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# Clay-Lime Stabilization: Characterizing Fly Ash Effects in Minimizing the Risk of Sulfate Heave

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ABSTRACT

Clay soil stabilization with lime is a well-established, low-cost and effective way of enhancing the physical properties of the ground, particularly strength or bearing capacity, prior to construction. However, many clays contain soluble sulfates that can also react with lime to form ettringite, with a corresponding increase in volume, referred to as heave. Indeed, there have been several notable examples of this type of problem, including the M40 motorway in the UK and Stewart Avenue in Las Vegas. The reactions are similar to sulfate attack in concrete and thus the protection that fly ash brings in that application could potentially help to reduce heave in lime-stabilized clays. Work at the University of Dundee, reported at WOCA 2009, has indeed demonstrated the effectiveness of fly ash in the application, but the mechanism by which heave is suppressed appears to be different to that in concrete. In this paper, the Authors will present key data arising from several projects, covering a range of fly ashes and clay soil types. Ettringite formation will be considered in the context of lime-stabilization. Based on physical (scanning electron microscopy and mercury intrusion porosimetry) and compositional (X-ray diffraction) analyses and heave test data, the Authors will show that, contrary to expectation, the incorporation of coarser fly ashes is more effective than finer materials in limiting sulfate heave. The processes involved will be discussed and guidance given on a fly ash-based solution.

## INTRODUCTION

Lime-stabilization of clay soils provides a geotechnical solution for difficult ground conditions that is both sustainable and economic. The technique normally involves the spreading of quicklime to the soil treatment area at 2-4 % by mass, rotovation and mellowing to enable material interaction, and finally compaction. The processes occurring during lime-stabilization improve the handling and engineering properties of the material and the technique has been used around the world in a range of applications for the last 30 years or so.[1]

The appropriateness of the method for ground improvement can, however, come into question if the soil being treated contains sulfate. Indeed, the application of lime in this situation can lead to ettringite formation causing heave and associated damage to components supported by the treated soil.[2] Initial work reported by the Authors at WOCA 2009 demonstrated the feasibility of fly ash for limiting heave and this appeared to be due to both physical and chemical effects and to depend on the properties of fly ash used.[3] This paper considers the outcomes of follow-up studies carried out to establish material influences, mechanisms involved and possible means of identifying how fly ash can be used in this role.

## FACTORS INFLUENCING SULFATE HEAVE

During lime-stabilization of soil, the main factors governing the degree of ettringite formation and hence heave occurring are the availability of aluminates and sulfates, (initially their release into solution and ultimately the total quantity) and the level of lime present.[4, 5] The clay mineral content and type have also been reported to affect behaviour, with high clay content and alumina-rich soils tending to promote greater heave.[6, 7] Similarly, the exposure conditions, including access to water[8], its pH[9] and the temperature[10] influence the process.

The results of linear swelling tests (using specimens of ∅40 mm × 24 mm) on various clays sourced from the South of England, UK, stabilized with 6% $Ca(OH)_2$ and containing different levels of naturally occurring sulfate, following storage in a room temperature water bath, are shown in Figure 1. These indicate progressive increases in swelling with time and sulfate level over the 15 day test period. The similar levels of swelling noted for clays with sulfate levels up to 0.4% and then noticeable increases beyond this highlight the concept of trigger level in relation to damage of the treated soils. Furthermore, the results illustrate the difficulty associated with lime-stabilization at high sulfate levels.

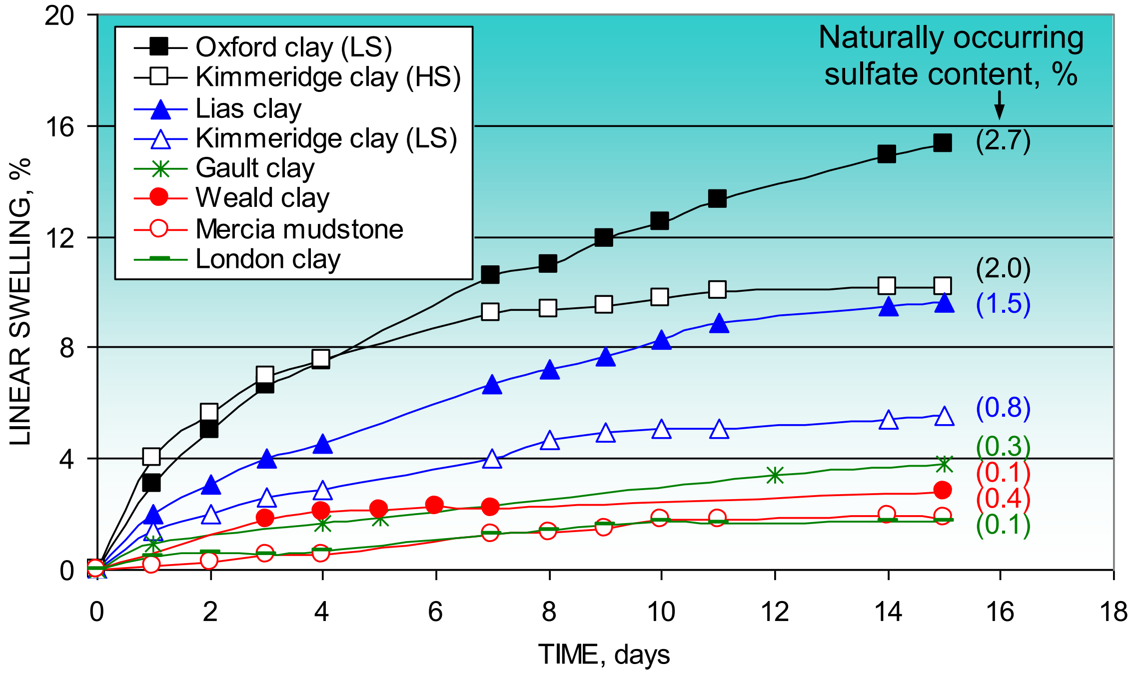


**Figure 1.** Linear swelling of lime-stabilized clays containing various sulfate levels (stabilized with 6% $Ca(OH)_2$, no fly ash)

## FLY ASH POTENTIAL FOR LIMITING SULFATE HEAVE

Several approaches have been considered to limit sulfate heave in lime-stabilized soils, e.g. References 11 and 12. These mainly focus on preventing the conditions necessary for ettringite formation. The effects of parameters associated with the construction process have been examined, e.g. repeat application of lime, extended mellowing period and increased field moisture contents. Other work has considered the application of barium compounds, given the low solubility of barium sulfate and hence ability to fix sulfate in the soil.[13]

Arguably, techniques which regulate the lime content of the soil, while also contributing to its developing stabilized structure, would be particularly effective in reducing damage. Fly ash exhibits these properties, while also offering environmental and economic benefits, being simple to apply and common to this form of construction.[1] In addition, the material has been used previously in limiting this type of problem in grouts and concrete.[14, 15] Despite its potential, it is apparent that the use of fly ash in this role has only received limited coverage in the literature.

## TEST MATERIALS, LIME-STABILIZED MIXES AND SAMPLE PREPARATION

Given the initial work suggested that fly ash properties had an effect on the level of heave occurring, a range of materials were considered during the project.[16, 17] These included fly ash, (i) obtained dry and having various fineness / LOI, (ii) with different storage histories (stockpiled and pond-stored materials) and (iii) of relatively high sulfate / lime content. Except for FA3-1 and FA3-2, all fly ashes were from different sources. A summary of the main properties of the materials is given in Table 1 and more details can be obtained in Reference 17. Of these, FA1 and FA3-1 conformed to BS EN 450-1.[18]

Following tests on a wide range of clays, including those shown in Figure 1, bulk samples of five main test materials were obtained. The three with sulfate contents likely to provide a risk of heave (i.e. $SO_3 \geq 1.0\%$) following lime-stabilization, are considered here. Details of their main properties are given in Table 2.[16] As indicated, the sulfate contents ranged from 1.0 to 1.8%, similar levels of alumina were present and the clay mineral contents highest to lowest were Lias, Kimmeridge and Oxford. Kimmeridge was slightly finer than the other clays, while Oxford had a slightly greater lime-demand with regard to stabilization.

A quicklime to BS EN 459-1 and typical of those adopted in the application (CL 90) was selected for use during the test programme.[19]

The lime-stabilized mixes had CaO added at a level of 3.0% which is typical of the levels normally applied. In studies considering fly ash for this application, relatively low levels of less than 10% have tended to be used.[20] Initial tests suggested that greater quantities may be necessary to limit heave to acceptable levels. Fly ash was therefore applied at levels from 6 to 24%, which is similar to those used in fly ash bound mixtures (FABMs).[21]

After mixing lime with the test soils, samples were allowed to mellow for 24 hours prior to fly ash addition (when used) and compaction was carried out following the BS EN 13286-53 procedure.[22]

**Table 1.** Main characteristics of test fly ashes

| CHARACTERISTIC | FA1 | FA2 | FA3-1 | FA3-2 | FA4 | FA5 | FA7 |
|---|---|---|---|---|---|---|---|
| OXIDE COMPOSITION, % | | | | | | | |
| CaO | 3.6 | 4.6 | 3.4 | 4.5 | 3.1 | 12.0 | 1.9 |
| $SiO_2$ | 44.5 | 37.6 | 58.8 | 50.0 | 43.7 | 38.8 | 43.9 |
| $Al_2O_3$ | 22.4 | 26.3 | 21.1 | 20.0 | 28.3 | 14.5 | 24.6 |
| $Fe_2O_3$ | 7.5 | 8.0 | 4.5 | 5.0 | 5.7 | 4.7 | 8.0 |
| $K_2O$ | 2.5 | 2.1 | 2.4 | 2.5 | 1.0 | 2.2 | 3.0 |
| $Na_2O$ | 1.8 | 0.9 | 0.4 | 0.5 | 0.5 | 0.7 | 0.6 |
| $SO_3$ | 1.6 | 1.1 | 0.4 | 0.8 | 0.6 | 4.1 | 0.3 |
| PHYSICAL PROPERTIES | | | | | | | |
| Initial moisture content, % | 0.4[1] | 1.5[2] | 0.3[1] | 28.2[2] | 56.0[3] | 16.5[2] | 20.0[2] |
| Loss on ignition, % | 4.5 | 10.0 | 3.4 | 15.6 | 10.7 | 20.0 | 12.5 |
| Fineness, 45 μm sieve retention, % | 10.0 | 47.6 | 18.6 | 56.4 | 53.5 | 36.5 | 30.1 |
| Particle density, $Mg/m^3$ | 2.30 | 2.09 | 2.23 | 2.11 | 2.10 | 1.95 | 2.16 |

[1]dry, [2]stockpiled, [3]pond-stored

**Table 2.** Composition and other main properties of test clays

| COMPOSITION, % | KIMMERIDGE | LIAS | OXFORD |
|---|---|---|---|
| CaO | 11.1 | 10.7 | 8.9 |
| $SiO_2$ | 49.3 | 46.8 | 50.2 |
| $Al_2O_3$ | 18.2 | 21.2 | 19.1 |
| $Fe_2O_3$ | 5.4 | 6.2 | 5.8 |
| Quartz | 16.3 | 8.8 | 11.7 |
| Calcite | 9.0 | 10.3 | 5.0 |
| Total clay mineral | 29.9 | 45.3 | 20.3 |
| Feldspars | 6.0 | 7.8 | 20.9 |
| Gypsum (g) or pyrite (p) | 0.9 (p) | 1.1 (g) | 3.4 (g) |
| Optimum moisture (OMC), % | 24.5 | 20.7 | 25.0 |
| Maximum dry density (MDD), $Mg/m^3$ | 1.54 | 1.61 | 1.52 |
| Classification* | CI | CH | CH |
| Fineness**, $d_{(10)}$, μm | 1.8 | 2.2 | 2.0 |
| $d_{(50)}$, μm | 6.7 | 8.9 | 7.6 |
| $d_{(90)}$, μm | 26.4 | 32.6 | 25.7 |
| Fines content** (fraction < 75 μm, #200), % | 99.4 | 97.7 | 96.8 |
| Initial consumption of lime (ICL), % | 2.0 | 2.5 | 3.0 |
| Total potential $SO_3$, % | 1.0 | 1.5 | 1.8 |
| Acid soluble $SO_3$, % | 0.1 | 0.4 | 1.5 |
| Total organic content (BS 1377-3)[23], % | 1.6 | 1.0 | 3.1 |

* CI: intermediate plasticity, CH: high plasticity (BS 5930).[24]

** Determined by LASER granulometry.

INFLUENCE OF FLY ASH ON COMPACTION AND SOIL STRUCTURE

Research examining the effect of fly ash on the compaction and structure of lime-stabilized soils in terms of moisture content / dry density relations indicates that a range of behaviour has been noted. As optimum moisture content (OMC) and maximum dry density (MDD) was the basis of comparison used to investigate sulfate heave, reflecting practice, this was investigated for the range of materials.[17]

The application of lime to the test soils was found to increase OMC and reduce MDD compared to the soil alone. This corresponds to the changes occurring in the soil due to its interaction with lime[1] and the influence this has on the compaction process.[25, 26] As with many lime-stabilized materials, it was also noted that the typical bell-shaped compaction curves tended to flatten out with the application of lime.[25, 27] This has been found previously and is beneficial with regard to controlling the compaction process.[28]

An example of the relationship between MDD and OMC for Lias clay stabilized with 3% CaO and the test fly ashes applied at levels of 6 to 24% is shown in Figure 2. This indicates that the behaviour was influenced by fly ash properties. In general, the finest fly ash gave greatest MDD and least OMC, and minimal changes in these with increasing application level. Thereafter, the MDD tended to reduce and OMC increase with increasing coarseness and LOI (and reducing particle density) of the fly ashes and with greater application level. These effects were also noted for fly ashes that had been wet-stored. This tends to give particles with rougher surfaces and agglomerates, see Figure 3, and these would also be likely to influence the compaction process.

The results from these tests, therefore, indicate that coarser fly ashes tend to give a more open structure to the lime-stabilized soil and to have increased water contents. It may be expected that these effects will have some influence on the behaviour of the material in relation to sulfate heave.

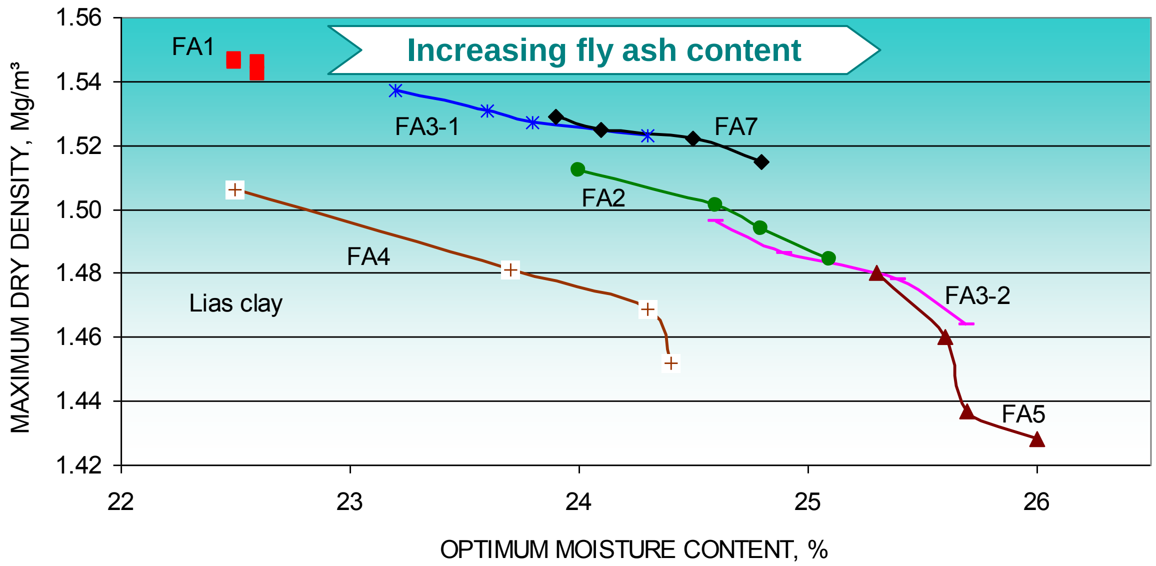


**Figure 2.** Effect of fly ash on OMC and MDD relationship for lime-stabilized Lias clay

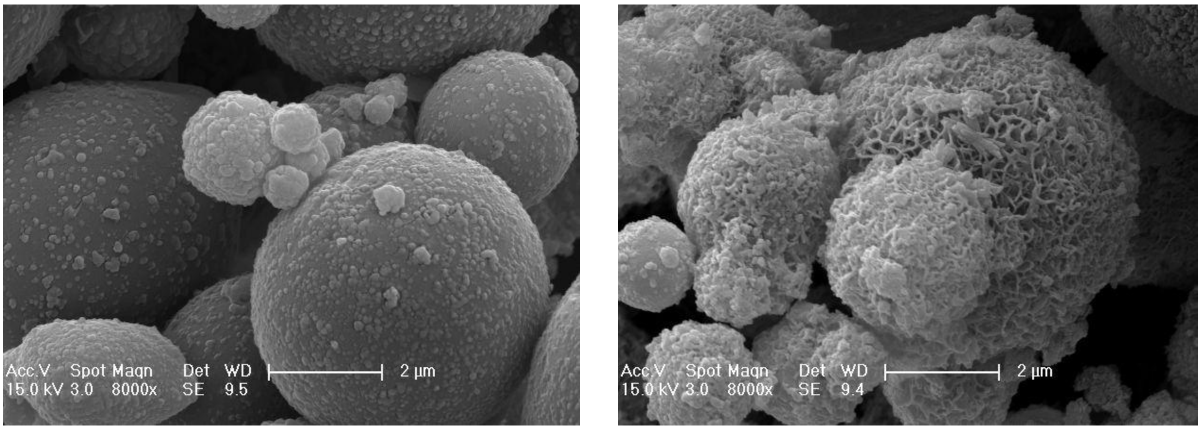


**Figure 3.** Morphology of FA1 (dry / fine), left, and FA4 (pond-stored / coarse), right

## FLY ASH EFFECTS ON STRENGTH DEVELOPMENT

Unconfined compressive strength test results for FA1 and FA4 containing Oxford clay samples (moist-cured at 20°C) are given in Figure 4. Strength was found to increase with lime application and further with the addition of fly ash. There was also an increase in strength with age.

Between fly ashes it was noted that soil treated with FA1 at a given application level and age gave higher strength than FA4. While FA1 specimens indicated noticeable increases in strength between 28 and 90 days, these were less for FA4.

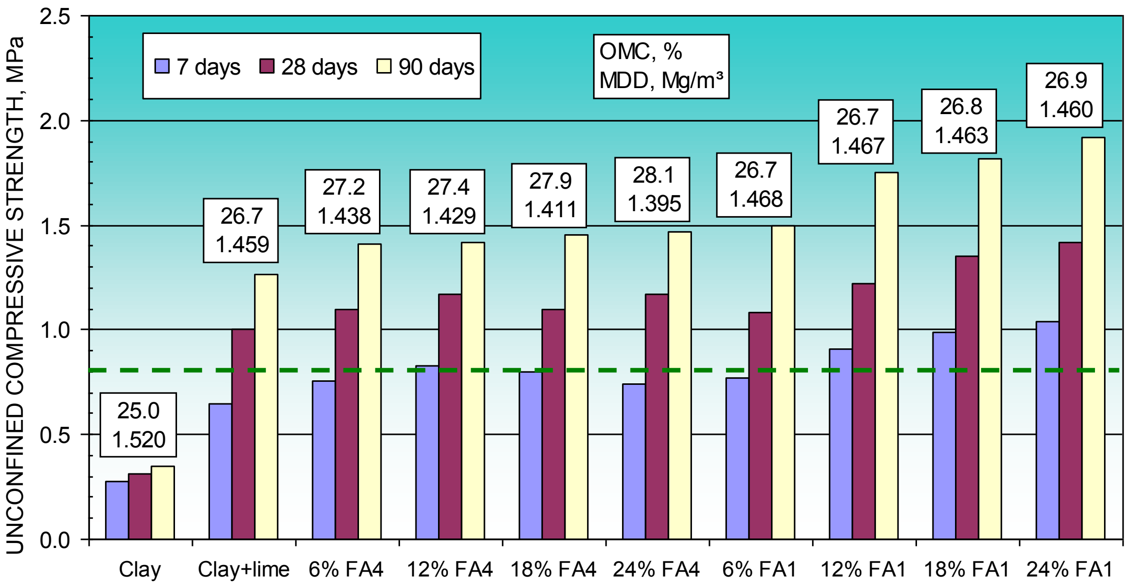


**Figure 4.** Strength gain of moist-cured Oxford clay specimens (stabilized by 3% CaO and 0 to 24% FA4 and FA1 fly ash)

*Broken line indicates minimum requirement (0.8 MPa) for soils treated by fly ash and lime at a specimen slenderness ratio of 2:1*[29]

The effects occurring between the two fly ashes can be attributed in part to particle packing within the material. Indeed, the MDDs, as indicated in Figure 4, were higher for FA1 reflecting a more densely packed structure. As noted above, while there was little change in MDD for FA1 with increasing application level in the lime-stabilized soil, this reduced for FA4. In addition, the effects are also likely to be due to differences in pozzolanicity. Indeed, FA1 conforms to BS EN 450-1[18] for use in concrete, while FA4, taken from a pond, did not meet these requirements.

## FLY ASH EFFECTS ON SULFATE HEAVE

Swelling in lime-stabilized specimens was determined using the BS EN 13286-49 test method[30], which involved measurement of volumetric changes occurring following exposure of these, with limited confinement, to a water bath at 40°C. Three specimens of ∅50 mm × 50 mm were prepared for each lime-stabilized soil.

### Dry Fly Ash Fineness and LOI

The results obtained from tests on dry / near-dry fly ash covering the effect of application level for the three test clays are shown in Figure 6. These show a systematic reduction in swelling with increasing fly ash level with similar behaviour noted between test clays (with sulfate level effects of these also apparent).[17] The benefits of fly ash were greatest for material exhibiting highest sieve retention (i.e. coarsest) and LOI. As noted above, this also corresponds to material exhibiting least MDD and pozzolanicity.

It is also apparent that for the fly ash application levels used in the study, i.e. up to 24%, the material was effective in reducing swelling to the generally accepted level, i.e. < 5.0% in the test[31], although the quantity of fly ash required to achieve this was dependent on the fly ash / clay combination. The exception to this was Oxford clay (with the highest $SO_3$ level 1.8%), where swelling in all cases was > 5.0%.

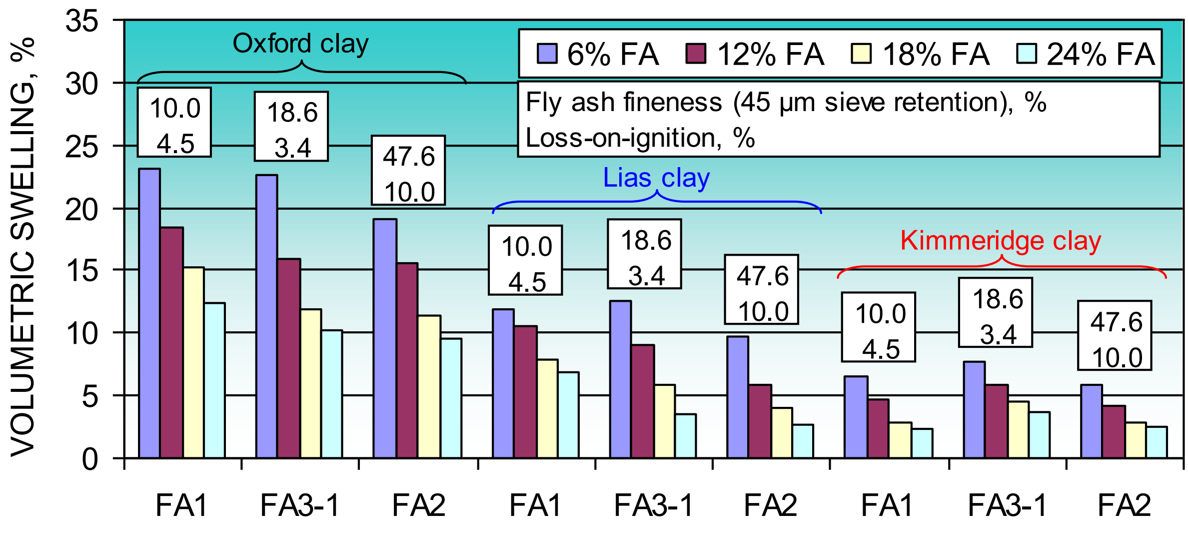


**Figure 6.** Effect of fly ash fineness and loss-on-ignition on swelling of clays (stabilized with 3% CaO and 6 to 24% fly ash)

Fly Ash Storage Conditions

In addition to dry storage in bags or silos, fly ash can also have water added at low levels around 15% and be introduced wet to mounds (stockpiles), or be slurried and kept in an excess of water (ponds). Periods of storage can vary and work has shown that these conditions can lead to changes in the physical properties of fly ash (e.g. agglomeration) and reactivity.[32] There are significant quantities of material stored in this way that are available for recovery and use.

The results from tests examining the effect of storage on the material's ability to limit sulfate heave with 18% fly ash applied are shown in Figure 7. These indicate that the wet-stored fly ashes gave lower expansion during the test. It is apparent that in addition to their storage conditions (which may also influence their $SO_3$ level) the wet fly ashes shown in Figure 7 were all relatively coarse and of high LOI. Thus this would appear to confirm that less reactive material, giving lower MDD, is more effective in treating soils representing a risk of heave.

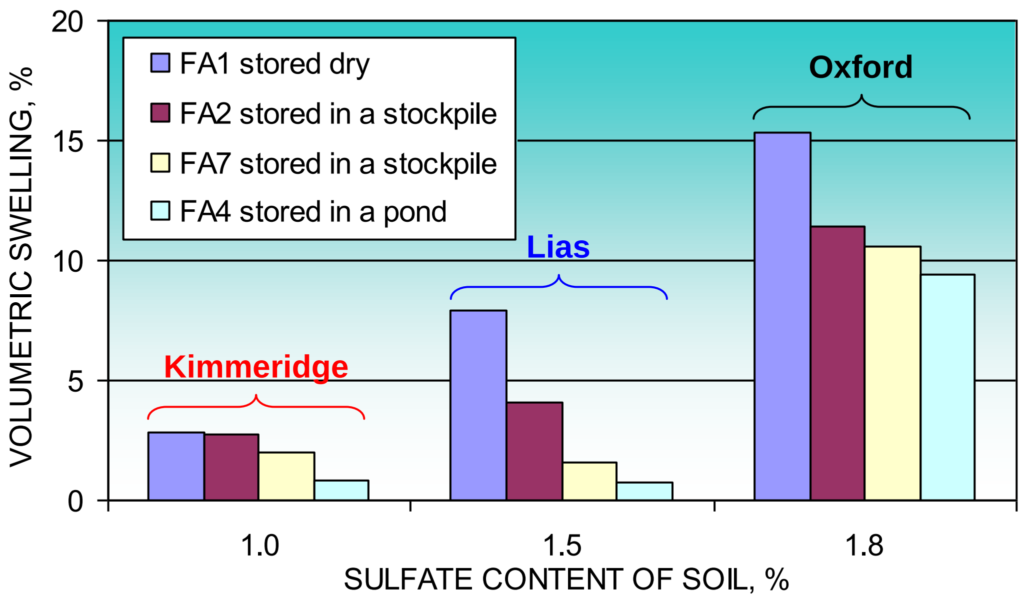


**Figure 7.** Effect of fly ash storage condition on swelling of Kimmeridge, Lias and Oxford clays, stabilized with 3% CaO and 18% fly ash

Sulfate Level in Fly Ash

The burning of high sulfur coal can lead to the presence of sulfate in fly ash, which will add to that in the lime-stabilized soil if the material is used in the application. Rather than limiting the process, it may then contribute to heave.

The effect of this is shown in Figure 8 for the three test clays, where a comparison is made between FA5 and FA3-2, which had similar properties and storage conditions (stockpiled), but different sulfate contents. FA5 was from a high sulfur coal, with lime injection used in the flue gas stream (c.f. desulfurization, which accounts for its CaO content). The results indicate that the same general effect occurred in terms of fly ash level reducing swelling. However, the swelling occurring was between 2.0

and 5.0% greater with the high sulfate fly ash. The results therefore highlight the importance of establishing the sulfate level of fly ash, prior to use in the application, as required for clays.[33, 34]

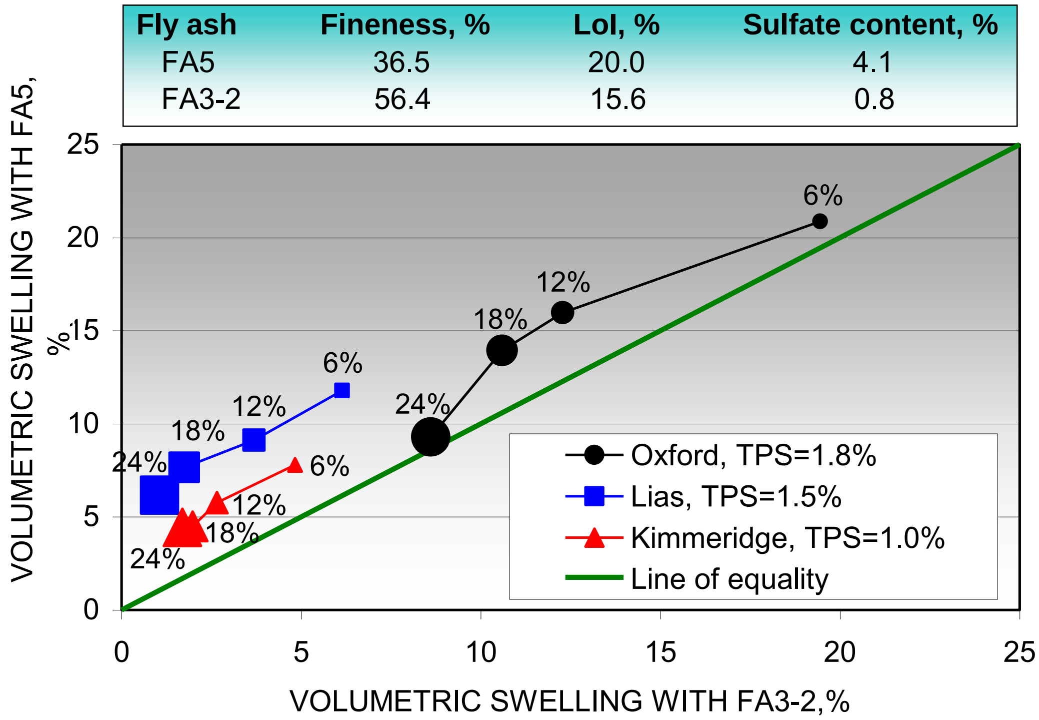


**Figure 8.** Effect of fly ash sulfate content and addition level on swelling of Oxford, Lias and Kimmeridge clays, (stabilized with 3% CaO)

## MECHANISMS OF SULFATE HEAVE LIMITATION WITH FLY ASH

In the course of the research, it was consistently found that fly ash addition reduced sulfate swelling in lime-stabilized soils. The possible mechanisms influencing this effect are i) differences in the quantity of ettringite formed between lime-stabilized mixes; ii) provision of internal space to accommodate expansive product formation; and iii) enhanced strength of the matrix, whereby it may resist the stresses exerted by expansive products. In order to examine this further, tests to consider the microstructure and ettringite formation were carried out.

The results from mercury intrusion porosimetry tests on Lias clay for the various fly ashes are shown in Figure 9. These show general agreement with the effects noted for MDD, with greater porosity observed as the coarseness and application level of fly ash in the lime-stabilized soil increased. These material and mix effects correspond to where greatest reductions in swelling were noted during these tests. The changes occurring to the pore structure during the swelling test are shown in Figure 10. These indicate that in the regions where the majority of pores occurred, i.e. around 10 and 0.1 μm after 3 days moist curing, there was refinement, shown by the arrows. It is likely that this, in part, corresponds to ettringite formation in the lime-stabilized soil during the 7 days in water at 40ºC.

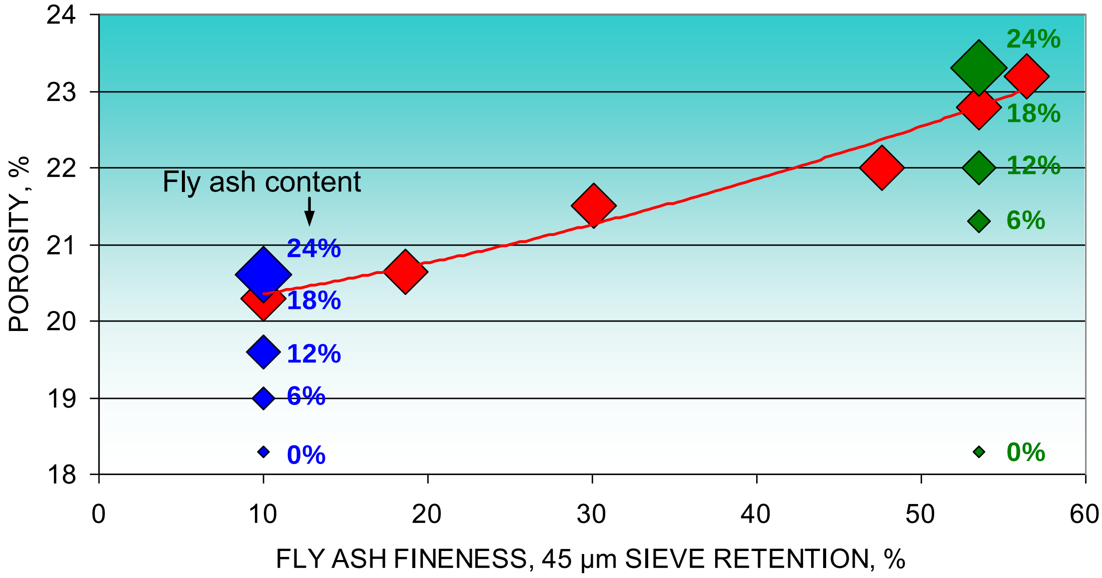


**Figure 9.** Relationship between particle size of fly ash and porosity of Lias clay mixes (stabilized with 3% CaO and different fly ash levels, moist-cured for 3 days)

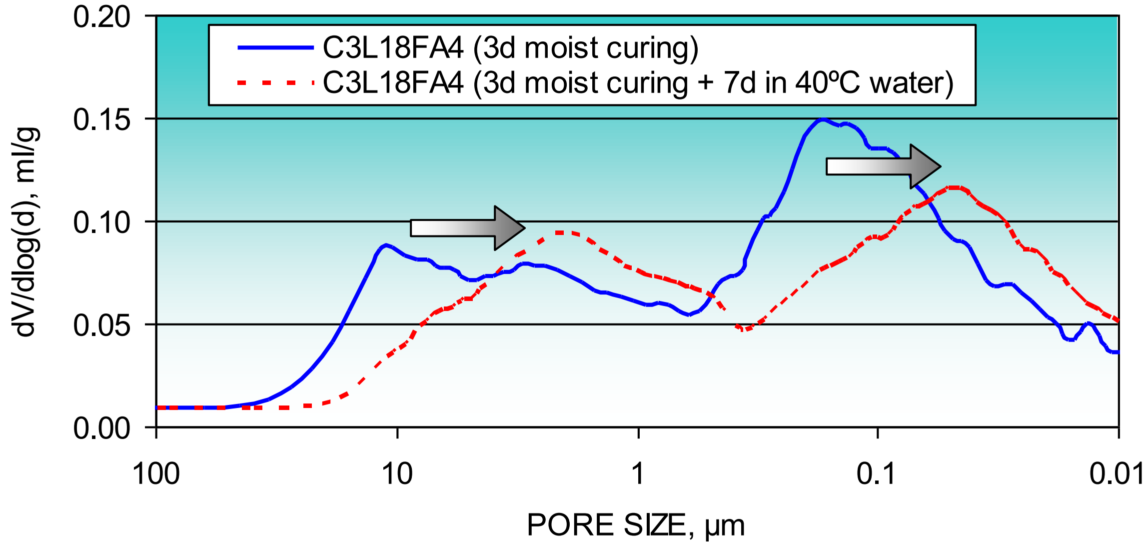


**Figure 10.** Refinement of porosity observed for 3 day moist-cured Lias clay (stabilized with 3% CaO and 18% FA4 fly ash) after immersion in 40°C water for 7 days

In order to examine the mechanisms behind the behaviour observed in more detail, the results of ettringite content (from quantitative XRD), unconfined compressive strength, porosity and volumetric swelling tests are compared for stabilized Lias clay using FA1 and FA4 in Figure 11.[16]

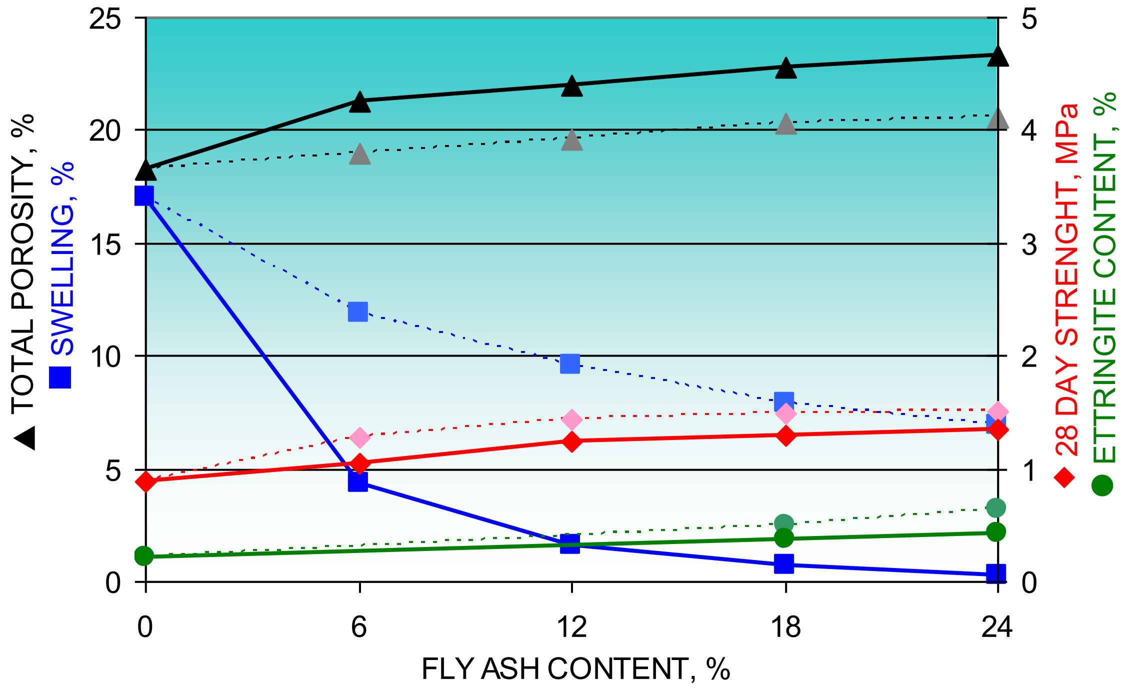


**Figure 11.** Relationship between porosity, swelling, strength, ettringite content and fly ash level in Lias clay (stabilized with 3% CaO, test age 7 days except for strength, FA1: broken lines, FA4: solid lines)

From the results, and microscopy tests also carried out, it appeared that ettringite was present throughout the samples and availability to cause damage was not limiting. The minor differences in ettringite levels noted between the stabilized clays may relate to sulfate introduced by fly ash. The strength of the lime-stabilized matrix is generally enhanced with greater quantities of fly ash and with the finer, more reactive FA1. On the other hand, the porosity increased with application level and was greater for the coarser FA4. Given these effects and the differences in swelling occurring between fly ashes, it appears that the porosity of the compacted soil has an important role in the process by providing a structure capable of accommodating the expansive effects of ettringite. It is possible given the results that the relative importance of strength and porosity may change between fine and coarse fly ash.[16]

## FLY ASH-BASED SOLUTIONS

The role played by the compacted structure in limiting sulfate heave provides a potential route to establishing a fly ash solution for limiting heave in lime-stabilized sulfate-bearing soils.[17] This is illustrated in the chart shown in Figure 12 for Lias clay, treated with 3% CaO for fly ash having a sulfate content of < 1.6%. This is based on relationships between sulfate swelling, MDD, fly ash fineness and level. From this, possible options in terms of fly ash properties and level can be determined to limit heave as indicated by the arrows. It is apparent that charts of the type in Figure 12 relate to the materials / compositions used in this project and are demonstrative of what could be developed for fly ash to assist in material selection for limiting sulfate-induced damage.

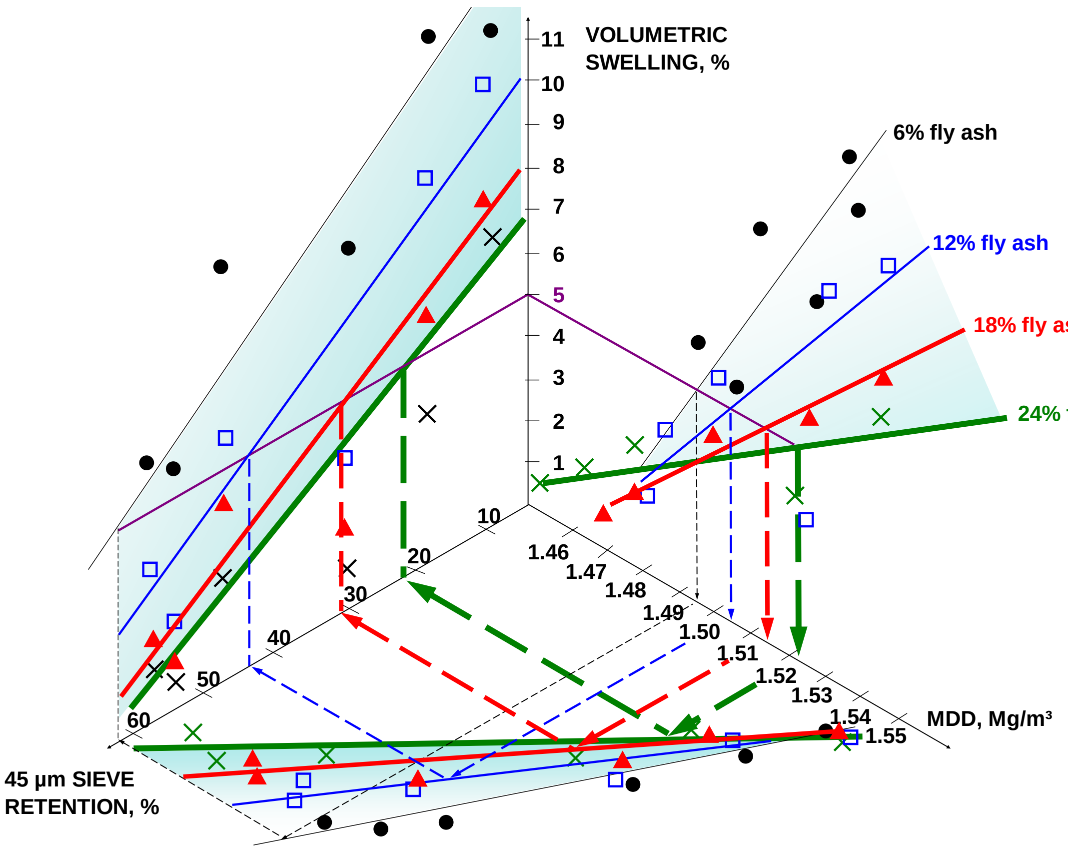


**Figure 12.** Chart relating volumetric swelling, maximum dry density, fly ash fineness and level for Lias clay stabilized with 3% CaO, at 6-24% fly ash addition

## CONCLUSIONS

1. Accelerated volumetric swelling tests, carried out to BS EN 13286-49, on sulfate-bearing clays demonstrate that fly ash addition reduced swelling. This effect increased with the quantity of fly ash applied.

2. The decrease in swelling was greater with coarse / high LOI fly ash compared to similar quantities of fine / low LOI material and this applied to clays over a range of sulfate contents. This was also noted for fly ashes with prior wet storage.

3. The effectiveness of fly ash is reduced where it contains high sulfate levels. For the fly ashes tested, it appears that the maximum allowable sulfate content should ideally be less than 1.0% by mass (expressed as % $SO_3$).

4. The mechanism by which fly ash minimises sulfate heave appears to be different for mixes with coarse fly ash compared to those with fine fly ash. The former tends to mostly increase the porosity and hence provide space to 'accommodate' ettringite, while the effectiveness of the latter appears to be influenced more by improved strength to withstand expansive forces occurring.

5. Given the material effects observed, a chart, relating sulfate swelling, MDD and fly ash fineness and level of application is developed. This illustrates a possible methodology in relation to fly ash selection for limiting damaging sulfate heave.

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