Assessment and Management of Sulphate Attack in Lime and Cement Stabilised Clay Soils in the UK

Introduction

Furlong Ground Stabilisation have researched, that in the United Kingdom, primary sulphate minerals most frequently encountered are gypsum ($CaSO_4 \cdot 2H_2O$) and anhydrite ($CaSO_4$). These minerals are associated with marine sedimentary limestone and mudstone deposits. Under near surface conditions, gypsum represents the stable hydrated form of calcium sulphate.

Recent Failures and BRE's Review

Over the past three years, BRE has been involved in several cases where lime and cement stabilised clay soils have failed due to sulphate attack. Such incidents have highlighted the need to review current methods for assessing sulphate-bearing ground prior to stabilisation. This section outlines the causes of failure and suggests improvements for site assessment.

Sulphate Attack Mechanism in Stabilised Ground

The addition of lime and cement to cohesive (clay) soils is a well-established method for improving their engineering properties and is generally reliable. However, sulphate attack occasionally causes the stabilised layer to fail specification. During such attacks, sulphates and aluminium silicate minerals in the soil react with lime or Portland cement in the presence of water, forming expansive sulphate hydrates such as ettringite and thaumasite.

This process has affected structures including capping layers for roads, vehicle hardstanding, and ground-bearing floors in warehouses and retail units. Ettringite ($3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 32H_2O$) typically forms under wet conditions at various ambient temperatures. BRE identified this reaction product at the site of a retail store, where lime/cement stabilisation of Lower Lias Clay resulted in over 100mm of ground heave between May and September.

Thaumasite ($CaCO_3 \cdot CaSO_4 \cdot CaSiO_3 \cdot 15H_2O$) forms preferentially in cool (usually below 15°C), wet conditions typical of UK ground, and requires a source of carbonates, often supplied by shell fragments or limestone in clay soils. BRE found thaumasite to be the main expansive mineral causing heave at a building site following cement stabilisation of Kimmeridge Clay.

Historical Cases and Pyrite's Role

During the construction of the Banbury section of the M40 motorway in the late 1980s, both ettringite and thaumasite were reported following lime stabilisation of Lower Lias Clay, with a 250mm stabilised layer heaving by up to 150mm (60% expansion). Investigations indicated that ettringite formed initially in summer was converted to thaumasite during cold winter conditions.

Some of the sulphate involved in these expansive reactions originated as iron sulphide (FeS2), commonly found in clays such as Lower Lias Clay as fine pyrite grains. Exposure to air and water oxidises pyrite, forming sulphuric acid, which reacts with calcium carbonate to produce gypsum—a process that is itself expansive and can raise sulphate levels to harmful concentrations. While clay oxidation is slow in nature, the mixing ('maceration') required for lime/cement stabilisation accelerates pyrite oxidation, exposing it to water and air and increasing pH.

Guidance and Standards

Current British Standard BS 1924:1990 does not address failure from sulphate reactions nor include specific tests for sulphates or sulphides. Its swelling test procedure is not ideally suited for identifying swelling from sulphide/sulphate reactions. Designers often refer to Highways Agency publication HA 74/00, which provides guidance on assessing sulphates and sulphides in materials for highway construction. However, it does not warn that cement-stabilised clay soils may be similarly affected as lime-stabilised soils—a phenomenon observed on UK sites and analogous to recognised sulphate attack on concrete.

New European standards, BS EN 13286 Parts 1 to 53, are being introduced to replace BS 1924:1990, including specifications for stabilised materials (future BS EN 14227).

Protocols for Sulphate and Sulphide Assessment

BRE has led UK research and guidance on sulphates and sulphides in ground and construction materials since 1938. Recent publications include Special Digest 1 (SD1) and BR 279, with BSI standards following BRE's precedent. The revised BRE SD1, addressing the thaumasite form of sulphate attack (TSA), introduced formal procedures for accounting for pyrite content in disturbed ground. Failure to consider pyrite oxidation has been implicated in over 30 TSA cases in motorway and highway bridges founded on pyritic Lower Lias Clay.

Furlong Ground Stabilisation adopt Modern instrument-based chemical analysis methods, such as ICP-AES, have replaced manual procedures for sulphate and sulphide testing, harmonised with the TRL 447 protocol for highway structural backfills.

Testing Methods

Total Sulphate Content

Total sulphate (acid soluble, AS) indicates the reservoir of sulphates available to react with lime or cement. In soil stabilisation, this differs from concrete durability assessment, which focuses on sulphate concentration leached into groundwater. HA 74 recommends BS 1377 procedures, which are slow and costly. SD1 and TRL 447 recommend ICP-AES analysis, which is faster and economical, with results reported as %SO4.

Total Sulphur Content

Total sulphur (TS) measures the potential sulphate that could accumulate from pyrite oxidation. The BS 1047 wet chemical method is labour-intensive and expensive; BRE recommends high-temperature combustion using instruments such as Leco SC-144, providing rapid results at low cost. Microwave digestion (TRL 447 Test 4A) is another practicable method, though it requires two hours per sample.

For pyrite detection, the BRE SD1 procedure involves calculating total potential sulphate (TPS), comparing TPS with AS to determine oxidisable sulphides (OS), which reflects pyrite content. Significant OS levels warrant a detailed review of material suitability for stabilisation.

Water-Soluble Sulphate Testing

While not a primary parameter for soil stabilisation, water-soluble sulphate tests aid in assessing suitability and the need for site drainage. HA 74 specifies testing materials within 500mm of stabilised capping, though this may be insufficient for the built environment. Analysis methods include gravimetric and ion-exchange (BS 1377 Part 3), but BRE SD1 and TRL 447 recommend ICP-AES, with results expressed in g/litre SO4. Magnesium cations increase the risk of severe sulphate attack on Portland cement binders.

Groundwater Sulphate Testing

Testing for sulphate in groundwater is essential to evaluate the risk of sulphate ingress under poor drainage conditions. HA 74 recommends BS 1377 Part 3 methods, and BRE SD1 suggests using ICP-AES analysis.

Swelling Tests

Swelling tests on candidate mixes are important when significant sulphate/sulphide is present. HA 74 refers to BS 1924: Part 2:1990, soon to be replaced by BS EN 13286-47:2004, which specifies testing at 20 ±2°C. However, BRE notes that this temperature is too high for thaumasite formation and recommends testing at lower temperatures typical of UK ground. The minimum test duration of four days may be insufficient to detect swelling from pyrite oxidation. BS EN 13286-49:2004 allows lateral expansion and freer access to water but uses a high test temperature unsuitable for sulphate expansion. HA 74 provides swelling limits for highway construction, but these may be too generous for built development where tolerances are tighter.

Strategy for Appraising Clay Sites and Materials

Furlong Ground Stabilisation recognise the variability of sulphate concentrations, the following strategy is suggested for evaluating clay soils for stabilisation in built development:

1. Conduct site investigations to determine geological and manmade materials and assess hydrology.
2. Note the presence and distribution of sulphates/sulphides in sedimentary strata and made ground, with high concentrations often found below the weathered zone.
3. Perform systematic or targeted sampling using trial pits or boreholes, typically on a grid pattern or for visually identified materials.
4. Carry out total sulphur tests on sample fractions using high-temperature combustion.
5. Review total sulphur results; if TPS exceeds 0.2% SO_4, take closer spaced samples and proceed to further tests.
6. Conduct acid-soluble sulphate tests on materials with high TPS and compare with TPS to identify pyrite.
7. For materials with AS >0.2% SO_4 or pyrite present, perform swelling tests on candidate mixes and consider modifying test procedures.
8. Evaluate risks to development from swelling, noting that HA 74 limits may be unsuitable for building applications.

Conclusions

Numerous cases of failure due to sulphate attack in lime and cement stabilised clay soils intended for built development have occurred in recent years, causing ground heave and softening. Many have gone unpublicised but have been costly to rectify, highlighting several deficiencies in current practice:

- Use of inadequately qualified practitioners for appraisal.
- Insufficient sampling in areas with variable sulphate concentrations.
- Reliance on inappropriate guidance for sulphate, sulphide, and swelling testing.
- Selection of unsuitable stabilisers when sulphate levels are high (e.g., GGBS may be more tolerant than lime or Portland cement).
- Use of swelling tolerance limits designed for roads, not buildings.

This situation echoes past under-specification of fills for building construction, which led to the development of model specifications for engineered fill. An authoritative guide for soil stabilisation in the built environment is needed. This paper, founded on BRE's experience, is a step towards new guidance, but further experience pooling and research, particularly on swelling tests, are necessary to underpin future recommendations.