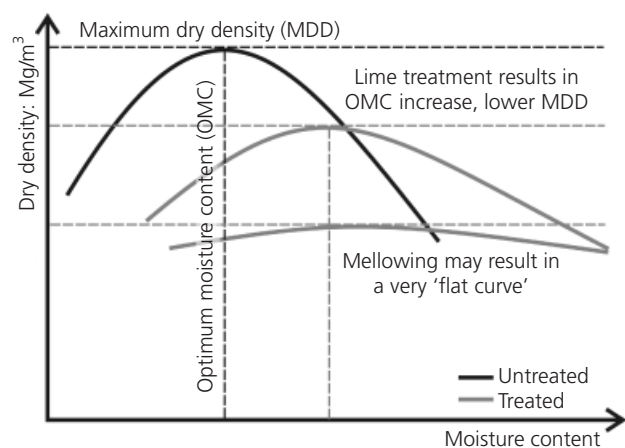

Figure 4. Interpretative plot indicating the influence lime treatment has upon a 'Proctor' compaction plot

micro-porosity (i.e. pore spaces <1 μm) were minor. The key influences on this inter-clod porosity are clod ductility, clod size and compaction effort (Benson, 1990). Sweeney *et al.* (1988) identified how both increased quicklime content and mellowing period (from 1 to 24 h) promote the early lime clay reactions that reduce the ductility of clay soil. With a shorter mellowing period and lower amounts of added quicklime the modified Proctor (4·5 kg) compaction results showed an increase of the MDD at OMC, while a flat compaction curve resulted with normal Proctor (2·5 kg) compaction. However, for samples subjected to longer mellowing periods, a much less ductile material resulted and the higher compaction energy did not realise an increase in MDD. Instead a weak and friable specimen, prone to breaking up, was produced (Sweeney *et al.*, 1988). Other authors have similarly noted that increased mellowing periods promote a substantial increase in the percentage of air voids (Bell, 1988; Holt *et al.*, 2000). The early lime–clay reactions introduce a brittle response and moisture conditioning to the wet of OMC will have only limited effects. Further compactive effort may result in additional voids by fracturing brittle clods and inducing dilatancy.

3.4 Clod size/strength heterogeneity

The initial clod size of treated clays plays an important role in the timing of lime–clay reactions and the potential for inter-clod porosity. Whereas compaction of (untreated) smaller clods

reduces inter-clod porosity (Benson, 1990), the lower volume of clay over which ion diffusion must progress causes lime–clay reactions to develop throughout small clods (e.g. 5 mm or smaller) at a faster rate than for larger clods (e.g. 20 mm or larger; Beetham *et al.*, 2014; Bozbey and Garaisayev, 2010; Petry and Wohlgemuth, 1988). The rotovating action of site plant produces a range of clod sizes, thus the rate of change in clod ductility/strength will be heterogeneous – fast for the small clods, slow for the larger clods. When the range in clod size is within a reasonable banding before lime coating (i.e. as attained by the initial rotovation only), this should not prove a major issue with regard to compaction timing. However, the use of quicklime, particularly in combination with initially large clods, has high potential to exaggerate this heterogeneity. Beetham *et al.* (2014) reported on the effects of a sequence comprising the addition of quicklime followed by a 1 h mellowing period and then remixing before compaction. They observed that this caused fine particles to break away from clods (up to 20 mm size) of a moderately high plastic clay. As these fines originated from the clod periphery, these contained a disproportionately high concentration of lime, which is then isolated within the fines and away from the larger clods. This effect further exaggerates the heterogeneous development of early lime–clay reactions (Figure 5). It is also logical to suggest that the use of quicklime powder would worsen this effect. The rapid liberation of heat when category 1 quicklime (BSI, 2006) slakes would encourage both a
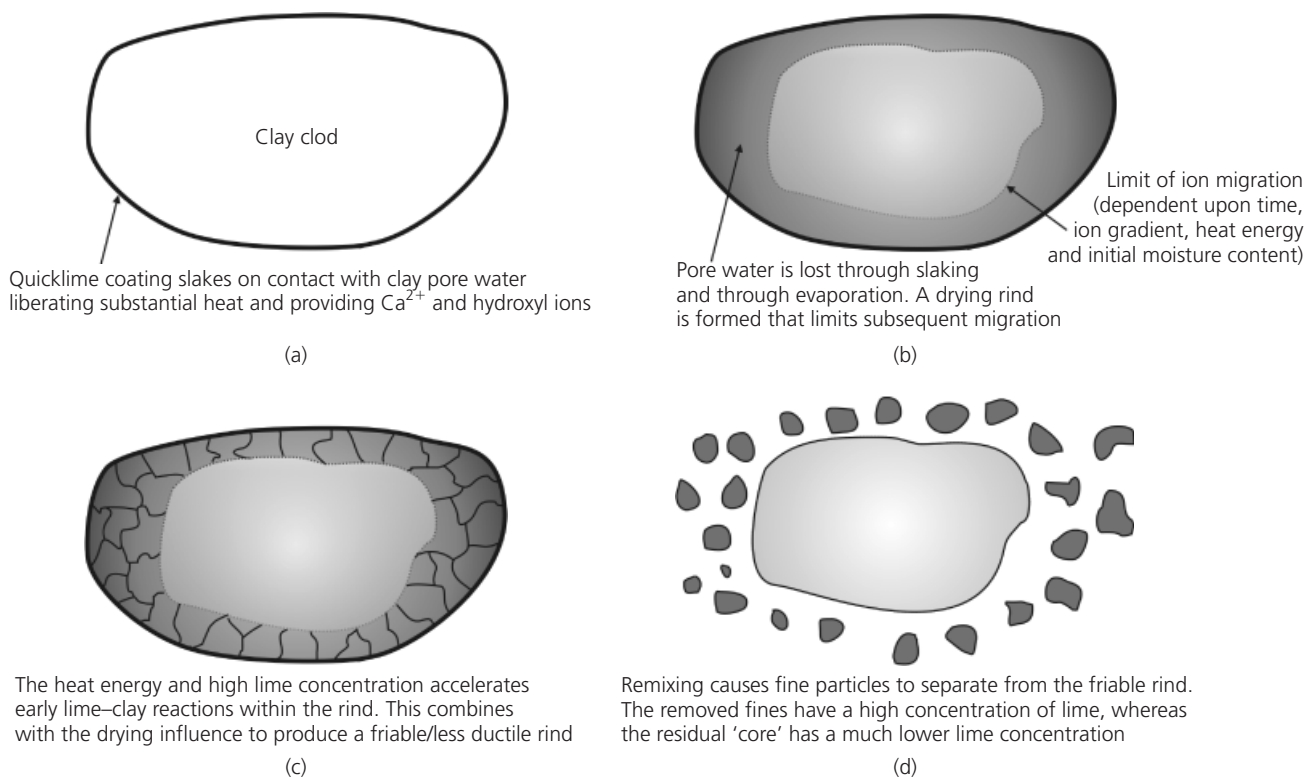

Figure 5. Sequence illustrating the influence of quicklime slaking upon larger clay clods to produce a heterogeneous distribution of lime (after Beetham *et al.* (2014)): (a) upon quicklime addition; (b) mellowing – dehydration influence on ion migration; (c) mellowing – physical effects; (d) remixing – fine particle removal

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localised drying and an acceleration of lime−clay reactions. As
diffusion is optimal with a saturated clay soil, migration to the
centre of these clods would then be restricted and a drying, brittle
rind would rapidly form, leaving a core zone where relatively little
alteration takes place (Figures 5(c) and 5(d)). Therefore, unless the
remixing phase is accompanied with further binder addition, the
large remnant cores may receive very little lime.

3.5 Working method influences

To limit heterogeneous distribution of lime and moisture, the
mellowing period may be extended to allow the lime improve-
ment processes to substantially complete throughout clay clods.
The lime improvement process is usually complete within 24 h,
but subject to clay mineralogy and content may require up to
72 h (Rogers and Glendinning, 1996). Large clods may require
even further time. Encouraging heterogeneity with a prolonged
mellowing process would promote the high air voids issue
previously identified, especially when quicklime powder is used.
This suggests that, unless the application of quicklime can realise
the pulverisation specification within a relatively short mellowing
period either high air voids percentage or a heterogeneous mix
will result. To avoid heterogeneity and minimise air voids where
larger clods persist, the use of hydrated lime powder in lieu of
quicklime is preferable. This would avoid the complication of a
drying rind (Figure 5) and permit longer mellowing periods
before ductility is lost. A further option involves the use of
hydrated lime/slurry and to deliberately target a substantially wet
of OMC condition, perhaps with minimal mellowing. The
principal issue here is to accept a reduced immediate strength,
and rely on optimising diffuse cementation processes to achieve a
higher strength as curing continues to take place (Figures 6(a)
and 6(b)). This may be most suited to highly plastic clays in
which pulverisation is inherently difficult and the clay mineralogy
promotes diffuse cementation in a more expedient manner.

It becomes apparent that different combinations of moisture
conditioning, mellowing periods and lime binder type will suit
different clay materials and the key consideration to achieve the
optimal approach is the performance requirements of the com-
pacted fill. The performance element should consider the medium
(31 d) and long-term (more than 6 months), which may not be
indicated by immediate or short-term (7 d) testing and would
instead require an in depth understanding of the principles behind
durability (Section 4.2) and cured strength gain (Section 4.1.2). It is
worth repeating here that the OMC for immediate strength does not
necessarily coincide with the moisture content required for maxi-
mum long-term strength and durability. Providing that sufficient
strength is gained to permit immediate construction requirements, it
may be preferable for some applications to target higher moisture.

4. Cured strength and durability

4.1 Pozzolanic reaction and reactant timing

With respect to a detailed micro-chemical explanation for the
pozzolanic reactions, it is important to acknowledge that this is a

complex subject and the present state of science has not achieved
complete agreement. For this reason, a complete discussion
would require a separate review paper and a detailed summary is
not attempted here. Instead, it is noted that of the different
reaction mechanisms suggested in the literature, they may
generally be grouped into those involving the topo-chemical
alteration of an alumino-silicate host to form the new phase in
situ (e.g. Stocker (1975)), or via a through-solution process,
namely the dissolution of reactants from an alumino-silicate host,
followed by transportation and then precipitation of the new
phase at an alternative location (e.g. Beetham *et al.* (2014)).
While the topo-chemical reactions would explain surface changes,
such as Diamond and Kinter's early pozzolanic alteration (Dia-
mond and Kinter, 1965), the ongoing growth of reaction products
into the inter-aggregate pore space (Wild *et al.*, 1987; Wilkinson
et al., 2010) suggests that a 'through-solution' mechanism is
necessary for any further pozzolanic reaction to take place
beyond initial contact amelioration. It has already been identified
that the efficient distribution of hydroxyl groups is driven by a
connected pore water and this would be a prerequisite to the
initiation of both topo-chemical and through-solution processes.

4.1.1 Through-solution mechanism

When the pore water alkalinity exceeds a pH of 9 it generates a
corrosive environment in which the alkaline hydrolysis of
covalent bonds between Al−O and Si−O releases monomeric
silicate and aluminate (e.g. SiO_4^{-4} and $Al[OH]_4^-$) into solution
(Cristelo *et al.*, 2012). Water forms an essential component to
enable this reaction and further highlights the importance of
connected pore water for the sustained supply of reactants. With
regard to the supply rate of these reactants there are three direct
influences

- the availability of alumino-silicates
- the strength of the covalent bonds in the alumino-silicate
- the corrosivity of the pore water.

Additives comprising bases stronger than $Ca(OH)_2$ have been
shown to enhance alumino-silicate dissolution (Diamond and
Kinter, 1965), with NaOH and KOH providing a pH of 13·5 to 14
and substantially accelerating this attack (Duxson *et al.*, 2007;
Elert *et al.*, 2008). The availability of alumino-silicates is
essential to pozzolanic reactions, although the quantity of dis-
solved silicate and/or aluminate required to sustain the reaction is
small and once an initial minimum is met (e.g. plasticity index
more than 10) the clay content is not limiting (Bell, 1988). The
rate at which these reactions result in an increase in strength is
linked to a hierarchy of clay minerals in which expansive clay
minerals, such as montmorillonite, are recognised as providing
the greatest rate of dissolution, thus enabling maximum efficiency
of pozzolanic reactions. The high reactivity of these expansive
clay minerals is determined, among other things, by their very
high surface area and the extra silicate layer within 2:1 minerals
(Table 2; Elert *et al.* (2008); Ingles and Metcalf (1972)). These
cannot be the sole factors, because Ingles and Metcalf (1972)

Clay mineral	Layer structure	Surface area: m²/g	Swelling properties
Kaolinite	1:1	10	None
Allophane	1:1	700–900	None
Smectite	2:1	800	Extensive
Illite	2:1	20	None/very little
Vermiculite	2:1	400	Limited
Chlorite	2:2	10	None

Table 2. Basic properties of common clay minerals (after Rowell (1994))

consider the reactivity of illite to be less than that of kaolinite. In this regard, Bell (1988) suggested that not all the silica in 2:1 clay minerals would be freely available, with illite and chlorite as examples in which ionic bonding might restrict silica availability. Additionally, Al–O covalent bonds are weaker than Si–O bonds and therefore aluminate supply will initially exceed silicate supply. However, as clay soils have greater overall silica content, this supply rate will gradually reverse with ongoing dissolution (Cristelo *et al.*, 2012). The degree of crystallinity within the alumino-silicate source also has a high influence on bond strength and in comparison with well-ordered clay minerals, amorphous alumino-silicates rapidly dissolve (Duxson *et al.*, 2007). This also explains why some industrial processed alumino-silicates, which have been subject to prior significant heat (e.g. ggbs, meta-kaolin), have little order and are rapidly activated by calcium hydroxides (Cristelo *et al.*, 2012).

The newly formed minerals are produced from solutes released into the pore water. An initial Al/Si complex of high reactivity and mobility will form and its subsequent evolution is highly dependent upon the supply of other ions (Cristelo *et al.*, 2012). Where calcium is available, the rapid formation of C-S-H gel takes preference, although the composition of the reaction product will depend upon the concentration of ions and local energetics (Duxson *et al.*, 2007). A connected pore water environment would assist in the promotion of a more homogeneous reaction product. Locally greater concentrations of aluminate may result in precipitation of poorly crystalline C-A-H or C-A-S-H phases. This is an inherently meta-stable system and phase changes may continue as ion supply alters, although as the solid component of the gel increases, reorganisation becomes progressively high energy and a greater resistance to dissociation develops (Duxson *et al.*, 2007). Furthermore, as the newly formed minerals grow within the inter-aggregate pore space, this progressive reduction in permeability (Beetham *et al.*, 2014; Wild *et al.*, 1987) would limit any new ion supply, further encouraging stability.

4.1.2 Strength gain rate
Although the above sequence is an ideal progression, strength development and transition to a relatively stable, low permeability

condition are dependent upon a number of factors that limit reaction rates and are listed here.

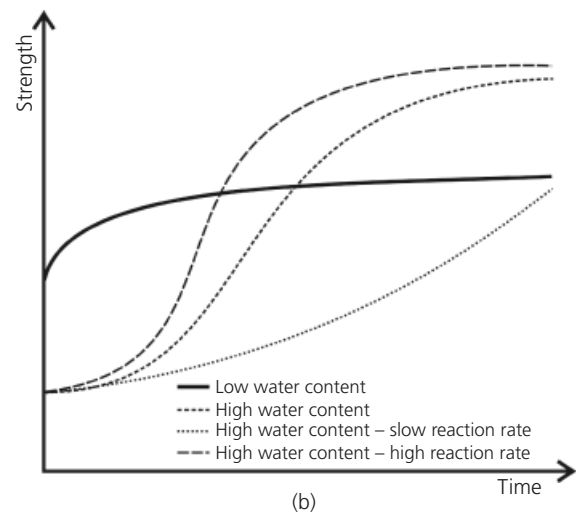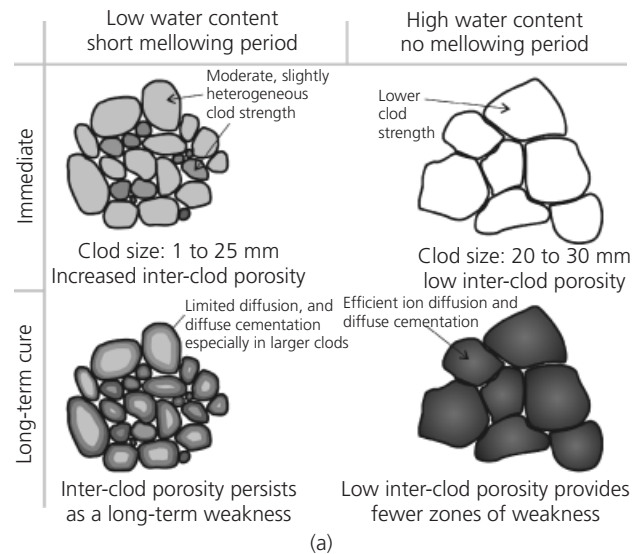- Initial ion diffusion efficiency – such as clay clod volume, degree of saturation, quantity of added lime.

(a)

(b)

Figure 6. Interpretative sketch (a) and plot (b) indicating how the pre-compaction condition of lime-treated clay clods may influence the shear strength over time. When comparing a low water content system (an optimum moisture content for a maximum dry density) to a high water content system (efficient diffuse cementation), the latter will contain a period of time during which the shear strength is less before it is recovered with curing. The duration of this period is influenced by the pozzolanic reaction rate (Section 4.1.2). Inter-clod porosity which persists as a long-term weakness is increased where clod strength is initially high and resists the compaction effort applied. In (a) strength indicated by shading intensity – darker zones indicate greater strength

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- Alumino-silicate reactivity – this is influenced by clay
  mineral type.
- Other factors – such as curing temperature, pH-reducing
  organic matter or high sulfur content (Section 4.3).

The time-dependent strength influence of ion diffusion rate and
alumino-silicate reactivity is indicated in Figure 6.

4.2 Stabilised soil durability

Durability of a lime-stabilised soil is judged against the sustained
achievement of the required engineering properties. In view of
the near-surface environment, changes caused by fluctuations in
water content and temperature (including freeze–thaw cycles) are
foreseeable events with the potential to impart changes upon the
soil strength and volume stability.

The ingress of water has the potential to influence the residual
clay mineralogy in a similar manner to a natural clay soil
although, as previously noted, the low surface area of the resilient
clay aggregations will lessen this influence. Thereafter, the
stability of the pozzolanic reaction products becomes of interest.
When submersed within water of neutral pH and low Ca^{2+},
C-S-H gel will de-constitute into $Ca(OH)_2$ and silicate (Taylor,
1990). The release of these components will then effectively raise
the pH and Ca^{2+} of the water, and for this attack to be sustained,
further water must then be supplied. This is supported by
McAllister and Petry (1992) who identified that where permeabil-
ity is high, the leaching of Ca^{2+} from a cured lime–clay system
is sustained at a high level for an ongoing period. Conversely, for
the low permeability system, initial Ca^{2+} leaching was much
lower and then stopped after only a short time period (McAllister
and Petry, 1992). Therefore, a high-permeability material can
potentially lose strength through softening and removal of the
pozzolanic reaction products (Le Runigo *et al.*, 2009).

Frost susceptibility is also primarily controlled by permeability,
with the accumulation of water within the inter-clod void space
(Figure 6(a)) comprising the main area where these expansive
forces concentrate (Sherwood, 1992). Thus, the persistence of
high air voids is directly associated with a reduction in durability
and it is recommended that compaction achieves a minimum
value of air voids throughout the fill (Sherwood, 1992)

4.3 Adverse chemistry

In addition to the effects of poor compaction, various deleterious
effects are associated with adverse chemistry. For example, heave
and strength loss of lime and cement-stabilised soils has been
associated with high sulfur contents in the host soil, leading to
the formation of the expansive and strength-depleting minerals
ettringite and thaumasite (Hunter, 1988; Snedker, 1996).

The formation of ettringite requires a pH greater than 10 and an
adequate supply of chemical reactants namely Ca^{2+}; SO_4^{2-};
Al_2O_3; H_2O to form (Little *et al.*, 2005)

$$Ca_6[Al(OH)_6]_2(SO_4)_3 \cdot 26H_2O \ \ (ettringite)$$
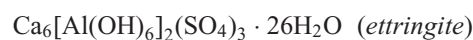
Thaumasite may form in a similar fashion, or can generate upon
alteration of ettringite (Little *et al.*, 2005; Winter, 2009). A low
temperature of between 4 and 15°C and humid conditions are
associated with thaumasite formation (Collett *et al.*, 2004;
Winter, 2009). For the formation of thaumasite the following
reactants combine: Ca^{2+}; Si^{4+}, SO_4^{2-}; CO_2^{-3} and H_2O (Little *et
al.*, 2005)

$$Ca_3[Si(OH)_6](CO_3)(SO_4) \cdot 12H_2O \ \ (thaumasite)$$
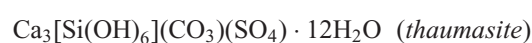
Several strategies to prevent deleterious mineral growth, with a
primary focus on ettringite, are described in the literature. These
are listed below and discussed under appropriate sub-headings.

(*a*) Limiting/preventing access of one or more of the reactants.
(*b*) Deliberate ettringite nucleation before final compaction.
(*c*) Amending the chemical balance of a system to instead
    precipitate a non-deleterious mineralogy.

4.3.1 Limited reactants

It is apparent that sufficient quantities of calcium, aluminium,
sulfate and water must be available to provide an environment in
which ettringite can be formed. A primary factor is the presence
of sulfate and a minimum soil sulfate value of 0·2–0·3% is
regarded as the level at which substantial growth of this hydrated
crystal, which may potentially lead to swelling pressures affecting
the integrity of engineered structures, becomes a risk (Little *et
al.*, 2005). However, where heave has caused noticeable distress
to overlying engineering works, a wider range of sulfate (0·3–
1·4%) has been attributed, which suggests other factors may limit
ettringite development. The (un)availability of aluminium (from
the clay minerals) is one such component that may reduce the
rate of growth (Little *et al.*, 2005). When soils are compacted to
achieve a low air voids ratio (i.e. less than 5%) this will
drastically limit the potential for subsequent water ingress (Perry
et al., 1996) and it will also limit the leaching of calcium ions
from any prior-formed C-S-H or portlandite (McAllister and
Petry, 1992). It is interesting to note that widely reported sulfate
swell failures (e.g. Stewart Avenue, Las Vegas, US reported by
Hunter (1988); and the M40, Oxford, UK reported by Snedker
(1996)) occurred when a quicklime binder was applied. Inter-clod
porosity may have been a substantial factor in facilitating
ettringite growth and subsequent swelling. Inter-clod porosity
would be of further significance where it provides a pathway for
ingress of sulfates from an external location.

4.3.2 Controlled ettringite growth

Ettringite is only expansive if the water is sourced from outside the
immediate system – that is, post compaction (Little *et al.*, 2010).
Furthermore, where all reactants are immediately available, ettrin-
gite will form and reach a steady state within 150 h (Little *et al.*,

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2005). However, the heterogeneous distribution of reactants, in combination with the low solubility of sulfate, will further slow ettringite precipitation in a site application. If diffusion of reactants is encouraged through the addition of sufficient water at the mixing stage (3–5% greater than the OMC) and it is coupled with an extended mellowing period (e.g. 3–7 d), this promotes the widespread nucleation and some early ettringite growth before final compaction takes place (Little *et al.*, 2010; Petry and Little, 2002). This strategy will limit expansion by encouraging initial ettringite growth before compaction, and then facilitating any subsequent expansive ettringite growth (as sulfate solubility allows) over a greater area. The latter would promote the wider distribution of smaller ettringite crystals, so there is increased potential for this volume change to be accommodated by the inter-clod pore space, thus avoiding expansion hotspots (Little *et al.*, 2010).

4.3.3 Chemical balance/timing
Increasing silica activity in a clay soil which has a chemistry that would normally form ettringite could instead lead to the formation of a volumetrically stable mineral, such as the calcium alumino sulfo silicate – prehnite (Little *et al.*, 2005). Thus binder mix designs including products with rapidly available silica such as ggbs have been linked with the prevention of sulfate heave (Higgins, 2005). As an alternative hypothesis of how ggbs restricts sulfate heave, Wild *et al.* (1996) suggested that the ggbs particles, which also contain aluminium, provide an alternative surface for ettringite nucleation. They proposed that ettringite growth extending from the surfaces of ggbs particles was nonexpansive, whereas if ettringite growth nucleated from the edgesite of a clay mineral this was associated with expansion (Wild *et al.*, 1996). It may be that the non-expansive nature of ettringite growth in this case was a function of the rapid supply of aluminate (rapidly dissolved from a relatively amorphous ggbs source) to combine with the other immediately available reactants, thus permitting the rapid formation of ettringite in the controlled manner described by Little *et al.* (2010).

In terms of reactant timing, the oxidation state of sulfur is also of interest. Dependent upon the geological depositional environment, sulfur may be present as sulfate (e.g. gypsum Ca_2SO_4), or sulfide (e.g. pyrite FeS_2). While sulfates may release their SO_4^{2-} ions relatively rapidly into solution, the reduced sulfur in pyrite is unavailable for combination until it is oxidised. An oxygen-rich environment, high pH, available water and Ca^{2+} is encouraged by the lime stabilisation process and facilitates rapid oxidation of pyrite to calcium sulfate (Casanova *et al.*, 1997; Floyd *et al.*, 2003). Hence, when assessing the sulfate swell potential of a soil, in addition to quantifying the immediately available sulfate, it is important to also determine the quantity of sulfate that may potentially oxidise from sulfide sources and combine these into a total potential sulfate (TPS) value (Longworth, 2004).

4.3.4 Summary of methods to control sulfate swell
To avoid sulfate-related heave in lime stabilisation, the lowest risk approach involves avoidance of high sulfur clay soils and

areas where groundwater may form a conduit for sulfate transport. A significant challenge is this regard is that sulfur-bearing minerals are unlikely to be uniformly distributed through the host clay, and the initial identification of sulfur species may be missed at the site investigation stage. As a consequence, substantial advice has been published on suitable approaches to site investigation for identifying elevated sulfur content (Czerewko *et al.*, 2003; Highways Agency, 2007; Longworth, 2004) and UK formations that are known for their potential to contain elevated sulfur are well documented (Figure 7). A suggested safe maximum limit with the sulfur avoidance approach is 0·25% TPS, although this may be increased to 1% if soaked California bearing ratio (CBR) tests do not indicate a swell problem (Highways Agency, 2007). However, it must be noted that the suitability of soaked CBRs to identify sulfate swell has been questioned (Highways Consultancy Group, 2008).

Where TPS levels above these low values are considered, any soil stabilisation must be considered an increased risk and the control strategies employed become a means of risk management. Regarding the previously noted strategies (see Sections 4.3.1 to 4.3.3), some potentially complicating factors exist and these
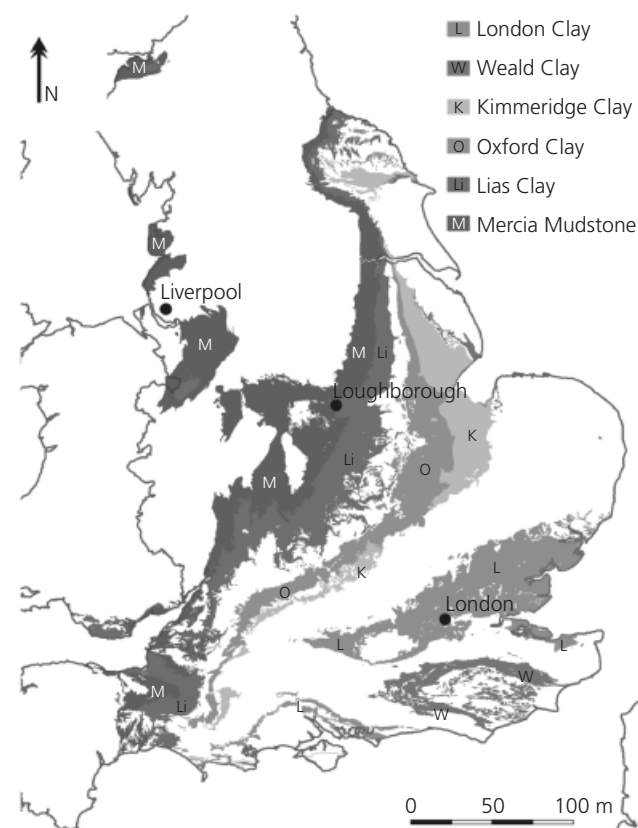
Figure 7. Distribution of UK strata that potentially contain sulfates and sulfides (DigMapGB-625, reproduced with the permission of the British Geological Survey © NERC. Contains Ordnance Survey data © Crown Copyright & database rights 2012)

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highlight areas where the direction of future research may assist the lime stabilisation industry. For strategies involving the deliberate growth of ettringite, the prolonged application of mellowing periods may result in significant clod strength before compaction takes place, and a high air voids percentage in the final compacted product. This conflicts with strategies seeking to improve durability by limiting access to water inflow, especially if this water contained further sulfate. The long-term stability of ettringite is subject to environmental conditions promoting conversion to thaumasite. In this regard, the increased solubility of CO_2^{-3} in water of reducing temperature is considered as a possible trigger (Collett *et al.*, 2004; Snedker, 1996). Therefore, a strategy pursuing the minimisation of air voids, such as minimal mellowing and hydrated lime use, to avoid ettringite formation by denying reactant combination may seem preferable. However, future changes in environmental conditions, such as further addition of drainage trenches into the stabilised material, may trigger swell issues, for example by exposing/oxidising pyrite previously located deep within large clods (Floyd *et al.*, 2003). The timely incorporation of industrial by-products, ggbs for example, into the process may well alleviate some of these problems. For example, where air voids result from long mellowing periods, along with suppressing ettringite expansion, ggbs activation may promote the rapid growth of volumetrically stable reaction products to limit water ingress through the inter-clod porosity.

It can be concluded that, in isolation, all of the discussed strategies would lessen the risk of deleterious mineral formation in the field. However, there would still be reasonably foreseeable field scenarios with the potential to instigate sulfate-related attack and the most challenging scenario would be a highly plastic, high TPS clay. It may prove that a combination of the strategies into a specific working method may overcome this residual risk. Without further research work, this method is not clear. A further challenge is the absence of a satisfactory routine test for assessing the sulfate swell of site materials (Highways Consultancy Group, 2008). The soaked CBR test and accelerated swell test (BSI, 2004) are indicators of sample resilience to water and may indicate swell/strength reduction from water uptake by the clay minerals and, potential ettringite formation from immediately available sulfate. However, as the potential triggers of sulfate swell, such as the introduction of an oxidising/humid atmosphere (sulfide oxidation; Floyd *et al.* (2003)) and a reduction in the soaking water temperature (e.g. for thaumasite growth; Snedker (1996)) are absent from these routine swell tests, there is presently no way for practitioners to fully assess sulfate swell potential during pre-contract testing. Thus, an appropriate swell test remains a priority for industry (Snedker, 1996).

5. Summary
This paper has covered the key aspects relevant to the field practice of lime stabilisation and has demonstrated that much of the subject is well understood and applied. However, some routine practices such as mellowing periods, quicklime use and

moisture conditioning close to the OMC may not always be suitable. If durability and/or long-term performance are to be optimised, treatment of some materials (e.g. clay soils of medium to high plasticity) may require adaptations to these working practices. This is of particular relevance to high sulfur material, where minimisation of inter-clod air voids must be considered a primary defence against sulfate swell. Notwithstanding this, there is still considerable research work which must be undertaken to identify the optimum working approaches for limiting sulfate swell risk. Fundamentally, future research must work towards addressing true industry need and use laboratory preparations which reflect site practice/conditions (Beetham *et al.*, 2012).

5.1 Current understanding and required knowledge
The following list summarises the key points discussed in this paper and also highlights where limited knowledge may be met with future research effort.

(a) Other than initial access to very wet sites (which may use coarse lime nodules), current UK practice almost exclusively uses category 1 quicklime powder; the use of hydrated lime powder or lime slurries is rare.

(b) The use of a small percentage of quicklime is well suited to some applications, specifically the rapid moisture conditioning of clay soils which will denudate to meet pulverisation specifications (Highways Agency, 2009) with minimal mellowing period. This is ideal for a bulk fill compaction slightly wet of the OMC for MDD.

(c) Irrespective of specifications that require a mandatory mellowing period of 24–72 h (Highways Agency, 2009), the inclusion of mellowing periods is not a straightforward issue. Mellowing periods of such long duration may permit clod strength to increase significantly before final compaction, leading to inter-clod air voids that persist throughout the compacted material.

(d) Where quicklime (as opposed to hydrated lime powder/ slurry) is used, the heat generated by slaking will further increase the potential for significant inter-clod voids and/or heterogeneous clod strength. This is a particular issue in lime treatment of clay soils of medium to high plasticity.

(e) Minimising inter-clod air voids limits access to any soaking water, optimising durability and restricting volume change potential. The use of hydrated lime binders/slurries, minimal mellowing periods and a moisture condition significantly wet of OMC may minimise air voids, although the immediate strength may be less.

(f) Longer mellowing periods (e.g. >12 h) and quicklime may be suited to some applications – for example, where the mellowing period is followed by a second mix treatment of further binder such as Portland cement. In such a scenario, the early lime–clay reactions improve pulverisation and reduce subsequent water demand from clods, then inter-clod cementation may both strengthen this region and infill some of the air voids. If the degree of inter-clod voiding is high

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(as may occur with prolonged mellowing (Sweeney *et al.*, 1988), the degree of subsequent void infilling may be limited.

(*g*) The current state of the art demonstrates that lime migration may instigate diffuse cementation throughout larger clods of clay soil. The rate that strength gain is achieved with diffuse cementation is influenced by several factors and a high degree of soil saturation is of substantial significance.

(*h*) The optimal combination of binders and different working methods for every different soil type is not known. This acknowledges the absence of a 'one size fits all' approach and the importance of selecting binder type, mellowing periods and moisture conditioning etc. based upon suitability to achieve the required engineering performance.

(*i*) Our current specifications may be improved through allowance of a more flexible design/field approach, with facility for the controlled relaxation of some requirements. Specifically, mellowing periods and pulverisation should become appropriate to the material/binder type and whether the treatment intent is to promote a diffuse or inter-clod cementation. Pre-start, site-specific mix designs that use a laboratory preparation method closely reflecting the intended field approach should play a role in controlling this (see Beetham *et al.*, 2012 for an example of this preparation). A key focus of this approach would apply consideration of minimising air voids to maximise durability and mellowing durations should become an element of design and not specification.

(*j*) The treatment of clay soils with a high TPS may result in sulfate swell. There are working methods which may reduce the risk of sulfate swell; however, the current understanding as to which of these methods, or combination of these methods is durable over longer cures and environmental changes is limited. Future research should address this with an industry-focused approach, including development of a swell test which explores environmental changes.

(*k*) Laboratory studies indicate that waste-derived binders (e.g. waste paper sludge ash, red gypsum waste) have the potential to work as secondary binders within soil stabilisation. However, it is not clear how these may be incorporated into field applications. Required knowledge in this regard includes: how these binders influence diffuse or inter-clod cementation processes; durability implications; and how specifications may be adapted to include their controlled use.

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