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Hydraulically treated soils in residential construction

John Kennedy and Julie Bregulla



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John Kennedy (Consulting Engineer) and Julie Bregulla (BRE)

John Kennedy is a consulting engineer specialising in pavement engineering and soil treatment.
www.jkpavementconsulting.co.uk

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BRE publications are available from www.brebookshop.com
or
IHS BRE Press
The Capitol Building
Oldbury
Bracknell
Berkshire RG12 8FZ
Tel: +44 (0) 1344 328038
Fax: +44 (0) 1344 328005
Email: brepress@ihs.com

Printed using FSC or PEFC material from sustainable forests.

BR 513

First published 2017

ISBN 978-1-84806-464-5

Acknowledgements

The authors wish to to thank the NHBC Foundation for its contribution to the funding to complete this review. The NHBC Foundation was established in 2006. Its purpose is to deliver high-quality research and practical guidance to help the house-building industry address the considerable challenges of delivering twenty-first century new homes (www.nhbcfoundation.org). The authors would also like to thank the industry steering committee, including United Kingdom Quality Ash Association (UKQAA), Abbey Pynford, Dynamic Ground Solutions, Earth-Tech Solutions Ltd and Britpave (Soil Stabilisation Task Group), for its work.

The authors are also grateful to Earth-Tech Solutions Ltd and Beach Ground Engineering Ltd for providing photographs for use within the report.

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Glossary

CBR	California bearing ratio; ratio used to characterise the bearing capacity of a soil, material or mixture, determined immediately after compaction or after a period of curing. The ratio can be determined in situ or in the laboratory on compacted specimens.
Coal fly ash	Byproduct from the burning of coal in a power station.
Curing	With hydraulically treated soil, the period and conditions that are necessary to allow enhancement to take place (whether that be improvement or stabilisation).
Degree of pulverisation	A measure of the effectiveness of mixing and breakdown of cohesive material after mixing with lime or other treating agent.
Fill	Term used here to describe the use of untreated material or hydraulically treated soil under house foundations to either fill a depression or raise the house or housing above the natural level of the ground.
Ggbs	Ground granulated blastfurnace slag.
HRB	Hydraulic road binder; a factory-produced hydraulic binder, supplied ready for use, having properties specifically suitable for road and rail bases, sub-bases, capping layers, soil stabilisation and soil improvement.
Hydraulic binder	A material that sets and hardens in the presence of water, eg cement, ground granulated blastfurnace slag.
Hydraulic reaction	The chemical reaction, in the presence of water, of a hydraulic binder (eg cement) or hydraulic constituents (eg lime with clay, lime with coal fly ash) that effectively produces a hydraulic combination.
Hydraulically improved soil	A process that improves a soil, even temporarily, using a hydraulic treating agent or combination of treating agents.
Hydraulically stabilised soil	A process that significantly enhances a soil, rendering it permanently stable and durable to water and frost, using a hydraulic binder (eg cement) or combination of treating agents (eg lime with coal fly ash, lime with ground granulated blastfurnace slag).
Hydraulically treated soil	A process that changes a soil so that it can fulfil its intended purpose (whether that be improvement or stabilisation), using a hydraulic binder or combination of treating agents.
Immediate bearing index	The immediate California bearing ratio value without surcharge.
In situ method of production	The 'in-the-ground' mixing of treating agent (previously spread onto the surface of the soil) with the underlying soil, and water if necessary, into an intimate mixture of the two. This is also described as 'mix-in-place stabilisation'. The result is a mixture that is present in/on the ground. Usually this would then be compacted by rolling and left in situ as a finished product. However, the resulting mixture can be 'picked up' for use elsewhere.
Lime	Quick lime (CaO) or slaked lime ($Ca(OH)_2$) produced by burning calcium carbonate ($CaCO_3$) in a kiln.
MCV	Moisture condition value; the value describing the moisture state of a mixture relative to its compactibility.
Mellowing/maturing period	With clayey soils, the time period necessary for modification.

Modified Proctor density	Laboratory reference density determined from the dry density/water content relationship obtained by the modified Proctor compaction test with a specific energy of ~2.7 MJ/m^3.
Moisture content	The loss in weight, expressed as a percentage of the dry material, when that material is dried to constant weight at 105°C.
OMC	Optimum moisture content; the moisture content at which a specified amount of compaction will produce the maximum dry density. Also sometimes referred to as 'optimum water content'.
Pavement	The whole of the artificial construction made to support traffic above the subgrade.
Pavement base	That part of the pavement construction resting upon, and through which the traffic load is transmitted to, the pavement foundation, whether it be sub-base, subgrade or supporting soil.
Pavement sub-base	The construction layer between the pavement base and subgrade.
PI	Plasticity index; the numerical difference between the liquid limit and the plastic limit of a soil.
Podia	Term used here to describe fill constructed as a 'plateau or platform' under the housing foundations, either to raise the housing above existing ground level or located within the existing ground.
Pozzolan	A silico-aluminous material generally poor in bound or free calcium oxide (typically < 5% by mass) and which, when dissolved in an aqueous solution of calcium hydroxide, produces compounds with binding properties like a hydraulic binder, eg clay, coal fly ash.
Proctor compaction test	Laboratory-determined dry density/water content relationship obtained by the Proctor test with a specific energy of ~0.6 MJ/m^3.
SHW	*Specification for highway works.*
Soil modification	With clayey soils, the rapid cation exchange and flocculation-agglomeration effects when treated with lime in the presence of water.
Standard Proctor density	Laboratory reference density determined from the dry density/water content relationship obtained by the standard Proctor compaction test with a specific energy of ~0.6 MJ/m^3.
Stationary plant method of production	Process where the soil and relevant stabilisers are introduced via hoppers and silos to a mixing unit, usually a pug-mill trough mixer or rotating pan mixer, before discharge into a waiting lorry or truck for transport to the point of use. This is also referred to as the 'stationary plant method', 'central plant method' or 'ex situ method of production'.
TPS	Total potential sulfate; chemical test for geotechnical and civil engineering purposes determining the total sulfate that would become available if all the sulfide converted to sulfate.
Treating agent	Term used here to describe lime, cement, ground granulated blastfurnace slag or coal fly ash.
Workability period	Duration of time counted from the end of the mixing process, during which the setting of a treating agent remains nil or very low.

I INTRODUCTION

1 Overview

This publication focuses on soil treatment for residential construction using lime, cement, ground granulated blastfurnace slag (ggbs) and coal fly ash. Whilst the application of soil treatment has been common for road and airport construction since the 1970s in the UK, its use in residential application has been more limited. This guidance draws on available knowledge and provides information on the technical issues to be reviewed when considering its use.

This report is subdivided into four parts, followed by appendices:

- Part I: Introduction
- Part II : Principles of soil treatment
- Part III: Design
- Part IV: Realisation in the field
- Part V: Appendices.

The guidance is intended to inform developers, engineers and other building professionals considering the use of soil treatment and wanting to learn more about the subject and its application. It also suggests a regime of validation and testing to support the review of suitability and appropriateness of the technique.

In this guidance, 'treatment' refers to the process of using lime, cement, ggbs and coal fly ash to render mainly wet natural or reworked natural soils suitable for use as engineered fill. The treatment, which uses the ability of the treating agents to alter favourably the properties of the soil, usually by removing free or excess water from the soil, is then competent to support foundations, ground floors, services and infrastructures without excessive deformation.

The processes reviewed in this report use the traditional technique of in situ soil treatment to produce successive horizontal layers of treated soil. There are also techniques that use deep column mixing or injection techniques applied vertically. These are not covered.

Horizontal-layer soil treatment using lime and/or cement has a long history in the road and pavement sectors. It is also used for:

- improvement of trafficking on construction sites
- construction of car and lorry park pavements
- foundations for industrial floor slabs (mainly large commercial)
- pavements for airport runways, taxiways and aprons
- reclamation and remediation of contaminated land.

As a result of this diversification in use, there is a substantial body of work and information on the subject, the vast majority of which is concerned with pavement works and remediation. There is little, if any, current authoritative guidance specifically for housing development in the UK. The guidance here draws together learning and experience to provide recommendations for consideration of the technique for residential construction. The reader should ensure to refer to the latest version of all standards referred to in this report.

2 Background

Treatment of soils is based on the hydraulic reaction resulting from the addition of lime or cement and, more recently, ggbs and coal fly ash. It has been used in UK road and pavement construction for more than 50 years.

The application of such treating agents to improve unsuitable soils (eg soils of significant variability and soft wet ground characterised by low shear strength, high compressibility and low bearing capacity) has been successful in rendering previously unsuitable soils fit for use as sub-base materials below roads. The treatment has enabled the soils to be retained on site, reducing the need for what is often termed the 'dig-and-dump' practice.

In recent years, the practice of improving unsuitable soils to enable effective use on sites has been expanded into other construction sectors. The house-building industry, in particular, proposes the treatment of unsuitable soils for sites where the ground is historically considered to be too marginal for load-bearing purposes without substantial re-engineering of the ground or provision of deep foundation solutions. The prime objective of such treatment is to provide a development platform that gives adequate support to shallow house foundations, infrastructures and services, rather than transferring construction loads via deeper foundations to lower competent strata, or by importing and placing engineering fill.

The application of treated soil is relatively new to the house-building sector and understandable caution about the adoption of this technique is prudent, due to:

- the sensitivity to settlement movement
- the 60-year design life requirement for housing
- the more fragmented supervision and control of construction on residential development projects than would normally be the case on large road and airport construction projects.

Notwithstanding these concerns, economic and environmental considerations and thriving house-building conditions will look to techniques like soil treatment to provide more accessibility to and useability of previously unavailable sites. This advice is to review the principles and use of soil treatment for residential developments and aims to provide background to the interested user. The guidance reviews current knowledge and experience of use from other sectors*.

Figure 1: Construction of house footings in treated soil (Image courtesy of Beach Ground Engineering Ltd)

The guidance is restricted to:

- treatment of natural and reworked natural soils using cement, coal fly ash, ggbs and lime
- treatment using traditional in situ mixing methods based on purpose-made spreaders for discharging the treating agent on the ground and purpose-made rotovators for mixing the treating agent with the ground in horizontal layers
- treatment that enables placement and compaction by traditional methods
- treatment that realises a performance status equivalent to that expected of the same natural or reworked natural soil had it been suitable in the first place for use on housing developments without treatment.

The intention of this approach is that stakeholders, including specifiers, supervisors, builders, developers and treatment contractors, gain experience and confidence in the use and benefits of soil treatment within the housing sector and are alert to any inherent problems or issues where experience is still quite limited.

Further advice that includes other treatment techniques, non-natural materials and enhancement beyond that normally associated with untreated engineered fills may form the basis of future guidance in light of positive experience from the soil treatment techniques described in this report.

* The guidance covers the traditional road and pavement sectors as well as, where available, the housing sector.

3 Purpose and objectives

The purpose of this report is to give guidance and advice for on-site treatment of existing natural and reworked natural soils, using lime, cement, ggbs and coal fly ash as appropriate, for application on residential developments.

The objectives of treatment are:

- to enable the soil to be handled and placed such that maximum compaction with minimal air voids is achieved
- to achieve a volumetrically stable treated soil
- to realise a development that is free from detrimental settlement.

The technical suitability of hydraulically treated soils for domestic building applications is addressed in detail, with guidance on:

- construction
- the potential of the technology
- any limitations that should be considered in particular circumstances.

A review of the available treating agents, site investigation techniques specific to the technology and necessary soil chemical analysis appropriate to ground treatment is included, together with verification testing requirements, including, for example:

- laboratory evaluation tests
- corresponding site control tests during construction
- site performance tests after construction.

Verification testing is recommended to ensure that the treatment is competent, stable and durable for the design life of the development.

As with all construction techniques, the use of competent, experienced personnel who understand the processes and potential problems is essential to successful soil treatment. Every job is unique and needs to be assessed on its own merits. There is no blanket recipe to cover all situations.

For soil treatment under housing, it is important to note the following:

- It will form just part of the overall foundation to the development as it will have to perform in combination with the underlying/adjacent untreated ground and the overlying substructure for the development.
- It may also need to integrate with other ground engineering issues such as contamination, aquifers, water dispersal and/or attenuation.

For these reasons, it is recommended that a single, suitably qualified, adequately insured professional party be contracted to offer 'a duty of care' overview of the works. The appointed party should be capable of:

- specifying the correct site investigation at the outset to ensure that soil treatment is an appropriate solution
- designing and monitoring the soil treatment, taking account of the advice given in this report
- understanding and controlling the effectiveness of the completed engineered groundworks, including the treated soil and its integration with other ground engineering activities and issues on the site
- understanding the overall performance of the treatment and the underlying untreated soils.

Finally, it should be noted that the construction equipment used for soil treatment consists of many pieces of plant, each of quite significant size. Thus the recommendations that follow assume that the use of soil treatment will normally be limited to large housing developments where soil management can be carried out effectively and the construction equipment has the room to be used efficiently. Therefore, reference to 'plot' or 'footprint' in the following sections relates to the ground underneath a group of houses rather than an individual dwelling. It is difficult to make comment here on what constitutes a viable plot/footprint size as this will be site-specific. The best advice can only be determined following discussions between developer and contractor.

II PRINCIPLES OF SOIL TREATMENT

4 History

The treatment of soil using cement, lime, ggbs and coal fly ash is not new. The technique is first believed to have been used in ancient Egypt for mortars based on impure gypsum containing lime in the form of calcium carbonate. Progress is evident through the Graeco-Roman period. The discovery of materials possessing pozzolanic properties like volcanic ash, when used with lime, led to the manufacture of the first 'cements'. In the twentieth century, with the development of soil mechanics and laboratory testing, soil–cement and soil–lime mixtures were evaluated and further developed.

The engineered process of soil cement became established in the 1950s for sub-base work[1], followed by lime stabilisation in the 1960s[2]. Although a limited amount of site work was carried out in the UK in the 1950s and 1960s, lime stabilisation was not widely used in the UK until the 1970s. Use of these processes, particularly for road and airport construction, increased during the early 1980s, mainly in south-east England, and culminated in a method for lime and cement stabilisation of subgrades for capping purposes being incorporated into the Department for Transport's Specification for highway works (SHW) published in 1986[3]. This stabilisation of subgrades to produce a capping layer – in effect a lower sub-base layer between the subgrade and the normal sub-base, with requirements similar to that of sub-base – is widely used today (Figure 2).

At the same time, considerable work on site investigation and testing of soils to be stabilised was carried out by the Transport Research Laboratory on behalf of the Department for Transport[4, 5].

Since then, aided by technical reports and documents from cement industry bodies (the Cement and Concrete Association and British Cement Association) and the British Lime Association, stabilisation has been used extensively in the UK. Its use is predominantly for infrastructure construction. Several contractors specialise in soil stabilisation treatment. In the UK Britpave (www.britpave.org.uk), an organisation that represents such contractors and other soil treatment professionals, offers advice and provides a forum for discussion and further development of techniques.

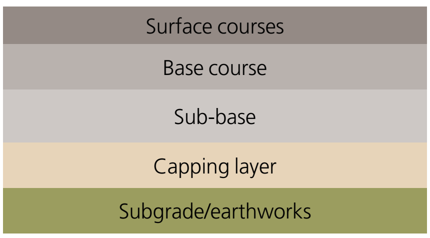


Figure 2: Road structure in common use in the UK

Soil stabilisation treatment has not been limited to the UK. In France, the technique was used successfully in its autoroute (motorway) building programme from the 1960s. France developed the technique for the treatment of unsuitable soils for earthworks use, not just for roads[6] but also for the TGV (high-speed rail) network[7]. Furthermore, from the 1980s the French developed special treating agents for road and rail earthworks and pavement use, first standardised as 'hydraulic road binders' (HRB) in BS EN 13282[8, 9, 10] (*Hydraulic road binders*). The technique has also been used in the US[11], other parts of Europe and elsewhere around the world.

Similar to the development and use of HRB in France, the Cementitious Slag Makers Association (CSMA) and the UK Quality Ash Association (UKQAA) have promoted in the UK the development of, respectively, ggbs and coal fly ash (also known as 'pulverised-fuel ash' or 'pfa'), for use with lime and cement in soil treatment, including:

- from the early 1990s, the use of lime and ggbs in combination for the treatment of granular soils
- from the late 1990s, the use of lime and ggbs in combination for the treatment of sulfate-bearing soils where lime alone or lime–cement combinations proved to have limitations[12].
- from the mid- to late-1990s, the use of lime and coal fly ash in combination for the treatment of granular material[13] and soil[14].

Parallel development has taken place with equipment and techniques, with a process that was first carried out using agricultural-type equipment (still used for some work today) evolving to a process based on purpose-made ploughs for earthworks use, and increasingly sophisticated rotovator-type mixing plant for pavement applications.

Such development does not mean that the technique of soil treatment has not been without setbacks. Problems have occurred in the past, primarily with sulfate-bearing clay soils, sometimes coupled with naturally expansive soils and/or poor construction practice such as working dry of optimum moisture content (OMC). However, these problems have been relatively few in number and have served to educate the industry and improve the technique. Examples are discussed in Appendix A.

5 The basis of soil treatment

5.1 Introduction

This section introduces the most common treating agents and their behaviour and, for completeness, includes a note on construction/mixing methods.

The understanding of the chemistry and mechanisms of soil treatment is firstly explained via the fundamental principles associated with the use of lime in clay soils before consideration of cement, or lime or cement with either ggbs or coal fly ash.

5.2 Lime

5.2.1 Lime chemistry

The lime referred to in this report is the product resulting from the burning of chalk or limestone ($CaCO_3$) at high temperature. Provided the temperature is high enough, the following chemical reaction takes place:

$$CaCO_3 \rightarrow CaO + CO_2\uparrow \quad \text{(Reaction 1)}$$

During the reaction, carbon dioxide (CO_2) is driven off leaving calcium oxide (CaO), also known as 'quick lime'. This is a granular product that can be ground to produce different 'fineness' grades depending on end use.

When quick lime is exposed to controlled amounts of water (H_2O), in what is effectively a hydration or slaking process, the following chemical reaction takes place, producing calcium hydroxide ($Ca(OH)_2$), also known as 'slaked' or 'hydrated lime'. This has the appearance of a fine powder:

$$CaO + H_2O \rightarrow Ca(OH)_2 \quad \text{(Reaction 2)}$$

Reaction 2 is a highly exothermic and highly alkaline reaction, both of which play an important role in the treatment of soil using lime. This is covered in greater detail later in this report.

Quick lime and slaked lime are the lime products used for soil treatment and are not to be confused with agricultural lime, which is simply ground calcium carbonate, ie ground chalk or limestone.

It should be noted that if quick or slaked lime is exposed directly to air for any significant period of time, it can, in combination with CO_2 from the air, revert to chalk or limestone ($CaCO_3$). Thus chemical reaction 1 is reversible. This reversion is known as 'carbonation'. The reversion effectively converts the lime from an 'active' state back to its original 'inert' state and thus prevents the possibility of any beneficial reaction with soil.

Carbonation is reported to be a problem in hotter climes, particularly layers left exposed to the elements and thus CO_2 from the air. It only applies to un-reacted lime rather than lime combined chemically with silicates and aluminates from the soil, which is an irreversible reaction. Even in hotter climes, this reversion would not occur with properly constructed and cured treatment. There is no record of such problems in the UK.

Because of the relatively wet climate in the UK, soil treatment using quick lime, rather than slaked lime, has become the norm and the process is described in more detail below.

5.2.2 Lime treatment: initial reactions

Detailed background and advice on lime treatment can be sourced from the British Lime Association (www.britishlime.org). The following text gives a summary of the generic information available in this field.

When quick lime is added to a wet soil, the soil rapidly becomes drier and slaked lime is produced (chemical reaction 2). This is a highly exothermic reaction, which, together with the chemical combining of water with quick lime, significantly reduces the moisture content of the soil. The reaction from quick lime to slaked lime also raises the alkalinity (pH) of the soil.

If the soil is clayey (cohesive) and sufficient quick lime has been added to raise the pH of the soil high enough (~12–13), a second change takes place. The clay minerals undergo a physical transformation of flocculation/agglomeration, known as 'cation exchange', whereby the soil becomes behaviourally and appearance-wise less clay-like and more friable or sand-like.

This change with cohesive or clayey soils is known as 'modification' and the time period over which it takes place, usually very rapid, is sometimes referred to as the 'mellowing period'. Thus with cohesive soils, the overall initial result of adding quick lime is drying and modification. Note that modification cannot occur with granular soils or soils that do not contain clay.

The modification of a clay soil changes its properties and characteristics, including:

- an increase in OMC, enabling full compaction at higher moisture content
- an increase in the plastic limit and as a consequence a marked fall in plasticity index (PI); in other words, a less clay-like appearance and behaviour, which results in enhanced handling characteristics
- an increased interparticle attraction leading to greater shear strength and improved bearing capacity
- a reduced susceptibility to shrinkage and swelling
- a lowering of the coefficient of compressibility and thus a material with lower settlement and heave characteristics.

This drying and modification occurs rapidly, usually within 24 hours, but sets in motion a further chemical reaction with clayey soils, which, with sufficient lime, continues in the long term and is permanent. This reaction is termed 'stabilisation'.

5.2.3 Lime treatment: pozzolanic reactions and stabilisation

Clays are complex compounds, but essentially consist of silica and alumina. Provided sufficient lime has been added to the soil to raise the pH to the required level, silica and alumina are dissolved from the clay and react with the lime to produce complex calcium silicates and aluminates that are, in effect, 'cement'. (Note that cement manufacture is effectively a combination of lime and clay. See Section 5.3.)

The result is a matrix in which the clayey soil plays its part hydraulically with the lime and, given the right environment of proper investigation, production and construction, leads to strength development and increasing resistance to outside influences such as water, frost and loading. This is what is meant and intended by stabilisation, which, with correct design and proper construction practice, is a permanent process.

The stabilisation reaction commences more or less at the same time as modification and immediately imparts a significant increase in strength, which can continue to develop over many years.

Because lime stabilisation results ultimately in a 'cemented' matrix of clayey soil and lime, the mixture needs to be 'cured' (ie prevented from drying by sealing the surface of the layer with bituminous emulsion) like concrete in order to prevent loss of moisture through drying. If not properly cured the full cementing potential will be compromised. Again, as with modification, it is impossible to stabilise granular soils using lime alone.

5.3 Cement

The following text describes the use of Portland cement (PC), designated CEM I – see BS EN 197-1:2011[15] (*Cement – Composition, specifications and conformity criteria for common cements*).

Compared with lime, which depends on other constituents (eg clay) for cementitious chemical reactions and thus strengthening to take place, cement treatment is more straightforward.

PC is manufactured by combining calcium carbonate and oxides of silica and alumina under high temperature. The former can be limestone or chalk and provides calcium hydroxide (lime) for the process; the latter, the relevant oxides, are present in clay. Note the chemical analogy with lime stabilisation described above.

Cement is an example of a hydraulic binder, ie a powder that hardens in the presence of water. It will thus bind into a cementitious matrix inert materials like sand and gravel without the addition of another material other than water. Cement is used primarily with granular soils and aggregates and the reaction is both very quick and permanent. Caution is advised with the use of PC, however, as the chemical reaction produced can be too quick for the overall time required for the treatment of soils, particularly those mixed at source for subsequent excavation and transportation to the point of use. This is discussed later.

For comparative purposes and illustrative of the difference between cement and lime, lime needs a source of reactive silica (as in clay) in order to produce the hydraulic reaction; cement does not. Note that pozzolans like volcanic ash or coal fly ashes also provide reactive silica for reaction with lime.

Although cement may be used with cohesive soils, it is not as effective as lime in breaking down the clay content and rendering it friable. It can be effective, however, with low-plasticity materials such as clayey sands and gravels, where there may be insufficient clay present for effective lime stabilisation. Cement may sometimes be used as a follow-up to initial lime treatment in such cases; lime firstly rendering the soil friable to enable cement to be intimately mixed with the modified clay to produce a more robust and stronger 'cementitious' matrix.

Cement used in this way provides additional benefits; lime is liberated during cement hydration and is then available for a secondary reaction with the silica dissolved from the modified clay. Unlike the initial quick reaction with water, this reaction can continue over many months, even years. It is, however, very much the secondary reaction compared with the initial cementing.

Cement is also available blended with other products (eg ggbs and coal fly ash). These are designated CEM II, III, IV and V – see BS EN 197-1. These various blended cements have different and usually more appropriate properties for soil treatment than CEM I. Because of this, they deserve closer scrutiny than normally given when determining the appropriate product to use for specific situations. This issue is covered in Section 5.6.

5.4 Ground granulated blastfurnace slag (ggbs)

As its name suggests, ggbs is produced by grinding granulated blastfurnace slag, a vitrified sandy material usually produced by the rapid water quenching of molten blastfurnace slag. Ggbs consists of oxides of calcium, silica, alumina and magnesium and is thus chemically similar to cement.

Like cement, therefore, ggbs is a hydraulic binder, but when used on its own the rate of reaction or cementing is very slow compared with that of cement. The reaction can be enhanced, however, by use with lime or a source of lime (from cement), which acts like a catalyst. It is also possible to enhance the reaction through sulfatic activation.

Ggbs was first used for soil treatment in the UK in the early 1990s when, under trial conditions and in combination with lime, it was used to treat granular soil. Cement was being used in the main works. Following laboratory comparison of strength, which indicated that the soils treated with lime–ggbs yielded similar strengths to that of the cement-alone treatment, the opportunity was taken to carry out a site trial using the lime–ggbs combination, which proved successful.

Towards the end of the 1990s, the lime–ggbs combination was used for the stabilisation of gypsum ($CaSO_4$) bearing London clay to produce sub-base for a major county road project. Laboratory testing results for the lime–ggbs combination gave greater strengths than the lime–cement combination and showed significantly greater resistance to sulfate attack than lime alone and the lime–cement combination, both of which expanded significantly during laboratory immersion testing. The successful performance of the lime–ggbs combination was attributed to the fact that the ggbs was able to combine favourably with the gypsum in the clay, giving rise to a sulfatic reaction that, rather than disrupting the mixture, contributed instead to strength gain and stability.

This benefit of the inclusion of ggbs in the lime treatment of sulfate-bearing soils was also confirmed by Higgins[12]. Higgins' paper reported that the addition of ggbs did not prevent the formation of ettringite† – the usual cause of swelling/expansion/disruption – but appeared to modify the ettringite morphology, resulting in a change to the composition of the ettringite; in particular reducing its calcium content and thus potential for water absorption and, in turn, swelling.

Since the work in the 1990s, the lime–ggbs combination has been used for sub-base treatment on schemes involving glacial till/boulder clay, including one with sulfate-bearing soils and the other with the potential for sulfate contamination. In both cases, preliminary laboratory testing indicated that both strength-wise and for the suppression of sulfate-based expansion, the lime–ggbs combination compared favourably with the lime–cement combination.

Also evident on these schemes was the increased 'working' time for the construction process using the lime–ggbs combination compared with the lime–cement combination. This is a significant benefit and is considered in more detail later.

The lime–ggbs combination has, more recently, been used in the treatment of chalk and Mercian mudstone. Neither of these projects involved sulfate-bearing ground, but the lime–ggbs combination was selected purely on the basis of the test results and the advantage of the increased working time for the construction process.

Ggbs is standardised in BS EN 15167-1:2006[18] (*Ground granulated blastfurnace slag for use in concrete, mortar and grout – Definitions, specifications and conformity criteria*). Further information on the chemistry and action of ggbs is described in greater detail in the aforementioned Higgins paper[12].

5.5 Coal fly ash

Coal fly ash is a relatively new addition to soil treatment in the UK, but of direct relevance here is that it has actually figured prominently in soil treatment on housing developments during the last 10 years (Appendix C).

The fly ash referred to here (coal fly ash) is a byproduct of the combustion of pulverised coal in energy-generating plants, which is captured by mechanical or electrostatic precipitators. It should not be confused with other ashes including furnace bottom ash (also obtained from coal-fired power stations) and incinerator bottom ash (the ashes from waste-incineration plants referred to as 'IBA'), neither of which possesses the significant pozzolanic properties that are a characteristic of coal fly ash.

Coal fly ash has three main elements – silicon, aluminium and iron – the oxides of which account for 75–85% of the material. Chemically it is thus similar to cement and ggbs, but with minimal amounts of calcium oxide. The latter means that it can be stored wet as well as dry, unlike the other treating agents described in this section.

Calcium oxide being largely absent, coal fly ash is therefore a pozzolan, being a product that, in combination with lime or a source of lime, hardens in the presence of water. It has been used with lime in soil treatment, particularly for soils where the clay content is low.

Like ggbs, coal fly ash is also a primary component of HRB produced in France, typically factory-produced blends such as ggbs–lime–gypsum and coal fly ash–lime–gypsum. The use of gypsum demonstrates that, correctly handled and formulated, sulfate need not be deleterious and is both an essential and contributory component of HRB with significant effect on strength. Coal fly ash, like ggbs, can help with treating sulfate-bearing soils[14] (see also www.ukqaa.org.uk).

Coal fly ash is available, wet or dry, as run-of-station (ROS) ash, or processed to reduce carbon content but available dry only. It should be noted, however, that high carbon content does not mean the ash is less reactive; it just means more carbon, ~10–15% rather than the more normal 7% or less with processed ash. ROS ash has proven to be just as effective with lime as 'carbon-reduced' ash.

Coal fly ash for hydraulically bound mixtures and soil treatment is standardised in BS EN 14227-4:2013[19] (*Hydraulically bound mixtures – Specifications – Fly ash for hydraulically bound mixtures*). Coal fly ash in compliance with this standard has a proven history of application in highway schemes and is permitted by Highways England‡ (HE) for use in pavement bases[20], the main structural layer of trunk roads and motorways.

Coal fly ash that complies with BS EN 450-1:2012[21] (*Fly ash for concrete – Definition, specifications and conformity criteria*), the standard for fly ash for concrete, can also be used for soil treatment. Fly ash to this standard has stricter requirements than BS EN 14227-4, however. There is no problem with its use for soil treatment work; it just adds unnecessary cost to treatment.

5.6 CEM II, III, IV and V cements

From Sections 5.4 and 5.5, there is a compelling argument that CEM II and particularly CEM III, IV and V category cements, thus those cements with ggbs and coal fly ash added at the cement production stage, are better suited to soil treatment as they give an increased factor of safety in cases where perhaps sulfates have been missed or underestimated at site investigation stage. These cement types also have a greater handling time before setting than CEM I, which will be advantageous during construction. CEM II in particular has been used for soil treatment for fill purposes under housing (Appendix C).

5.7 Hydraulic road binders (HRB)

As already described, these are factory-produced blends of two or more of the following: lime, cement, ggbs, coal fly ash and gypsum. They are specifically formulated for use in soil treatment and for the treatment of aggregates in road, airport and rail applications.

Use of HRB is widely prevalent in Western Europe, particularly in countries like France, Belgium and Germany, where their use surpasses that of cement for such works. There is little evidence of their use in the UK, primarily because they are not manufactured to any great degree in the UK. They are standardised in BS EN 13282.

† Ettringite is a hydrous calcium aluminosulfate mineral that precipitates in environments with high pH and sufficient sulfate concentrations[16]. It forms in the early stages of the hydration of calcium aluminate and has a large expansion potential, up to 250%[17]. At lower temperatures and a falling pH, the mineral thaumasite may be formed instead of ettringite; this is also expansive.

‡ Highways England was formerly known as the Highways Agency.

5.8 European Standards

Soil treatment using the treating agents described above is covered by European Standard BS EN 14227, which has been developed by CEN/TC 227, the technical committee responsible for materials for use in roads. The emphasis of BS EN 14227 is roads and in particular pavement layers and it is not therefore formulated primarily for earthworks either in roads or in housing developments. Nevertheless, this does not mean that it is inappropriate as it does provide useful pointers for fill application in housing. This is discussed later in Parts III and IV.

Also at the time of writing, another CEN committee, CEN/TC 396 (*Earthworks*), is preparing the European Standard for earthworks, which will include treated soils for earthworks. However, this document is primarily aimed at highways applications. Its use for housing, where settlement issues are more critical and sensitive, is likely to be limited.

5.9 Construction methods

Soil treatment using lime, cement, coal fly ash and ggbs is usually carried out using one of two basic methods of production/construction:

- Stationary plant method of production. Constituents are introduced via hoppers and silos to a mixing unit, usually a pug-mill trough mixer or rotating pan mixer. This is variously referred to as the 'stationary plant method', 'central plant method' or 'ex situ method of production'. The constituents, including water if necessary, are intimately mixed together (usually in a trough or pan) before being discharged into a vehicle for transport to the point of use.
- In situ method of production. One or more of lime, cement, coal fly ash and ggbs are spread via a purpose-made self-propelled mechanical spreader onto the surface of the soil. A mixer-rotovator, again usually purpose-made, is used to combine together the stabiliser and underlying soil into an intimate mixture of the two. Water can be added at the mixing stage, typically by spray bar mounted within the rotovator hood. This is described as 'in situ' or 'mix-in-place' treatment. The result is a mixture that is present in/on the ground. Usually this would then be compacted by rolling and left in situ/in place as a finished product to be a permanent layer of a pavement such as the capping, sub-base or base. However, the resulting mixture can be excavated for use elsewhere and thus this method can be subdivided into three submethods:
  - as described, with the mixture remaining where it was mixed
  - mixed at the source of the soil, and then excavated and hauled for either stockpiling or immediate placement at the point of use
  - mixed in a dedicated area where the soil to be treated is taken for processing. The resulting mixture is then excavated and hauled for either stockpiling or immediate placement at the point of use.

It is also possible to use a combination of the two basic methods using the in situ method for pre-treatment purposes and then the stationary plant method for the addition and mixing of a subsequent treating agent. Specific detail on construction methods is provided in Part IV.

6 Current guidance and specifications for soil treatment in highways

6.1 Introduction

Guidance and specification documentation for improvement and stabilisation relating to earthworks, capping layers and sub-bases of road and other pavements is available worldwide.

In the UK, the primary source of information is HE's standards and advice notes. These draw in part from the aforementioned BS EN 14227. Guidance is also available from the following organisations:

- Britpave (www.britpave.org.uk)
- British Lime Association (www.britishlime.org)
- Concrete Centre (www.concretecentre.com)
- Cementitious Slag Makers Association (www.ukcsma.co.uk)
- UK Quality Ash Association (www.ukqaa.org.uk).

A summary of HE's requirements for hydraulically treated capping, earthworks and sub-base is provided below, with more detail in Appendix B.

6.2 Highways England requirements and guidance for treated capping layers

Capping is the layer used between the subgrade and the pavement sub-base. HE's structural design for capping (thickness and surface stiffness) is included in IAN 73 (draft HD 25)[22]) and the specification for construction is included in SHW Series 600[23].

Adherence to the requirements of these documents is intended to produce a capping layer capable of maintaining the necessary strength and durability over the design life of the pavement – typically 40 years – and therefore by definition to produce a layer that is permanent and thus 'stabilised'.

HE verifies that 'stabilisation' is achieved in the field through the use of California bearing ratio (CBR) testing on laboratory specimens. These should achieve a soaked CBR value of not less than 15%. In addition, the specimens should not on average exhibit a swell greater than 5 mm nor greater than 10 mm on any individual specimen This equates to an overall average expansion of ~4% and an individual maximum expansion of ~8%, values deemed acceptable for highway road use.

HE guidance for stabilised capping to IAN 73 and SHW Series 600 is found in HA 74[24], which details the necessary steps – 'using an experienced engineering geologist or geotechnical engineer' – for successful application as follows:

- a desktop study/preliminary sources exercise to establish local geology
- an initial walkover to look for tell-tale signs of sulfates/sulfides in exposures
- a preliminary engineering assessment, including consideration of anticipated geology, presence of fill, ground profiling with respect to cut and fill and transitions between groundwater, and potential for contamination
- the establishment of a ground investigation strategy that takes account of the information derived from the foregoing phases in order to establish appropriate intrusive investigation techniques and sampling philosophy
- execution of the ground investigation, including soil sampling, groundwater monitoring and contamination testing
- execution of the required laboratory testing to characterise and classify the soils, including:
  - plasticity
  - grading
  - organic material content
  - sulfate and sulfide contents
  - moisture content
  - moisture condition value (MCV), used to ascertain the ability to handle and traffic the soil
- interpretation of the classification tests to aid the decision on whether to undertake laboratory performance testing. For example, soils with an organic content > 2% are excluded from treatment. However, no specific limits are specified for sulfur content
- execution of the required laboratory performance tests to ascertain stabiliser contents to meet the soaked CBR, swell and frost susceptibility requirements. The swell testing is used to determine whether sulfate, if present, can be accommodated
- laboratory compaction tests to determine the MCV/moisture content parameters to ensure that treatment is carried out not dry of OMC in order to achieve less than 5% air voids
- construction controls and testing.

To summarise IAN 73, SHW Series 600 and HA 74, successful stabilisation for capping purposes is determined and monitored by:

- detailed preliminary assessment and investigation
- the use of controls on the parent soil (including sulfates, sulfides and organics)
- soaked laboratory CBR tests on the mixture
- volumetric stability/swell testing
- MCV control during construction to ensure the mixture is not treated dry of OMC and has the appropriate moisture content for compaction to achieve not more than 5% air voids
- surface stiffness testing on the finished compacted layer.

For construction purposes, HE requirements for capping also stipulate the use of purpose-made stabilisation equipment including:

- mechanical spreaders for the stabiliser
- mixer-rotovators for the mixing
- water addition via spray bar mounted within the mixing chamber of the rotovator.

More detail on the HE classification system for stabilisation to produce capping is included in Appendix C.

6.3 Highways England requirements and guidance for treated earthworks

HE's design and guidance for earthworks (eg embankment fill) is also included in HA 74[24].

In this case, the treatment is termed 'improvement' with the main objective to render soils, typically those too wet to be handled, appropriate for proper placement and compaction as acceptable fill. The approach involves:

- treatment at the soil source
- excavation and transport to the point of use
- placement and compaction of the mixture carried out in layers to method specification
- acceptability determined solely on the achievement of the appropriate moisture content for full compaction using, in the case of treated clays for example, the MCV test.

Irrespective of sulfur type and content, the swell testing used for capping is considered unnecessary for general fill purposes unless it is likely to impinge on and affect the uppermost 2 m of fill.

HA 74 also sets no limits for the organic content of treated soils in earthworks. In addition, the requirements for construction are not as strict for soil improvement work as they are for stabilised capping, allowing, for example, the use of ploughs for mixing. More information is provided in Appendix C.

6.4 Highways England requirements for treated sub-base

Treated soils are also permitted for sub-base (ie the layer above the capping and below the road pavement base). The structural design for sub-base is covered by IAN 73 (draft HD 25) with specification covered in SHW Series 800[25]. Both documents refer to the hydraulically bound mixtures standardised in BS EN 14227.

Overall, the HE emphasis for treated soil for sub-base relies on controls on:

- the soil/aggregates, including testing for sulfates and sulfides with a maximum limit of 0.25% total potential sulfate (TPS), unless otherwise deemed suitable by the overseeing organisation
- strength after immersion in water testing to determine the long-term volumetric stability with a requirement category of 0.8 (ie the specimen strength after immersion in water should not be less than 80% of the non-immersed specimen strength)
- strength specimens on the resulting field mixture
- in situ density testing on the compacted layer
- surface stiffness testing on the finished layer.

As is to be expected, performance requirements for sub-base are more rigorous than for capping, which in turn are more rigorous than for required fill.

As previously indicated, literature and guidance to support the HE approach for earthworks, capping and sub-base is also provided by the industry bodies – Britpave, British Lime Association, Concrete Centre, Cementitious Slag Makers Association and UK Quality Ash Association.

6.5 BS EN 14227-15:2015

BS EN 14227-15:2015[26] (*Hydraulically bound mixtures – Specifications – Hydraulically stabilized soils*) subdivides the requirements for the treated soil mixture into three parts:

- requirements for the fresh mixture
- laboratory mechanical performance classification of the mature mixture
- resistance to water, direct construction trafficking and frost of the mature mixture.

As is the case/philosophy of European Standards, it should be noted that these requirements are laboratory requirements determined on the mixture and not on the layer. The specific details are as follows. It should be noted that they apply primarily to road pavement layers rather than road earthworks.

6.5.1 Requirements for the fresh mixture

As the heading suggests, this deals with the required characteristics of the mixture during construction. In particular:

- moisture content
- pulverisation (particle size) of the mixture after mixing
- immediate bearing index
- MCV
- workability period (the time available between mixing and final compaction).

Even though these are tests carried out on the mixture, the success or otherwise of the results of these tests is used to establish what is achieved in the field mixing-wise and compaction-wise. These in turn will determine the strength and durability of the constructed layer.

6.5.2 Laboratory mechanical performance classification of the mature mixture

The standard classifies performance in one of three permitted ways: CBR, compressive strength and the combination of tensile strength and elastic modulus. The choice is the designer's. Testing would normally be carried out after at least 28 days on the hardened mixture.

6.5.3 Resistance to water, direct construction trafficking and frost of the mature mixture

Resistance to water can be determined in one of three ways, again at the discretion of the designer/specifier as to what is considered appropriate:

- strength after immersion in water
- linear swelling after soaking in water
- volumetric swelling after immersion in water.

Trafficability is characterised by compressive strength. Resistance to frost is left open for determination in accordance with practice at the point of use.

6.5.4 Applicability of BS EN 14227-15 for soil treatment in housing developments

Irrespective of the amount of treating agent used, the key to the realisation in the field of satisfactory mechanical performance, site trafficability and durability to water and frost lies with the adequate achievement of the fresh mixture characteristics detailed in Section 6.5.1. As already mentioned, these requirements have been formulated for road pavement use. They are thus stricter than would normally be required for road earthworks application, but are considered here as entirely appropriate for the more sensitive earthworks needs of housing. This is discussed later in Part III.

7 Experience of hydraulically treated fill for housing

There is, relative to roads and pavements, less experience of hydraulically treated ground for fill purposes under house foundations and thus less evidence upon which to base robust design guidance recommendations. Construction experience is currently a little more than 10 years old and performance experience, although positive to date, falls short of the 60-year design life for housing. There is, however, considerable experience of untreated fill in the housing sector and defined parameters for successful performance. These will be of relevance also for hydraulically treated fill.

To complement Section 6, which described soil treatment for roads, this section describes the guidelines for untreated fill in housing and experience to date with hydraulically treated fill.

7.1 BRE good practice for untreated fill

BRE Digest 471[27] (*Low-rise building foundations on soft ground*) provides an authoritative source of general information concerning foundations for low-rise buildings on soft ground. Within DG 471, there is a section devoted to key planning and regulatory matters, which also provides a summary of what are accepted overall 'good practice' requirements for foundation fill for low-rise building, including:

- the need to research conditions of ground instability from features such as geological faults, landslides and disused mines
- adequate bearing capacity of the fill material to permit proper placement and compaction
- acceptable settlement in both the short and long term to limit to acceptable levels the settlement of foundations on ground that is variable in its compressibility, laterally and with depth, so as to ensure that ground movements do not impair the stability of the buildings
- during construction, stable excavations for foundations and for trenches to carry drainage and other services
- adequate drainage of the property and surrounding ground
- adequate provision to cater for any differential settlement between the building and drainage and services runs
- minimal risk of flooding
- protection of the local environment.

Although these fundamentals have been written in light of current good practice for untreated ground/fill, they are considered equally appropriate for treated ground/fill. BRE Trust Report FB 75[28] (*Building on fill*), which also relates to untreated ground/fill, is the latest advice from BRE on this subject. As above, it is illustrative of the principles that should apply to hydraulically treated ground. BRE also has advised on sulfates in soil treatment[29]. This is referred to in Parts III and IV of this publication.

7.2 Actual experience of the use of soil treatment in housing

Appendix C provides a summary of experience to date with hydraulically treated soils for fill on housing developments, describing how the works were carried out, what was achieved and what was measured.

The examples generally follow the HE requirements for earthworks fill described in Section 6; thus soil improvement with modest content (~2%) of treatment agents to enable soil handling, placement and achievement of the specified compaction. However, construction control and performance testing after construction, more akin to HE requirements for capping and sub-base, was employed, specifically shear strength testing with the hand-vane apparatus (generally not successful because the treatment usually exceeded the capacity of the hand-vane test), in situ plate loading tests and settlement monitoring over time. In effect, these performance tests replaced the standard bearing capacity test, ie laboratory-soaked CBR as specified by HE for treated capping and the compressive strength and surface stiffness tests specified for treated sub-base.

The main objective of the work described in the examples in Appendix C was to enable wet soil to be 'dried' for ready handling, placement and compaction. Given the low plasticity of the soils treated, and the fact that such soils do not require high stabiliser contents, it is possible that some degree of stabilisation could have been achieved as well.

In summary, whether it is improvement or stabilisation, the following types of soils are likely to be most suitable:

- glacial tills and sandy clays of low to medium plasticity or compressibility
- soils with low propensity for shrinkage and swelling and volume change
- soils that are relatively easy to process because of their low plasticity.

With regard to sulfur content, no limits are provided in the case studies, but research suggests that 'low sulfur' probably meant < 0.5% TPS. In addition, research suggests that the upper permissible limit for organic matter was set at 5%.

III DESIGN

8 Overview

The use of hydraulically treated ground for residential construction is not yet mainstream and experience is limited. As such, performance expectations are still negotiated and agreed on a project-by-project basis. As a minimum, when considering hydraulically treated soils for residential development sites, it is recommended that the designer should:

- develop a specification for an appropriate site investigation
- consider the presence of sulfate-bearing soils
- consider the compatibility of the soil and treating agents
- review the integrity of untreated ground under the treated soil
- consider, however unlikely, other forms of ground improvement used in conjunction with soil treatment, and the implications of this
- apply monitoring and testing procedures to verify the long-term performance of the full depth of treated and untreated soils that comprise the bearing strata beneath the development.

When carried out correctly, soil treatment using lime, cement, ggbs and coal fly ash has been shown to be able to produce stable and permanent ground conditions.

Breaks through the soil treatment are best avoided, as with any engineered ground. Some breaks are impossible to avoid, eg breaks for the installation of deep services. The designer should check that:

- the soil treatment has been correctly implemented
- the backfill material has been correctly specified to achieve a similar degree of impermeability as the treated soil
- the backfill operations to the breaks are carried out thoroughly.

Assuming the above is considered, appropriately controlled and implemented, there should be minimal adverse effect on the treated soil, backfill material and underlying strata.

As with all groundworks, long-term performance is a function of correct implementation of site investigation, laboratory testing, construction and on-site testing, both of the treatment works and other materials/activities that impinge thereon. These issues are discussed more fully with recommendations in Section 10.

9 Soils and treating agents: suitability and compatibility

9.1 Introduction

Such is the range of hydraulic treating agents now available that most soils, including many organic soils and soils containing sulfates and/or sulfides, are treatable unless the levels of the aforementioned are so high that they give rise to a deleterious chemical reaction, or the soil is so plastic that mixing is too difficult for the equipment employed.

In the context of this report, therefore, where volumetric stability with hydraulically treated soils is a prerequisite to minimising settlement, soil selection and choice of treating agent are equally critical. Soils prone to chemical expansion or shrinkage and swelling are not generally considered suitable for sensitive applications such as engineered fill under housing.

With regard to soil/treating agent compatibility, it is useful to note:

- Lime alone usually reacts with cohesive soils with PI ranging from 10% to 50% but, unless the soil is wet, lime serves no useful purpose in predominantly granular soils.
- Cohesive soils with PI < 10% often require the addition of a pozzolan for lime to be effective as a treatment. Coal fly ash is commonly used as a pozzalan and ggbs may also be effective for this purpose, as will be the addition of cement. Alternatively, cement may be used on its own.
- Other than for drying purposes, lime has little effect with organic soils. Compatibility would need to be assessed even with as little as 2% organics. Cement–ggbs combinations at the level of proportioning found in CEM III cement have been used to treat organic soils[30]. CEM IV and CEM V cements may also be appropriate in such cases.

9.2 Sulfate/sulfide issues

There have been problems in the past with the treatment of soils with high sulfate/sulfide levels. These problems are now better understood, and potential performance issues can be minimised by ensuring that the following steps are followed:

- proper and thorough desktop analysis to flag up the potential for sulfates/sulfides
- extensive site investigation to identify the occurrence and degree of sulfates/sulfides
- correctly formulated laboratory testing using the relevant treating agents.

In this regard, reference should be made to Longworth[29] and BP/51[17], both relating to soil treatment; the former focusing on buildings, the latter on roads. In all considered applications, performance over time needs to be evaluated.

Longworth contains a succinct and thorough section on 'site and material appraisal strategy', which gives recommendations on sampling frequency. It also warns that problems can occur with TPS levels as low as 0.2% and that, where higher sulfate levels exist, any appraisal should include laboratory swell testing.

BP/51 provides comprehensive advice for the treatment of sulfate-/sulfide-bearing soils and the potential benefits of using ggbs and coal fly ash to mitigate problems. It covers:

- site assessment
- testing for sulfate and sulfide in soils
- trigger levels for sulfate/sulfide based on TPS content. These levels are based on findings by Sherwood[31], who found that swelling/expansion issues can occur with total (acid-soluble) sulfate levels as little as 0.25% (thus similar to the Longworth recommendation of 0.2%)
- the choice of treating agent compatible with these trigger levels to minimise the risk of sulfate/sulfide disruption
- laboratory swell testing of stabilised mixtures
- possible beneficial construction approaches such as extended mellowing periods and, in the case of lime treatment, a second-stage lime addition following the extended mellowing period[32].

The guidance trigger levels for TPS and treating agent recommendations in BP/51 are as follows:

- TPS < 0.25%: minimal risk whatever the treating agent.
- 0.25% < TPS < 1%: possible risk of expansion with lime alone or cement (CEM I) alone and thus prudent to use slag or coal fly ash in combination with lime.
- TPS > 1%: extreme caution should be exercised and evaluation employing extensive laboratory testing using lime with ggbs or coal fly ash and perhaps modification of normal construction practices.

HA 74 provides similar information to BP/51, but does not include trigger levels, instead relying solely on laboratory testing on a job-specific basis. The HA 74 approach concentrates on the use of lime and cement and relies primarily on the use of laboratory CBR swelling tests to verify swelling performance characteristics. This may arguably be appropriate for roads where average volumetric swelling due to sulfates of up to 4% in CBR moulds is considered acceptable. However, such a degree of swelling is unlikely to guarantee trouble-free performance of soil treatment under housing.

The presence of sulfate-bearing strata in the UK is illustrated in HA 74 using a geographical map found in BRE Special Digest 1[33] (*Concrete in aggressive ground*) – see Figure 3 – highlighting particularly:

- Weald, London, Kimmeridge, Oxford and Lower Lias clays
- Mercia mudstone (Keuper marl)
- glacial deposits like boulder clay where they overlie the aforementioned clays, on the basis that they may have been derived from the lower materials.

Figure 3 illustrates that sulfates/sulfides are more likely to occur in the UK below a line from the Humber to the Bristol Channel. (Paradoxically, it is probable that this is also the area where most soil treatment has taken place.)

HA 74 Appendix B lists potential sulfate-/sulfide-bearing soils as:

- alluvium
- Bembridge, Sandgate, Woolwich and Reading beds
- Gault clay
- Blue and Middle Lias clays
- Upper Fuller's earth
- Erdington formation
- Portsmouth sand
- Sherwood sandstone
- Nursling sand.

HA 74 also identifies carboniferous shales, Stonesfield slate and peat as potential deposits for sulfates/sulfides. The list is therefore extensive and not just confined to soils in the south-east of England as Whitby mudstone and Cleveland ironstone also include sulfate-/sulfide-bearing soils.

HA 74 also lists the soils that have been successfully lime stabilised for capping on HE trunk roads and motorways, including:

- estuarine, alluvial, London, Lower Lias and boulder clays
- brick earth
- glacial till
- Mercia mudstone (Keuper marl).

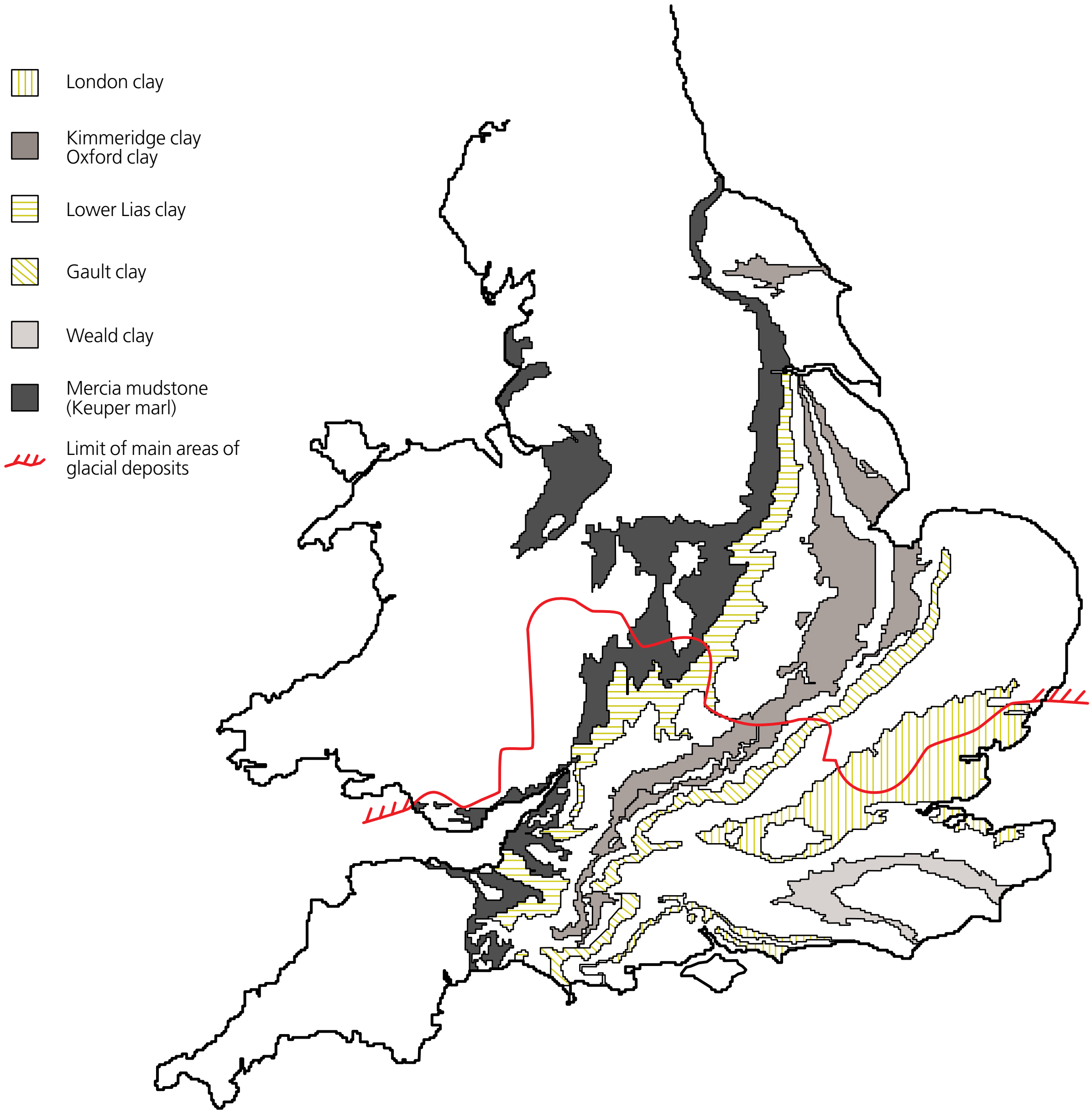


Figure 3: Principal sulfate- and sulfide-bearing strata in England and Wales[33]
(Note: North of the indicated line much of these strata are covered by glacial deposits, which, if partly derived from the indicated strata, may also contain sulfates and sulfides.)

HA 74 also says that other materials besides those listed have been successfully stabilised, but warns that problems have occurred with the lime stabilisation of Lower Lias, boulder and London clays. It adds, however, that the problems were investigated and satisfactorily addressed in the context of infrastructure construction.

Despite proven benefits with sulfate-bearing soil over the last 15–20 years, the current HA 74 document does not include specific guidance on the use of lime–ggbs and lime–coal fly ash combinations, except to say that the lime–ggbs combination is beneficial and the accepted option in this regard. How these combinations are best employed is left to the reader to investigate from other sources such as UKQAA and CSMA, as these will vary from case to case.

Other work[34] based on laboratory testing indicated that stabilisation of Weald, Gault, Oxford, Bedford and Kimmeridge clays could be possible, but it was crucial for the presence and levels of sulfates to be properly identified by laboratory testing.

Besides sulfates/sulfides, volume change can also occur with clays that are prone to shrinkage and swelling or with clays that, from a construction point of view, are difficult to mix homogeneously. In both cases, the defining parameter tends to be PI, and even if background and laboratory work shows treatment is possible, the mechanism of introducing stabilisers to very plastic clays may prove too demanding for the mixing plant available. These aspects are discussed in the following sections.

9.3 Shrinkage and swelling

Some clay soils undergo volume changes that occur independently of any applied loading as a result of variations in moisture content. This can cause shrinkage or swelling. These variations can be due to natural climatic or seasonal effects and/or the presence of trees or vegetation. Such volume changes vary depending on the composition of the clay and can give rise to substantive ground movements that may result in damage to buildings.

In the absence of suitably designed foundations, traditionally constructed low-rise buildings can be particularly vulnerable to such ground movements, as they generally do not have sufficient resistance to the forces arising from volume changes in the soils.

The principal cause of expansion is the presence of clay minerals such as montmorillonite, which can lead to swelling of up to 100% if the mineral is calcium montmorillonite, and up to 2000% if the mineral is sodium montmorillonite. Many soils in temperate regions such as Britain, especially in the south, south-east and south Midlands of England, possess the potential for significant volume change due to any change in moisture content.

The depth of the active zone in expansive clays, in which swelling and shrinkage occurs naturally during wet and dry seasons, varies. Historically in the UK, the maximum depth of the active zone in which seasonal swelling and/or shrinkage can occur naturally has been of the order of 1–1.5 m for clays with the highest volume change potential. However, the effects of trees and vegetation can significantly exacerbate the shrinkage of clay soils to much deeper depths due to the extraction of water by roots. Conversely, clays that may have become desiccated due to the effects of existing trees and/or vegetation may swell significantly if the trees are removed, resulting in significant heave of the ground.

Soils susceptible to volume change in the UK include:

- Mercia mudstone
- Lias, Blisworth, Kellaways, Oxford, Ampthill, Kimmeridge, Wadhurst, Weald, Atherfield, Gault, London and Barton clays
- Claygate beds
- clays of the Lambeth group
- Fuller's earth
- weathered shales
- some glacial tills derived from some of the above.

As with sulfates and sulfides, the list of susceptible soils is extensive. However, on a practical level shrinkage/swelling, and thus issues of compressibility and potential for volume change, can be linked to fines content and plasticity. This tends only to become an issue with clays with > 35% particles passing through the 63-micron sieve and natural PI > ~25, although some guidance very conservatively reduces the PI to as low as 10.

One of the purposes of treating clay soils is to modify the character of the material. Depending on the treatment, type and percentage of treating agent used, it will usually result in reduced plasticity and compressibility and thus reduced potential for shrinkage and swelling.

9.4 Constructibility

Where PI > ~25, the practicalities of soil mixing will need to consider the type and power of the mixing equipment. Although it is possible to treat such soils, it may require many mixing passes to achieve the necessary homogeneity, which will then have a bearing on economic viability.

A related issue, which is also discussed in more detail in Section 13, is the relationship between the time required for construction – namely the time from initial mixing of the soil with the treating agent to final compaction at the point of use – and the workability period appropriate for the treating agent concerned.

Of the four main treating agents previously discussed, treatment involving lime and coal fly ash presents little problem in this respect because speed of setting is protracted enough to allow adequate time (measured in days rather than hours) for the construction process.

On the contrary, cement (in particular CEM I) that has a setting and thus workability period close to two hours could present issues in those instances where mixing is carried out at soil source or at a dedicated mixing area remote from the point of use. However, cements incorporating coal fly ash or ggbs, such as CEM II but more particularly CEM III and CEM IV, are more suited for these scenarios, but even these will be unsuitable where stockpiling of treated material before use is anticipated or where compaction is delayed until the day after mixing.

Treatment based on the lime–ggbs combination falls between the two extremes described above, but it is recommended that compaction is completed the same day as mixing.

9.5 Low-plasticity clays, silty soils, clayey/silty sandy soils, collapsible soils like loess and brick earth

These soils are usually eminently suitable for treatment using cement, although the limited workability time periods for cement may restrict application in housing fill.

Sometimes it can be beneficial with such soils to employ a lime conditioning stage to render the soil sufficiently friable to enable proper mixing in of the cement. In such cases, consideration should then be given to a follow-up addition of either ggbs or coal fly ash in lieu of cement. The overall effect will be the same as cement, since the lime–ggbs or lime–coal fly ash combinations are, effectively, analogous to cement. However, their use has the advantage over cement that it will increase the working time window necessary for the construction process.

9.6 Organic/peaty soils

It is difficult to put an upper limit on organic content. Advice in this area is contradictory.

HE advice for capping layers prevents the use of material with > 2% organic matter, without defining what organic matter is. This is based on the premise that organic matter interferes, usually because of its acidity, with the hydration/cementing process. However, not all organic matter is deleterious in this way. If, for example, the organic matter exists as coal, this is known to be inert and, compared with other vegetative matter as present in, for example, peaty soils or as rootlets, also (relatively speaking) incompressible.

The HE requirement also ignores the fact that lime is more affected than other treating agents in this regard and particularly when compared with blended cements based on ggbs[30].

Such a blanket statement on organic content is therefore misleading. Certainly materials like peaty soils or soils where the organic content is patently recognisable as wood or vegetative matter that is compressible, degradable and susceptible to volume change are best avoided. But this still does not answer how much is acceptable. In this regard, BS EN 14227-15 states, in Note 2 to Section 5.6:

> *Laboratory mixture design work will determine whether soil containing organic matter can be accommodated. The amount of organic matter that can be accommodated depends on the type of organic matter.*

It is suggested here that the testing referred to should include laboratory strength and swelling testing[26]. It is possible that this sort of testing is adopted here but stakeholders should realise that this will involve strength and swelling testing that would normally be unnecessary for treated soil fill under housing.

Stakeholders may thus prefer the simple and safe, but perhaps unnecessarily restrictive, limit of 2% organic matter because it negates the need for strength and swelling testing. This route is recommended in Section 11 of this report, but in recognition of its restrictiveness suggestions are proposed for organic contents up to 5%.

10 Suggested design protocol for housing

Hydraulically treated ground for fill under house foundations:

- must have the characteristics necessary for optimum compaction with minimal air voids; this will realise satisfactory load-settlement performance and will also minimise the potential for collapse (inundation) settlement
- must be free from volume change that could affect settlement and/or stability in the long term (60-year design life).

This is in order not to compromise:

- the overall requirement of 'adequate, uniform and consistent support without undue movement' for a design life of 60 years
- for a situation where the purpose of treatment is to achieve parity with the same soil had it not required treatment in the first place.

Figure 4: Proof testing on surface of treated soil after compaction (Image courtesy of Beach Ground Engineering Ltd)

10.1 Optimum compaction with minimal air voids

The meeting of the first objective is straightforward since it can be achieved through tight controls on mixture consistency, moisture content and thus adequate compaction. The HE approach to soil treatment described earlier, whether it be for earthworks, capping or sub-base, has the same objective.

BS EN 14227-15, the European and British Standard for soil treatment, also recognises this, particularly in its section titled 'Requirements of the fresh mixture'. This section, as discussed in Section 6 of this report, focuses on the following fresh mixture properties during construction:

1. moisture content and/or MCV
2. immediate bearing index
3. pulverisation
4. workability time (the maximum permitted time between mixing and final compaction).

The first and second properties ensure that optimum compaction is achieved, whilst the latter two help to ensure consistency of performance is achieved by ensuring thorough mixing is undertaken within the correct time limits. It is proposed here that soil treatment for fill purposes under housing follows a similar approach.

10.2 Freedom from volume change

The meeting of the second objective will be met in part by following the BS EN 14227-15 approach, but equally importantly by being selective with regard to soils and only allowing the use of treatment for relatively inert soils known and proven to be volumetrically stable. Thus recommendations are limited to the soil types that are known to have been treated to support buildings over the past 10 years with no noticeable evidence of adverse effects to date.

Recommendations are therefore given here for soil treatment using the following soil types:

- low-sulfur, largely inorganic glacial tills and sandy clays
- soils of low to medium plasticity or compressibility, low organic content and low sulfates, hence with low propensity for volume change
- soils that are relatively easy to process because of their low plasticity.

As a final check to ensure satisfactory performance, proof testing is advised both during and after construction to verify the finished integrity of the treated soil. Overall, therefore, successful application for soil treatment will require robust analysis, appraisal and objectives as follows:

1. Thorough desktop review including site walkover.
2. Site investigation to identify the appropriate inert soils, including in situ testing and sampling for laboratory testing to check for homogeneity, presence of sulfur, organic content and highly plastic compressible soils.
3. Identification of a suitable, stable bearing strata and thus determination of the necessary depth of treatment.
4. Overall consideration of the treated soil's relationship with the surrounding ground and site conditions.
5. Selection of treating agents appropriate to the soil conditions and construction method.
6. Laboratory testing that focuses on the attainment in the field of full compaction with minimal air voids.
7. Good site practice involving excavation of firm untreated material with good bearing capacity (to be measured on site) and then properly managed site mixing using purpose-made plant to ensure mixture homogeneity (pulverisation), placement and compaction of the hydraulically treated soil to achieve high density and minimal air voids, all carried out within proper time limits.
8. Immediate evaluation of integrity using plate testing.
9. Medium-term evaluation using proof 'settlement' testing carried out during the development phase of construction.
10. All overseen by and with certification from qualified personnel.

This approach for soil treatment is consistent with BRE recommendations for untreated fill. There are also further parallels with untreated fill.

Construction of hydraulically treated fill is carried out in layers. Therefore, from a compaction point of view it is little different to construction using untreated material of the right nature, consistency and moisture content. The overall depth of treated soil used should thus be no more of an issue than the use of untreated material. Furthermore, because structurally nothing more is expected of the treated soil than that from suitable untreated material, normal house foundation design solutions may be applied.

In theory, also, since the treated soil is considered the same structurally as untreated material, it should be possible to 'mix' zones of treated soil with untreated zones, as would be the case where treated soil were used in 'podia' under a group of houses with untreated material used in between the 'podia'. This has largely been the case to date, but it is paramount that the same attention to design and construction detail is applied to all fill types, whether treated or not, to avoid differential performance problems related to compaction, settlement and drainage.

The relationship between the overall housing footprint and the extent and shape of the treated soil podia must also be given due consideration. Rather than terminate treatment abruptly at the perimeter of the intended footprint, the podia should be extended beyond the footprint. It is best to imagine the podia as a truncated pyramid in the ground and extend the top truncated surface some 2–3 m beyond the housing perimeter. It is also recommended that the side slopes of the pyramid should incline at ~45° so that the compaction of each superimposed layer of treated soil is properly supported and compacted at its edge. Overall, therefore, the loaded footprint will then be adequately supported with minimal risk of settlement issues (Figure 5).

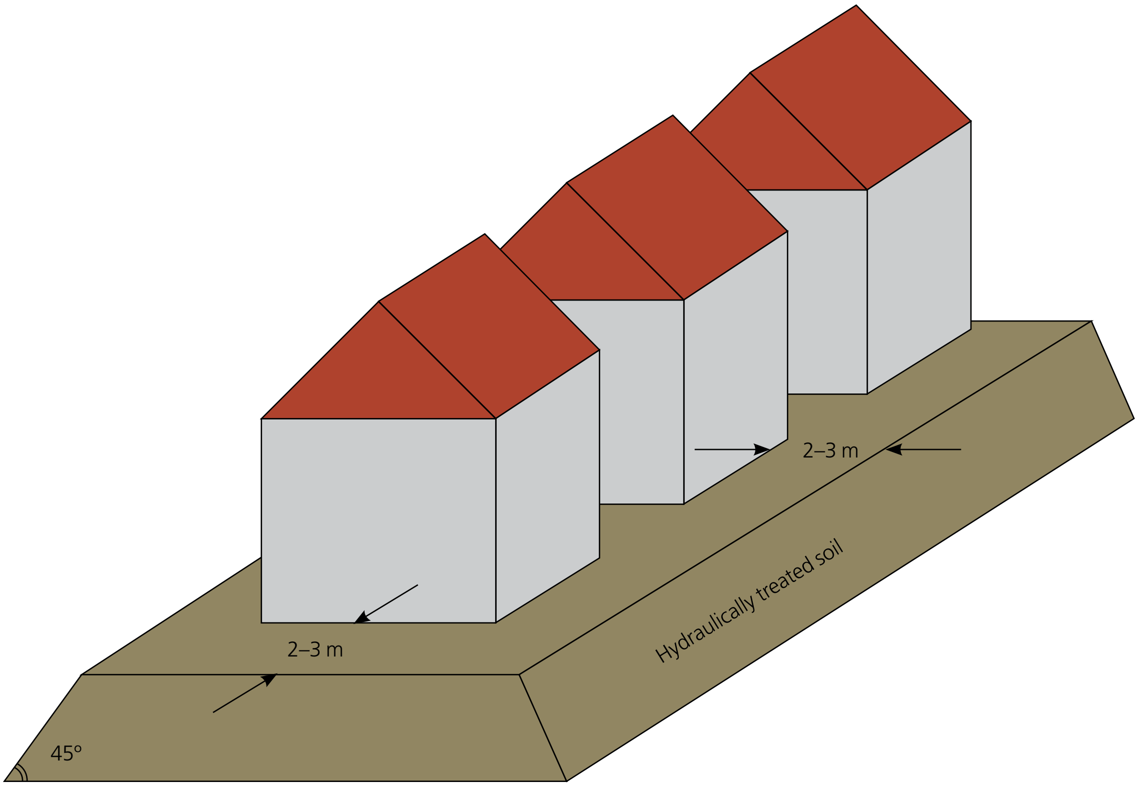


Figure 5: Hydraulically treated soil podia

11 Suggested laboratory design process for housing

11.1 Introduction

From the discussions in Sections 6–10, advice is limited to natural and reworked natural soils with:

- PI < 25
- organic content < 2%
- TPS < 0.25%.

These are essentially inert soils both chemically and physically and include, but not exclusively:

- silts
- collapsible soils like loess and brick earths
- chalk
- low-plasticity clays and glacial tills
- silty, clayey granular materials.

Despite their perceived inertness, the laboratory evaluation for such soils needs to be thorough. It is straightforward, however, being based on standard well-known laboratory testing that determines the appropriate moisture content and pulverisation (ie the breakdown of cohesive soils) to enable homogeneous mixing, handling, placement and optimum compaction.

Moisture content of the mixture needs to be at or close to the modified Proctor OMC, noting that the standard Proctor OMC may be more appropriate for some soils such as silts and silty clays with low sand and stone content. In addition, at or close to OMC here means ideally 'from OMC to a moisture content a little wet of OMC'. This ensures that there is enough moisture to adequately hydrate/activate the lime or other treating agents as well as minimising air voids in the compacted treated soil.

With the majority of the soils described above, this can be achieved and controlled in the field using the MCV test with a target range of typically 8–12 for the mixture where 12 corresponds to OMC and 8 wet of OMC, but not too wet to make handling difficult or to prevent adequate compaction. For some soils, the range could be 9–13. Laboratory testing will determine and confirm this, but it is recommended that, whatever the results, MCV 9–13 should be the maximum range considered for use here.

To summarise, therefore, the primary laboratory testing involves establishing the laboratory compaction curve for the mixture and from this the maximum laboratory density, the OMC and the maximum moisture content wet of OMC that achieves 95% maximum density. These limits then determine the MCV limits – the upper limit being the MCV value corresponding to OMC and the lower limit being the value corresponding to the maximum moisture content that permits the achievement of 95% relative compaction. Providing that these limits are observed, the treated material should facilitate adequate mixing, handling and proper compaction in the field. The lower MCV will normally be no more than four points lower than the upper limit (in line with the standard recommendation). More advice on this and the MCV test can be found in HA 74. The MCV test method is standardised in BS EN 13286-46:2003[35] (*Unbound and hydraulically bound mixtures – Test method for the determination of the moisture condition value*). For soil mixtures where MCV testing proves inappropriate, the corresponding moisture content limits should be used.

Adherence to the recommendations above, and where properly engineered and constructed as described, means that the resulting treated fill, whether cohesive or otherwise, should be compatible with the proposed cautious approach to soil treatment outlined in the introduction to this report.

The recommendations described are not the only way to guarantee successful application of treated soil used as fill under housing. In all potential approaches, however, the same overall principles and objectives should be followed.

11.2 Soils with PI < 25, organic content < 2%, TPS < 0.25%

Proposals are given in Table 1. It is important to note that these are suggestions. Other routes may be equally valid and every site should be considered as unique and on a case-by-case basis.

It can be seen that there are no restrictions on the type of treating agent other than caution regarding the use of CEM I cement on the grounds of its speed of setting, which severely restricts handling times. Note also that all the treating agents mentioned in Table 1 are standardised products and should be specified as such:

- BS EN 197: Common cements[15, 36]
- BS EN 459: Building lime[37]
- BS EN 15167-1: Ground granulated blastfurnace slag[18]
- BS EN 14227-4: Fly ash for hydraulically bound mixtures[19].

Laboratory testing guidance for the mixture objectives stated in Table 1 is described in Section 14, which includes, for example, specific advice on the required site compaction.

11.3 Soils with higher organic and TPS contents than allowed by Table 1

Where the organic or TPS contents (or both) are higher than those detailed in Table 1 but not greater than 5% and 0.5%, respectively, successful treatment is possible and thus the treatment of such soils should not be dismissed.

Specific suggestions are not given here, however, since such sites/soils require an individual and cautious approach and thus consideration on their own merit. Proposals should be presented that include, for example:

Table 1: Proposals for soil with PI < 25, organic content < 2%, TPS < 0.25%

Suggested soil groups	Treatment guidance* (options in no particular order)	Suggested mixture objectives
Silts, collapsible soils like loess and brick earth, chalk	1. Cement[†] alone	Determination of the treating agent addition to achieve: 1. MCV 8–12 or equivalent moisture content range 2. 60% pulverisation where appropriate 3. 95% relative compaction in the field
	2. Coal fly ash or ggbs followed by cement[†]	
	3. Lime alone	
	4. Lime with coal fly ash or ggbs (order of addition optional)	
Silty, clayey granular material, glacial tills with PI < 25, other clays with PI < 25	1. Lime alone	
	2. Lime followed by cement[†], coal fly ash or ggbs	
	3. Dry coal fly ash (as a drying agent) followed by lime or cement[†]	

* Subject to a minimum spread rate in the field of ~4 kg/m^2 unless a lower spread rate can be demonstrated to be practical and achievable.
† Blended cements containing ggbs and/or coal fly ash are preferred to CEM I for extended handling time.

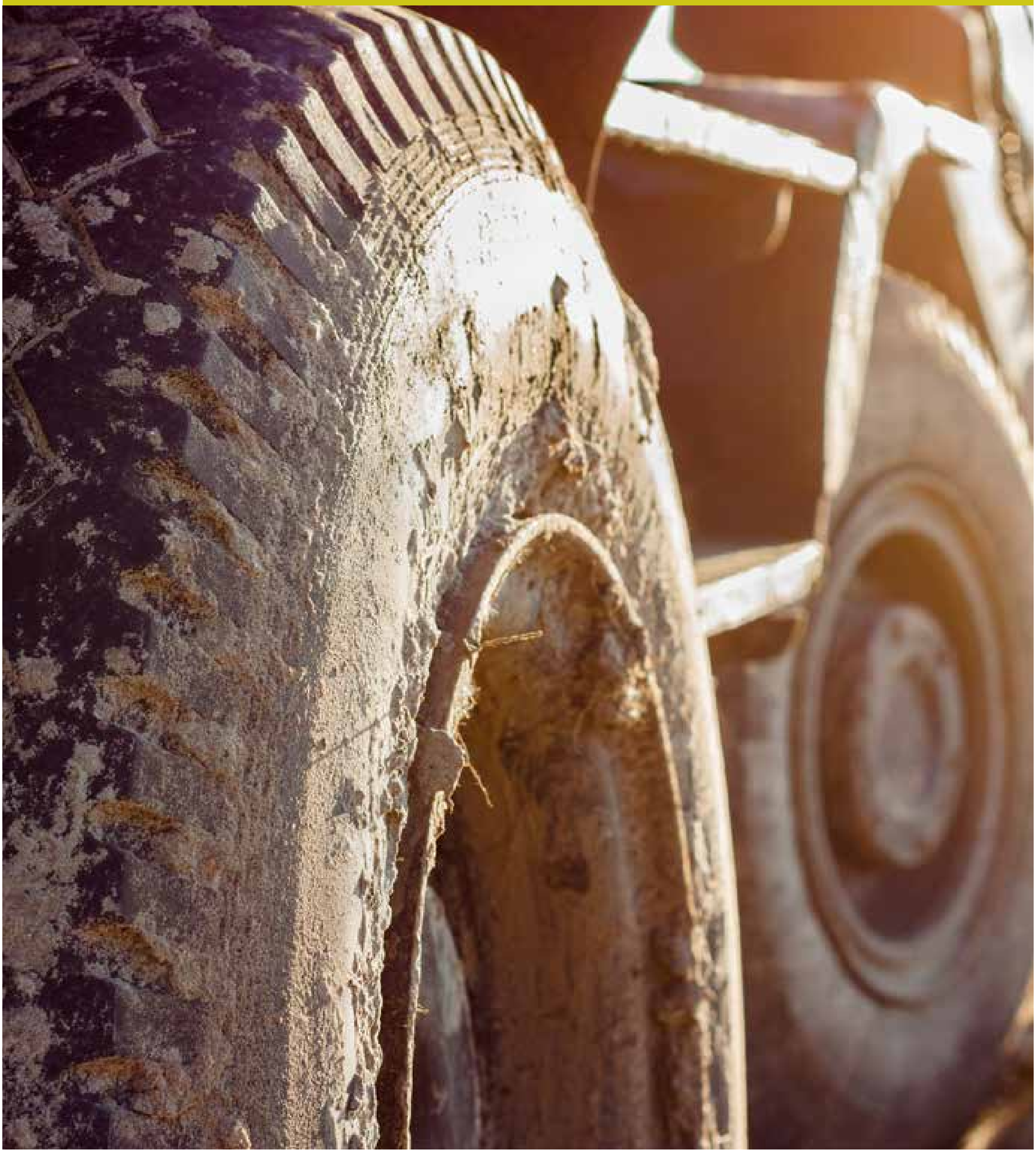
- detailed consideration of the type of treating agent to be used. For example, from discussions above, it may be prudent to:
  - exclude soil treatment using lime alone
  - exclude soil treatment using CEM I or CEM II cements alone
  - consider solely the use of factory or site blends of:
    - lime with ggbs or coal fly ash
    - cement (preferably CEM II) with ggbs or coal fly ash
    - CEM III, IV or V.
- laboratory evaluation testing to check and ensure the elimination of volumetric stability issues. This is discussed in more detail in Section 14.

11.4 Soils with PI > 25

As with the soils discussed in Section 11.3, treatment is possible but requires an individual and cautious approach. Factors that need consideration include, but not exclusively:

- Such soils being more plastic will require more mixing than those covered by Section 11.1 and this will impinge on the time window between addition of the treating agent and final compaction at the place of use. The allowable workability period of the treating agents will therefore need consideration before selection. In this regard, the use of CEM I and II is best avoided.
- Such soils may also, because of their nature, be more susceptible to shrinkage and swelling. As discussed in Section 11.3, volumetric stability after treatment will need checking.

IV REALISATION IN THE FIELD



12 Site investigation to establish soil characteristics and suitability

12.1 Introduction and desktop evaluation

It is important to note that a full site evaluation, comprising site investigation and sampling, laboratory classification and mixture design testing, is a prerequisite for soil treatment works. This requires a minimum of 6–8 weeks. Only then can soil treatment commence reliably and with confidence on site.

An integral part of the site evaluation is a desktop review and site walkover; the latter supplements, with little extra cost, the former. A thorough site walkover is particularly useful where soil exposures are present as it is possible to discern sulfides, sulfates (refer to Appendix A of HA 74) and organic matter.

The importance of this stage, which reviews existing geotechnical information for the site prior to commencement of the more costly intrusive sampling and laboratory testing, cannot be overemphasised. It is known as a 'preliminary sources study' and will give early warning of potential contamination issues and soils susceptible to shrinkage and swelling, for example.

The site investigation, sampling and testing strategy that follows should be based on:

- the quality of information gathered from the preliminary sources study
- any risks identified from the preliminary sources study.

The study should be used to identify and target specific areas for sampling and testing. For example:

- geological strata with the potential for sulfates and/or sulfides
- particularly weathered zones within soil layers, as these may be locations of high sulfate/sulfide concentrations
- in this regard it is not unusual to find, because of leaching, sulfates/sulfides absent from surface deposits to a depth of 1.5–2 m, but then evident at depths of 2–5 m, tailing off again below that depth.

The site investigation, sampling and testing frequency needs to make due allowance for these factors.

12.2 Site investigation, sampling and testing

It is important that tests are conducted on samples taken from the full depth of soil considered for treatment. In addition, the soil below the proposed treatment needs to be sampled and investigated to ensure that the full extent of the load-bearing strata are adequately characterised.

The location of mixing must be considered. Soil that will be mixed at source rather than at point of use, or soil that will be moved to a mixing area before final transport to the point of use, will undergo a degree of mixing during excavation, increasing the homogeneity of the soil. This homogenisation may have the advantage of diluting sulfate/sulfide 'hotspots'. Further testing of the soil may be required to demonstrate the dilution of sulfates/sulfides in the soil prior to treatment and placement.

Trial pitting provides a cost-effective means to both visually assess the ground conditions and gather good-quality samples for subsequent testing. Where sampling from levels too deep for trial holes, boreholes must be used.

Suggested frequency of sampling and testing should be formalised, using a 3D grid pattern that covers both horizontal and vertical extent. Ideally, more samples should be taken than may be tested initially. This entails relatively little extra cost other than storage, but allows further testing to be undertaken should extreme variability and/or organic or sulfate/sulfide hotspots be identified.

The horizontal grid spacing will be dictated by the plot layout and size and the anticipated variability of the soils as advised by the desktop review. It is suggested that the initial horizontal grid for samples should be ~25 m with vertical sampling at 0.25 m increments throughout the depth of soil to be treated. The strata below the proposed treatment depths should be investigated in 0.5 m increments. The samples collected in this procedure will form the starting point for laboratory testing, outlined in the following sections.

12.3 Material classification and consistency

The testing of material consistency and classification, often termed 'characterisation testing', is vital and requires sufficient number and size of samples. Best practice guidance for soil testing should be followed and the homogeneity or heterogeneity of the soils on the basis of the following must be determined:

- moisture content
- MCV of cohesive soils
- plasticity testing of cohesive soils
- grading including silt and clay contents
- pH
- organics
- sulfates/sulfides.

In relation to the sampling recommendations in Section 12.2, but also depending on the size of the development, the initial laboratory testing for basic classification, including moisture content, MCV, plasticity, grading and pH, should be carried out on the samples taken at 50 m horizontal grid locations and 1 m vertically as a minimum. Testing for organics and sulfates/sulfides should be the same horizontally but 0.5 m vertically. Possible sulfate/sulfide and organic hotspots can be identified and investigated further laterally and with depth using the remaining samples.

In general, the frequency of testing should be commensurate with the size of the site and soil stratification determined from the preliminary sources study. Testing for organics and sulfates/sulfides should be carried out on the same basis.

It is possible that the classification testing will reveal strata/deposits with varying or completely different characteristics. Where variation is significant, it may prove difficult to define one sole treatment strategy. Where differing deposits exist but can be easily defined, these should be investigated separately and may result in differing treatment strategies.

12.4 Testing for sulfates and sulfides

This section repeats the advice from *Guidelines for stabilisation of sulfate-bearing soils*[17].

There are a large number of test methods for the determination of sulfates/sulfides in soils. TRL Report TRL447[38] (*Sulfate specification for structural backfills*) reviewed these and recommended test methods that take advantage of advances in instrumentation and are quicker and less expensive than the historical 'wet-chemistry' methods. The test methods were introduced into HE specifications in November 2003 (note TRL447 was revised in 2005) and they are recommended here as the preferred methods.

To assess a soil for its potential for sulfate-induced expansion, it is necessary to establish:

- the acid-soluble sulfate content, which is a measure of the immediately available sulfate (use TRL447 Test No.2)
- the TPS content, which is the total sulfate that would become available if all the sulfide converted to sulfate (use TRL447 Test No.4). Note that TPS in % SO_4 is calculated by multiplying the total sulfur value in % S by 3.

TPS represents total potential sulfate and includes sulfur in organic and other matter. It should always be greater than acid-soluble sulfate; if not, the testing process and results should be reviewed. The difference provides a measure of the presence of materials that contain sulfur, but in a form other than sulfate. If the sulfur is present as sulfide (eg pyrite) then it can readily convert to sulfate and contribute to heave. On the other hand, sulfur in organic or other matter that is unlikely to convert naturally to sulfate is not considered a risk factor with respect to heave. Whilst it is possible to analyse further to distinguish between these forms of sulfur, the necessary tests are complex and expensive. Measuring TPS is therefore a conservative approach that may significantly overestimate the potential for sulfates and thus heave. Where there is a large difference between TPS and acid-soluble sulfate, it would normally be beneficial to understand the reason. This may require geological expertise or further testing.

One acceptable and relatively inexpensive method to measure total sulfur is to use an instrumental method based on high-temperature combustion in an oxygen environment. Sulfate appraisal is an essential part of the site assessment due to the potential damage that can be caused by heave if sulfates are missed or underestimated. More information is found in Longworth[29] and Bowley[39]. It should be noted that Longworth recommends that sulfur testing be carried out on a 10 m horizontal grid and every 0.2 m vertically.

Consideration should also be given to the potential for groundwater to bring in sulfates from the area beyond the stabilised ground. Testing groundwater (if present) is recommended as an additional indicator of the overall ground conditions, but should not be used as a substitute for soil sulfur testing. A concentration in the groundwater in excess of 0.4g/l of SO_4, the upper limit of Design Sulfate Class 1 for groundwater in BRE Special Digest 1, would be indicative of the presence of significant sulfate, but a lower concentration would not necessarily guarantee the absence of sufficient sulfate to cause a problem.

12.5 Testing for organics

This is determined in accordance with BS 1924-1:1990[40] (*Stabilized materials for civil engineering purposes – General requirements, sampling, sample preparation and tests on materials before stabilization*). In Part III, the recommended upper limit of organic matter for suitability without further testing is 2%. However, soils with organic contents greater than this (but it is suggested not exceeding 5%, and where the organic matter is not evident as obvious rootlets) should not be dismissed for successful soil treatment. Further advice on this is given in Section 11.

13 Construction

13.1 Introduction

The next stage after classification testing is laboratory design testing. However, it is recommended to always consider beforehand the construction process, since the laboratory testing should mirror as closely as possible construction intentions in the field.

Considering soil treatment construction in the manner most appropriate for the use of treated soil for fill or podia underneath and in the vicinity of building footprints, the stationary or mix-in-plant method of construction (thus where soil is introduced to a fixed mixing unit via a hopper) is usually not appropriate. This is apparent when the logistics and quantities are considered as follows.

Compared with the in situ method of construction, equipment in the UK for the stationary plant method of construction is in the main limited to machinery that can only produce up to ~250 m^3 of treated material per hour. In addition, there will be difficulties with the introduction of wet cohesive soils into the mixing chamber via hoppers usually suited to free-flowing aggregate.

This section therefore focuses on the in situ method of construction, as this method is likely to be the norm, and considers how the method could be applied to treatment of soil for use as fill under housing. Initially the focus is on lime treatment of cohesive soils, before consideration of the use of cement, coal fly ash and ggbs.

13.2 Construction recommendations

Prior to application in the housing environment, lime and cement treatment, and more latterly treatment involving ggbs and coal fly ash, had been used in the UK for over 30 years to produce stabilised capping layer for highways using the in situ method of construction at the place of final use.

The construction process is described fully in HA 74 and in the case of lime involves what is known as 'two-stage mixing' where an initial mixing of the lime with the soil is carried out followed by a maturing period of at least 24 hours but up to 72 hours and then a second stage of mixing. The necessity, however, for two-stage mixing, based on the capabilities of modern mixing equipment and possible detrimental effect on the resulting properties from treatment, is now being questioned and challenged for highway capping use following recent research[41].

Lime treatment to improve soils, generally cohesive soils, for use in earthworks fill for highways is a more recent development in the UK and is also catered for in HA 74. It is described as 'lime improvement'. Lime improvement is essentially a drying process to change unsuitable material (wet clayey, granular or chalky soils) into acceptable soils for optimum compaction. This is enabled, controlled and managed by adding sufficient quantities of quick lime to soil located in a cut or a dedicated mixing area in order to:

- raise the MCV of the soil from what might typically be less than 8 (ie very wet) and thus considerably much wetter than optimum (MCV 12–13) to within the MCV range (8–12 or 9–13)
- produce a soil drier and more suitable for excavation, transportation and placement at the point of use
- enable appropriate compaction using a method specification in order to achieve a fill with good density and minimal air voids.

The process of lime improvement as required in HA 74 for highway application is a one-stage mixing process. This type of process, whatever the treating agent or combination, is considered appropriate for housing fill and thus is reproduced and described here in full:

1. Preparation. Obviously this will depend on whether treatment is at source, at a dedicated mixing area or at the point of use. In all cases, the potential density of the soil after treatment and compaction will need to be established in order to determine the necessary spread rate of lime and treatment depth.
2. Quick lime spreading. This usually requires the use of towed spreaders fitted with flotation tyres for efficient traversing of wet and thus low-bearing capacity soil.
3. Mixing and pulverisation (with clays and chalks) to intimately introduce the lime to the soil and reduce the lump size. This will optimise drying and may involve at least two mixing passes of purpose-made rotovators. On soft ground, use of rotovators may be precluded because of their weight and it may be more effective to use ploughs or disc harrows fitted behind tractors or tracked dozers. Because mixing by plough or harrow is less efficient than by rotovator, the use of such equipment may require multiple passes, but has the advantage that mixing passes are faster than with pulveriser/rotovators and can be multidirectional to aid mixing. For housing fill purposes, however, final mixing should always employ purpose-made rotovators.
4. Excavation and transport to the point of use. Historically, excavation and transport was carried out by scraper, but recently is more usually undertaken by dozing the treated material to one end of the treatment area where it is loaded into trucks/dumpers for transport to the point of use.
5. Ensuring a grade profile to a slight fall to assist surface water run-off, placement of the treated soil in the fill in layers via the scraper or dozer. It should be noted that this operation, in combination with the excavation and transport, provides additional mixing.
6. Compaction of the improved soil.
7. Finishing of the final layer to produce a sealed and 'tight' well-closed surface.

As described above and where the site layout and soil management allows, this procedure is recommended for fill/podia-type construction for residential developments. Because of the housing end use, as opposed to highway embankment use, which is more sensitive from a settlement point of view,

Figure 6: Soil treatment under construction – spreading of treating agent prior to rotovator mixing
(Image courtesy of Beach Ground Engineering Ltd)

it is recommended that mixing should not rely solely on the use of ploughs or disc harrows, however much specialised for improvement application. They can of course be used in advance of purpose-made rotovators where, because of weight, the latter may initially have trafficking problems, but rotovators are recommended for the main mixing operation.

In addition, and in order to produce homogeneity without the inclusion of untreated soil through the full depth of the final construction, it is paramount to ensure that during the excavation process untreated soil is not excavated with treated soil and transported to the point of use.

Other construction procedures for consideration may include:

- ploughs and disc harrows for initial treatment at the source or at the dedicated mixing area followed by rotovator mixing at the point of use
- the technique known as 'stockpile and recover', which has proved effective as a mixing technique for road fill areas[6], although, to the authors' knowledge, has never been used in the UK. It comprises the following steps:
  - at the soil source, spread sufficient stabiliser for ~1 m depth of treatment
  - without mixing, front-excavate the stabiliser and 1 m depth of underlying soil and transport to a stockpile area where it is spread and lightly compacted in layers
  - when the stockpile is 3–5 m high, recover using front excavation for haulage to point of use for normal placement and final compaction.

Whatever method of construction is employed, the overall amount of time necessary for soil treatment will need consideration, particularly with regard to the nature of the treating agent. The use of lime alone, with slow chemical reactions that afford adequate time for construction involving mixing in a designated area or at source, followed by excavation, transport to the point of use, placement and then compaction, even stockpiling for a few days or more, is ideally suited to treated fill for use in the podia- or plateau-type earthworks operations that apply to housing developments.

Similar flexibility with regard to the time-dependent processes of mixing, transporting and placing treated material also applies to soil treatment using coal fly ash, employed either as a drying agent in its own right or in combination with lime. When used with lime, the use of coal fly ash obviously involves an additional spreading operation, normally within stage 2 described earlier. This aside, its use does not significantly affect the operation nor alter the time flexibility offered by lime alone. It has the advantage also of achieving enhanced bearing capacity (compared with lime alone) as a result of the hydraulic (cementing) reaction between the lime and coal fly ash.

The use of cement is not so straightforward, however. The speed of the chemical reaction, almost certainly with CEM I and possibly even with CEM II, means that it will always be necessary for the cement spreading and mixing addition to be carried out at the place of final use. The use of ggbs, being slower setting than cement, has a flexibility that lies between lime with coal fly ash and cement.

The following text summarises the procedures described above and is recommended as good practice:

- For lime-only treatment: placement and compaction at the place of use should ideally be carried out the same day as final mixing but no later than three days after initial mixing.
- For CEM I cement-only treatment: completion of compaction must be finished within two hours of mixing.
- For lime and cement in combination: if CEM I cement, placing and completion of compaction must be finished within two hours of mixing the CEM I, provided this is no later than three days after lime mixing.
- For ggbs with lime: placing and compaction must be finished the same day as the ggbs addition provided this is no later than three days after lime mixing.
- For ggbs with cement: placing and compaction should be completed the same day as ggbs addition and within two hours of the addition of CEM I.
- For fly ash with lime: whatever the order of addition, the soil mixture should be placed and compacted at the point of use within 72 hours of lime addition.
- For fly ash with cement: the mixture should be placed, compacted and finished within two hours of the addition of CEM I.
- For other cement types: it is difficult to be precise, but adherence to the normal two-hour requirement will not be so strict for CEM II-, III-, IV- and V-type cements that contain a proportion of either ggbs or coal fly ash. The workability period will be increased for these cement types and part of the hydraulic reaction and benefits will be the later and slow reaction between the lime liberated from the initial cement reaction and the ggbs or coal fly ash. The greater the proportion of ggbs or coal fly ash in the cement, the greater the workability period.

It is important that the various construction operations are carried out understanding the limitations of the plant being used. In this regard, whatever the treating agent and whether used solely or in combination, it is recommended that the minimum spread rate of any treating agent should be compatible with the capabilities of the spreading plant in order to ensure homogeneity; ~4 kg/m^2 is suggested; less than this gives rise to the danger of inconsistent spreading of the treating agent.

Figure 7: Soil treatment under construction – rotovator mixing
(Image courtesy of Earth-Tech Solutions Ltd)

14 Laboratory mixture design

14.1 General

As proposed in Section 11, the primary requirements for treatment are:

- MCV ~8–12 (category MCV8/12 in BS EN 14227-15) or equivalent moisture content range (note the desirable MCV category may be MCV9/13 but this will become apparent during and from the laboratory testing)
- 60% pulverisation (P_{60} in BS EN 14227-15)
- 95% relative compaction.

The identification of the correct MCV or moisture content range is paramount since it facilitates ease of use and pulverisation, the realisation of good bearing capacity and the achievement of the requisite degree of compaction in the field.

14.2 A suggested laboratory procedure

14.2.1 Soils where MCV and pulverisation testing is appropriate

The first stage in the mixture design procedure is the measurement of the MCV of representative samples of the untreated soil, noting that with very wet soils the MCV is likely to be < 8. The samples should cover the expected range of moisture contents anticipated for the soil prior to treatment. A minimum of three samples, covering, for example, the wettest, average and driest moisture contents, should be tested for MCV (Table 2).

For samples where the natural MCV is < 10, the second stage involves adding treating agent to the relevant samples of the soil, in increments of ~0.5% from a starting point of ~0.5%. At each increment of treating agent, continue mixing until no further breakdown of the soil appears possible. Determine the pulverisation, moisture content, MCV and density of the MCV specimen. Continue adding treating agent until both 60% pulverisation and MCV 12–13 are achieved. MCV 12–13 identifies the OMC and thus the point after which the soil becomes too dry for proper compaction. Pulverisation of 60% should normally be reached at this or lower (ie wetter) MCV value.

Table 2 shows hypothetical results of this laboratory process and is included for guidance and illustrative of the possible relationship between treating agent content, natural moisture content, MCV and MCV density. The optimum results are highlighted for each sample. As well as defining the upper MCV value (in this case 12) and then the lower MCV value (four points lower, ie 8) for site control purposes, they also, using the mid-range MCV value of 10, define the content of treating agent necessary for the soils with natural MCV < 10 that are anticipated across the site.

Thus:

- For soil with a natural moisture content up to 18%, addition of treating agent will not be necessary.
- For a natural moisture content range of 18–21%, 0.5% addition will be required.
- For a natural moisture content range of 21–24%, 1% addition will be required.

Furthermore, the corresponding MCV maximum specimen dry density for the three moisture content ranges (ie 1700 kg/m^3, 1670 kg/m^3 and 1650 kg/m^3) can also be used to establish the minimum acceptable field density target. This is discussed further below.

The third stage is to check the laboratory maximum dry density and thus the target density figure for the field work; it is recommended that the target density should be 95% of the laboratory maximum dry density. This requires the establishment of the OMC curve for the representative samples, including the just-determined treating agent content.

For a few soils – silts, silty clays, clayey silts with low sand and stone content – this should be carried out using standard Proctor compaction testing (2.5 kg rammer) to BS EN 13286-2:2010[42] (*Unbound and hydraulically bound mixtures – Test methods for laboratory reference density and water content – Proctor compaction*). For other soils, modified Proctor compaction testing is recommended. (Note: Experience with soil treatment of predominantly cohesive soils for fill in highways suggests that the modified Proctor compaction test produces a maximum density and thus a 95% (target density) figure that can be unrealistically high and impossible to achieve in the field.)

In the preparation of cohesive mixtures for OMC determination and identification of the target compaction figure, it is important that mixing is continued until 60% pulverisation and 95% of the cohesive element passing 28 mm is achieved. The OMC curve, as well as defining the OMC, will also define the moisture content wet of OMC that defines 95% relative compaction. The MCV should also be determined at these moisture contents. These will confirm the necessary MCV range for site control and confirm the results derived from Table 2.

The approach just described defines the minimum allowable site compaction as 95% of standard Proctor or modified Proctor dry density. This is different from the approach used for untreated fill in housing where the minimum dry density target for site compaction is usually defined as not more than 5% air voids.

Determination of conformance to < 5% air voids requires a calculation based on the specific gravity of the fill. This is considered appropriate for processed untreated fill where particle type and material grading homogeneity ought to be commonplace. This may not be the case, however, for soil treatment where soil type, granular content, plasticity and grading will vary; hence the proposal here to use 95% of standard or modified Proctor dry density.

Table 2: Results of laboratory process for treated soil (hypothetical) with optimum results highlighted

Natural moisture content* (%)	Parameter	Treating agent content (%)				
		0	0.5	1.0	1.5	2.0
18	MCV	10	12	14	–	–
	Moisture content$_{treated\ soil}$ (%)	18	16	14	–	–
	Dry density$_{treated\ soil}$ (kg/m^3)	1650	1700	1650	–	–
21	MCV	8	10	12	13	–
	Moisture content$_{treated\ soil}$ (%)	21	18	17	16	–
	Dry density$_{treated\ soil}$ (kg/m^3)	1590	1630	1670	1630	–
24	MCV	6	8	10	12	14
	Moisture content$_{treated\ soil}$ (%)	24	22	20	18	16
	Dry density$_{treated\ soil}$ (kg/m^3)	1500	1570	1620	1650	1550

* The moisture content is the oven-dried moisture content. The dry density result shown has been derived from this moisture content using the wet density of the MCV specimen. The wet density of the MCV specimen has been derived in turn from the mass of the MCV specimen and its volume, with the latter being the internal volume of the MCV mould.

Even this suggested approach has its shortcomings, however, since the OMC curve and the Proctor density may also vary as the soil and treating agent content varies. This is a recognised feature with treatment of cohesive soils. Thus the 95% target figure will vary. This problem is avoided by using the MCV test and the reason why it is proposed here.

Capping and earthworks experience in highways shows that with soil treatment and irrespective of the nature of the soil and treating agent content, a MCV range of 8–12 should always give the potential to achieve less than 5% air voids. Thus it is also suggested here that irrespective of the compaction results from the Proctor testing, the findings from Table 2 – treating agent content, MCV range and target field density based on 95% of maximum MCV density for each treating agent content – yield parameters that will provide the desirable performance result in the field.

Despite this, however, should a check of site compaction against an air void requirement be needed, a site density target corresponding to a maximum 5% air voids at the field moisture contents can be specified.

14.2.2 Soils where MCV and pulverisation testing is inappropriate

In the case of very sandy, stony soils like glacial tills or other such low-plasticity soils where MCV and pulverisation testing may/will prove inappropriate, the laboratory test procedure will be different. The less cohesive nature of the soil means that the treating agent addition will have less effect on the compaction characteristics – OMC and maximum dry density – of the original soil.

In this scenario, therefore, the first stage is the determination of the OMC curve for the virgin soil. This will provide the target dry density following treatment. In general, modified Proctor compaction should be used. The maximum particle size of the soil will dictate the mould size; either the standard Proctor mould or the CBR mould.

The second stage in the laboratory procedure is the testing of representative samples of the soil. The samples should cover the expected range of moisture contents in the field. A minimum of three samples is recommended, each with differing moisture content. As before, the testing involves adding treating agent to each of the samples of the soil, in increments of 0.5% from a starting point of ~0.5%.

At each increment of treating agent, continue mixing until the mixture is visibly homogeneous and the treating agent difficult to distinguish from the soil particles in the mixture. Using modified Proctor compaction and the mould used in the first stage, determine the wet density of the specimen and derive the dry density using the initial moisture content of the sample adjusted for the added treating agent. Continue the process until the dry density of the specimens starts to decrease.

As mentioned previously, the 'treated' compaction curve will usually be little changed from the 'untreated' compaction curve, but the reduction in moisture content with increased treating agent moves the treated soil's degree of compaction nearer to that achievable at the OMC. Similar to Section 14.2.1, it will then be possible to define the necessary treating agent content for each of the likely moisture content conditions pertaining to the site.

14.3 Soils with 0.25% < TPS < 0.5%

For this category of soils and despite suggesting a restricted choice of treating agents (Section 11), it will be necessary also to check resistance to swelling in the laboratory.

There are a number of possible ways of assessing resistance to swelling including European Standard test methods:

- BS EN 13286-47:2012: linear swelling test of CBR specimens carried out at 20°C, usually over a period of 28 days[43]
- BS EN 13286-49:2004: accelerated volumetric swelling test carried out at 40°C over 10 days[44].

These tests are based on experience gained in the UK and France, respectively, for highway works since the 1980s. Neither gives the complete answer, even for highways. The former test is carried out on specimens encased fully in the CBR mould and thus 'protected'. For this reason, access to water is restricted and the test may not therefore realise the full potential for ettringite/thaumasite reaction and thus exhibit the full swelling that might take place. The latter test, on the other hand, overcomes the issue of water restriction, but as it is carried out at 40°C it takes no account of the thaumasite reaction, which occurs at 15°C and less.

Another method, though not standardised, that is used to assess resistance to swelling involves the testing of unmoulded, unprotected treated soil specimens following complete immersion in water. This is carried out by monitoring expansion and determining the loss of compressive strength of immersed specimens against the non-immersed specimens. This test can be carried out at various temperatures and over various ages.

Although not formally standardised as a test method, the procedure is recognised in BS EN 14427-15 where retained strength categories of 60%, 70% and 80% are given. In this regard, 80% retained strength is the requirement in the SHW Series 800 for hydraulically bound mixtures (HBM) used in pavement bases and sub-bases. The test method provides effective results for pavement bases and sub-bases but has been criticised when suggested for use for capping construction, on grounds of severity and being too robust for conditions that actually occur in practice. It is arguable that it is too robust here also, or at least the 80% retained strength category, remembering that HBM for road bases and sub-bases will be of significantly greater strength than the case here. That accepted, the test is still of use to monitor possible expansion.

14.4 Soils with PI > 25

As with Section 14.3, volumetric stability testing is recommended.

15 Construction control

15.1 Introduction

Recommendations for the frequency of testing for site investigation purposes have been discussed previously. This is separate to what is being discussed here, which concerns testing and control immediately before, during and after treatment.

Immediately before treatment

- MCV, moisture content, organic matter, grading, plasticity, sulfates, pH.

During treatment

- stabiliser spread rates using collecting trays
- pulverisation of mixture
- MCV or moisture content
- depth of treatment and, equally importantly, excavation depth checks to ensure that untreated soil is not excavated for transport, either to a temporary holding area should it be necessary or to the point of end use.

After treatment

- in situ density measurement.

The frequency of the above tests and checks will depend on the extent of the works and homogeneity of the soil being treated. Nevertheless, assuming a 2–3 m depth of treated soil and an individual house footprint of ~100 m^2, testing every 250 m^3 is considered appropriate. Consideration may be given to reducing the testing rate where the 'works' proceed successfully, or for very large sites with uniform soils. For proper control, an adequately equipped mobile site laboratory is recommended.

15.2 Testing for MCV, moisture content, organic matter, grading, plasticity, sulfates, pH of soil before treatment

As discussed previously, these characteristics will have been established at the site investigation stage, but confirmatory testing will be required prior to treatment of the soil. Some of the tests, however, cannot be carried out at site or quickly, such as testing for sulfates, but will be necessary for audit purposes and records.

Those tests that will yield an immediate or relatively quick result, such as MCV, moisture content, plasticity and pH, and those where smell, feel and vision can play a part, such as grading and organics, should be monitored daily so that any variation can be catered for prior to treatment. This will permit adjustments to be made to the treating agent addition and/or mixing times. The moisture content of the material in particular should be monitored continuously so that the moisture content can be adjusted accordingly.

Where the material is significantly wetter than the optimum, the addition of more treating agent may be necessary. For treated cohesive soils, the MCV test is recommended for the monitoring of moisture content (Section 15.6). It is also recommended for other soils such as chalk that are also responsive to MCV testing.

15.3 Checks on stabiliser spread rates using collecting trays/sheets

The rate of powder spread from mechanical spreaders should be checked over the full working width of the spreader. This is carried out by placing a sheet of canvas or tray of known mass and area on the ground in a position that the spreader can pass over it. The canvas/tray and binder contained are weighed and the rate of spread thus determined. If necessary, the rate of spread can be adjusted and the test repeated until the desired rate is achieved. Sheets of canvas are preferred to trays, as they can be used to check the rate in the wheel tracks of the spreader, which is not possible with metal trays.

A useful check can also be carried out. Knowing the capacity of the spreader and the required rate of spread of binder, the theoretical coverage can be compared with the area covered by one load of the spreader. This check should be used throughout the duration of the project and is a very good indicator of any problem with the spreader.

15.4 Checks on homogeneity of treatment

Monitoring and checking of mixing homogeneity will need to be carried out. This includes checks on pulverisation, which are discussed in Section 15.5.

In the case, for example, of mixing carried out away from the point of use of the mixture, it will be the excavation of the mixture rather than the mixing depth that has to be accurately controlled. In this situation and assuming the treated soil will be dozed to one end of the mixing area, it will be necessary using GPS and laser-level control to ensure a match between mixing depth and dozer depth so that untreated soil does not end up at the point of use. This may mean a cautious approach employing, for example, the dozer deliberately undercutting when undertaking the excavation stage.

In the case of final mixing at the point of use where the resulting fill will consist of successive layers, it will be important to check construction so that unmixed or untreated soil is not left between layers. In this case, it will be necessary to excavate holes through the treated layer in question to check for untreated material. This may be apparent visually. If not, this can be checked by measuring the alkalinity of spot samples of the mixture taken from, and just above and below, the interface, using, for example, an alkalinity test probe or similar apparatus/methods. The method statement must clearly address this issue whatever the manner and location of the mixing.

15.5 Checks on pulverisation of mixture

It is important that the treating agent and the soil to be treated are intimately mixed to produce a fine tilth of uniform colour, texture and size in order that full and permanent treatment is achieved. This will become visually and readily apparent on mixing. With cohesive soils, more than one pass may be required in order to break down the soil into a fine friable texture.

With lime treatment of heavy clays (note: this is an academic point because they are not within the scope of this report), consideration should be given to a secondary mixing stage, maybe delayed by 24–48 hours to allow the lime to break down the soil. This reduction of lump size to a fine tilth is known as 'pulverisation' and can be quantified by measurement using BS EN 13286-48:2005[45] (*Unbound and hydraulically bound mixtures – Test method for the determination of degree of pulverisation*).

As suggested in Part III, it is proposed that adequate mixing can be assumed when the cohesive element of the mixture is reduced to lumps with 95% less than 28 mm in size and 60% of the cohesive element reduced to 5 mm and less. This degree of pulverisation is category P_{60} in BS EN 14227-15.

15.6 Checks on MCV/moisture content

For full hydration of the treating agent and for full compaction at the point of end use, the use of the correct moisture condition or content is paramount. The MCV test is most appropriate for this as it can be undertaken at site. The test procedure is described in BS EN 13286-46. Moisture content checks can also readily be carried out at site, employing quick techniques such as the frying pan method and/or the 'speedy' moisture meter.

These tests can be supplemented by what is sometimes referred to as the 'hand-squeeze' test whereby a handful of the treated soil is picked up and squeezed into a coherent mass of cricket-ball size using the pressure from both hands. If too dry, the mixture crumbles in the hand; if too wet, the mixture squeezes through the fingers. Seemingly crude, its effectiveness should not be doubted or underestimated.

15.7 In situ density measurement

In situ density is best determined using a nuclear density meter in direct transmission mode in accordance with BS 1924-2:1990[46] (*Stabilized materials for civil engineering purposes – Methods of test for cement-stabilized and lime-stabilized materials*).

It is essential that the gauge is accurately calibrated using a block of the treated soil mixture, also in accordance with BS 1924-2. Experience recommends that at any one location (the source hole), the gauge should carry out three readings by rotating the gauge through increments of 120°. The density at that location is taken as the highest of the three readings or at least the average of the higher two. The lower reading(s) should be ignored because it is impossible with the gauge to overestimate the density but very easy to underestimate the density through radiation loss if the gauge is not properly seated. The nuclear density method is suitable for layer/lift depths up to 300 mm.

Depending on the soil type, the site target is not less than 95% of the modified or standard Proctor density. However, due to the rather flat, dry density/moisture content curve (OMC curve) that can result with some hydraulically treated soils, some difficulty may occur in defining the OMC and thus the modified or standard Proctor density upon which to base 95% relative compaction. In such cases, either of the following is suggested:

- The OMC could be the moisture content that defines the maximum MCV specimen density from Table 2.
- The MCV at which the laboratory compaction curve crosses the 5% air voids line is taken as the OMC. Despite the reservations expressed in Section 14.2.1 concerning the air voids approach for treated soils, this value will approximate to the moisture content in the field that should ensure an acceptable state of compaction is achieved.

A further comment on air voids: for some treated soils, especially where the soil is of a more granular nature, it may prove impossible to achieve the 5% air voids requirement, but it is likely in such cases that the OMC is better defined anyway and this should then be used to derive the maximum density and thus the 95% target density figure. (Note: The air voids approach is the BRE preferred method for density control for untreated fill under housing[47]. More guidance on the air voids approach can be found in HA 74[24] and derivation of the air voids line can be found in Trenter and Charles[47].)

16 Verification of treatment

It is suggested here that treated soil fill under a housing development produces a platform that typically would extend at least 2.5 m beyond the external perimeter of the development or group of houses. Designed and specified requirements may include:

- bearing capacity
- maximum overall settlement
- maximum differential settlement
- maximum angular distortion.

Where evaluation of the above is carried out using plate-bearing tests and vertical displacement (settlement and heave) monitoring, the following advice should be noted.

In the case of plate load testing, it is suggested that this is carried out as treatment progresses so that problems are detected sooner rather than later. This is better achieved using small-diameter plate testing on thinner depths of lift rather than larger-diameter plate testing on greater lift thicknesses since less material will be at risk. Thus 300 mm-diameter plate testing on 500 mm depth of placed treated soils would be more appropriate than 600 mm-diameter plate testing on 1 m depth of placed treated soil.

Frequency of testing will depend on the size of the overall footprint and/or the number of dwellings. Duration of each load test will be a function of the applied test load, the treatment programme, the design requirements and the age of treatment at the time of test.

In relation to the time lapse between treatment and testing, it is important to note that the hydraulic reaction that will take place in the treated soils means that strength and stiffness will increase with time. The reaction is also temperature-dependent and will thus affect strength and stiffness. These factors will have a bearing on results. It is difficult to advise on these effects and thus such testing, the results from such testing or indeed the value of such testing must be viewed in this light.

If carried out, settlement monitoring is most useful when extended over at least six months and ideally one year, thus encompassing the four seasons. However, because of this timescale its usefulness is questionable, as it could delay construction.

Finally, it should be noted that load tests and settlement monitoring will not only be testing the hydraulically treated soil, but will also test the ground beneath the treated soil. Variation in the test results will apply where the depth of treated soil is variable across the site.

Figure 8: Plate-bearing test (minus loading jack for illustrative purposes)
(Image courtesy of Earth-Tech Solutions Ltd)

Figure 9: Proof testing of treatment at depth
(Image courtesy of Beach Ground Engineering Ltd)

17 Ancillaries

17.1 Roads and drainage

Once the decision has been made to employ soil treatment for the ground under the housing footprint, it would be appropriate to consider the use of the technique for any paved areas within the development including roads, accessways and parking areas.

Experience exists for road bases and sub-bases as, historically, this was a traditional area of activity for soil treatment and the technique known as 'soil-cement', which was developed in the 1950s, saw much adoption in the residential road market for base and sub-base application.

Programme permitting, no special measures are necessary concerning such application and advice is available from Britpave[48, 49]. The Britpave documents provide thickness design and specification information for the use of hydraulically bound mixtures in housing development roads including drainage and surfacing advice. With respect to drainage, advice on both subsoil and surfacewater drainage is given. Construction advice is also covered and relates, as does the design and specification recommendations, to both in situ and ex situ treated mixtures.

17.2 Remedials

It is probable that performance problems, should they occur, will manifest as differential settlement or heave. It is apparent, however, that remedial work to the treated soil will be virtually impossible. Even if feasible, it will be very expensive since it will involve rectification under the housing footprint itself. Specialist techniques will be necessary.

It is therefore paramount that all components in the soil treatment process described in this guidance are carried out comprehensively and in their entirety using competent, trained personnel at every stage. This will avoid performance problems and the need for remedials. The design and supervision of the works should be undertaken by appropriately qualified engineers.

17.3 Sustainability

The main overriding advantage of employing soil treatment is its ability to be used with indigenous soils, thus minimising 'dig and dump' activity. Haulage on site and off site of unsuitable material and replacement with suitable material can be significantly reduced.

Since construction trafficking will then be limited primarily to pressurised tankers supplying the treating agents, construction traffic and thus damage to the local road network can be reduced. Furthermore, energy consumption and therefore carbon footprint has been shown to be significantly less for soil treatment compared with conventional practice in road construction[13]. Similar benefits may accrue in the housing fill scenario. Benefits will be even more enhanced whenever coal fly ash and ggbs constitute part of the process.

17.4 Environmental and health & safety considerations

Both lime and cement are strong alkalis and require operatives to have adequate personal protection equipment. Similar protection is necessary when working with ggbs and coal fly ash.

In particular, measures should be adopted to minimise airborne dust to a level that will not present a risk either within the site or to health and the environment outside the confines of the site. These include:

- proper maintenance and working of the dust filters on the spreader units to minimise problems during filling of the treating agent from the delivery road tanker
- at the discharge point on the spreaders, use of rubber skirts that reach the ground
- cessation of working during windy conditions
- provision of water spray to damp/wet down the treating agent exposed on the ground
- once the treating agent is spread, prevention of plant from driving over it
- prompt mixing-in of the spread treating agent.

It is paramount that skin contact with cement and lime particularly should be avoided since, in the presence of water, burns can result. It is the responsibility of suppliers to provide safety data sheets to all purchasers. Specific advice on handling treating agents can be found in the Health and Safety at Work etc Act 1974[50].

Once mixed in, the possibility of treating agent leachate or run-off is unlikely because they will be promptly consumed chemically within the treated soil with correctly undertaken construction. If leaching were to occur, it would also be quickly consumed within the surrounding ground due to reaction with the soil minerals and water. Studies of the potential for quicklime to migrate through clay soils, for example, have found this to be negligible, ie less than 50 mm[51].

Should construction be carried out working dry of the OMC, however, the treating agents will not be fully consumed within the soil and high alkalinity could be present after construction. This may affect local water courses, aquatic life and vegetation. Such a scenario can and is to be avoided.

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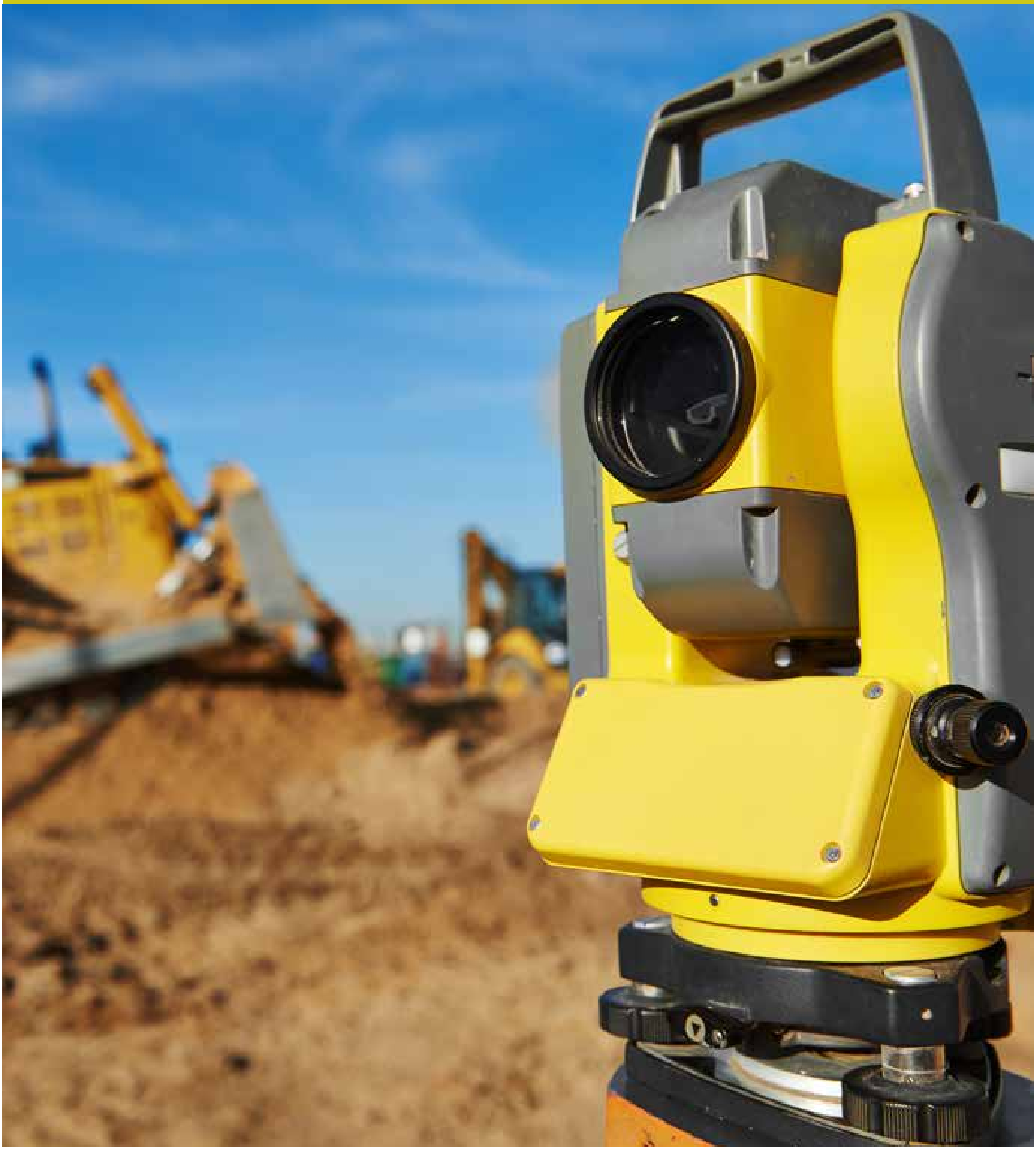
V APPENDICES



Appendix A: Hydraulically treated soil projects where expansion occurred

The authors are aware of expansion problems that occurred at the following projects in the 1980s:

- A12 Saxmunden Bypass, 1986
- Huntingdon Bypass, 1988
- M40, 1989.

The cause of swelling on the first two projects was attributed to a soil mixture that was too dry; on the other project the cause of swelling was attributed to sulfur. The failures are thus a reminder to avoid working dry and to check for sulfur. More detail on the problems associated with these projects is given below.

The authors are also aware, but not in detail, of building projects where problems have occurred: two involving sulfur in Lower Lias and one involving sulfur in boulder clay.

A1 A12 Saxmunden Bypass, 1986

The boulder clay at the northern end of the A12 Saxmunden Bypass was stabilised with lime for approximately 1 km in order to form a capping layer. The treatment was carried out in October 1986. The capping layer was sealed with a bituminous emulsion spray and then covered with 185 mm of granular material to be later stabilised with cement. However, only 100 linear metres were cement-stabilised before winter intervened.

When stabilisation work restarted the following spring, several soft areas were evident with ruts up to 300 mm being formed. Subsequent investigation revealed very high moisture contents in areas with correspondingly low compacted dry density material and CBR < 1%.

It was concluded that the problems were caused by several factors during the capping stabilisation: uncontrolled addition and mixing of added water; inadequate compaction; and the use of uncalibrated MCV control testing.

A1.1 Lessons learned

- Water was added by a bowser spray bar directly to the surface of the capping layer that had previously been 'ripped' by harrow. This meant that water ran along the surface and down the harrowed trenches in the direction of longitudinal fall or cross-fall. More water was taken up by the lime-stabilised material in the harrowed trenches and thus hard and soft lengths were produced across the width of the carriageway. The roller then tended to sit on top of the hard strips and less compaction was received in between. As a result of experience at Saxmunden and elsewhere, specifications now require water to be added via a spray bar mounted within the mixing chamber of the rotovator.
- The contract specified a target MCV of 10, a figure that was virtually plucked out of thin air, rather than a figure related to a MCV/moisture content/density calibration exercise, which is now the specified norm.
- Compaction was by smooth vibrating roller, which was subsequently deemed unsuitable for the nature of the clay. A sheep's foot roller would have been more appropriate.

A2 Huntingdon Bypass, 1988

In this project, a lime-stabilised capping experienced heave. The heave was attributed to high sulfates (~2.5%) in the subgrade material. Subsequent laboratory investigation suggested that working dry of OMC had contributed directly to the failure because working wet of OMC, even with very high sulfate content, did not produce the same levels of heave.

A2.1 Lessons learned

- The laboratory investigation indicated that the natural clay itself was prone to swelling and to a significant degree (~8%).
- This project confirmed that it is paramount to work on the wet side of OMC, as even with very high sulfate content this did not produce the same levels of heave as working dry of OMC.

A3 M40, 1989

Lime stabilisation was used on three of the four contracts on the 46 km length of the M40 between Banbury and the M42 interchange. In the south the route traversed both the Middle and Lower Lias geological series moving northwards onto the Mercia mudstone series. Each of these series provided soil for the lime-stabilisation works.

Lime stabilisation in the Mercia mudstone was successfully completed on the most northerly of the contracts, Warwick North. On the adjacent contract to the south, Warwick South, lime stabilisation was not carried out.

On the next contract to the south, Gaydon, lime stabilisation proved successful on its northern part. In November 1989, however, after some heavy rain and general lowering of temperature, the lime-stabilised material at the southern end of the Gaydon contract showed signs of deterioration. At this stage the stabilised material was either exposed or covered by rock capping. The lime-stabilised material was noted to have taken on a wavy vertical profile and had softened. Over the following months, investigation showed extensive continuing deterioration and ultimately the soft material was removed and replaced with rock capping.

Similar deterioration occurred on the most southerly of the four contracts, Banbury IV, but here the overlying sub-base and continuously reinforced concrete road base (CRCR) had been constructed. In the area of greatest heave (~150 mm), CBR values of < 1% and moisture content of 55–60% were recorded in the stabilised capping. The other layers of the pavement, the CRCR, sub-base and rock upper capping, were sound. The problem seemed in general to have been confined to areas of cutting formed through Lower Lias material.

Briefly and to summarise, deterioration was attributed to sulfates and the oxidation of sulfides to sulfates over time, both leading to the formation of ettringite and thaumasite, the latter only occurring when the temperature dropped below 15°C.

A3.1 Lessons learned

- Considerable care is required in selecting a soil for lime stabilisation.
- In the first stages of consideration, a desktop study establishing the geological history and mineralogy of the soil can identify a high-risk soil. This can avoid the cost of extensive and expensive investigatory testing.
- At the ground investigation stage, sufficient testing to establish total sulfur, total sulfate and the soil mineralogy is required together with groundwater sulfate testing.
- Swell tests on soaked specimens in CBR moulds proved to be unsatisfactory in reproducing either the degree of swell or the condition of the lime-stabilised material in the field.
- The most significant test was carried out on a sample of field material mixed with lime, compacted into a cylindrical mould and cured. The specimen was removed from the mould and immersed in water. Within minutes it began to disintegrate and within hours had collapsed completely.
- Swell tests should replicate the stabilisation process and the environment. Curing at 20°C should allow the formation of ettringite. At regular intervals, the temperature should be cycled below 15°C to observe the effects of conversion to thaumasite.

Appendix B:
Highways England protocol for soil treatment

This appendix presents information from HA 74 and provides further guidance to users on the suitability of the treating agent, testing and test references.

B1 Capping

A summary of the HE classification system for stabilisation to produce capping is shown in Table B1 using information extracted from HA 74. (Note: The table is limited to the use of lime and cement. Recent practice and experience with ggbs and coal fly ash is not included. It should not be concluded that this means that ggbs and coal fly ash should not be used, but rather that HE has not updated its advice in line with developments.)

Table B1 illustrates that treatment with respect to the HE practice for capping is not as straightforward as just saying that lime is used for cohesive materials and cement for granular soils. The table needs some clarification as follows:

- Class 6E is granular soil of inadequate quality to produce unbound capping so, being granular, requires cement treatment and produces stabilised capping designated Class 9A.
- Class 6R is similar to Class 6E, but being slightly plastic (cohesive) and wet needs some pre-treatment with lime to 'dry' the soil and 'agglomerate' the small cohesive nature of the soil before adding cement to produce Class 9F capping.
- Class 7E is cohesive soil (ie clay) with sufficient clay (PI > 10) that is also reactive to lime to allow lime-only treatment to produce Class 9D capping.
- Class 7F is relatively low-plasticity cohesive material as indicated by the liquid limit and plasticity requirements that therefore may not contain sufficient clay for lime-only treatment and thus responds better to cement treatment to produce Class 9B capping (note that cement liberates lime during hydration).
- Class 7G, compared with Class 7F, is a one-off covering the cement treatment of pfa (in other words coal fly ash) to produce Class 9C capping. (The HE classification ignores the fact that coal fly ash, being a pozzolan, responds equally well, if not better, to lime than cement!)
- Class 7I is cohesive soil but the clay element is/may be relatively unreactive to lime on its own so uses lime treatment as a precursor to the addition of cement to produce Class 9E capping. (Note: Ggbs could be used instead of cement.)

Table B1: Application of lime and cement treatment for capping[24]

Untreated material: class and description	Treating agent	Primary purpose of treatment	Resulting stabilised capping class
6E: Selected dry granular material, includes chalk	Cement	Increase in CBR	9A
6R: Selected wet granular material, LL < 45, PI < 20, also includes chalk	Lime with cement	Reduction in moisture content (or increase in MCV); increase in CBR	9F
7E: Selected cohesive material, PI > 10	Lime	Increase in MCV (or reduction in moisture content); increase in CBR; reduction in PI	9D
7F: Selected silty cohesive material, LL < 45, PI < 20	Cement	Increase in CBR	9B
7G: Coal fly ash (pfa)	Cement	Increase in CBR	9C
7I: Selected cohesive material, PI > 10	Lime with cement	Increase in MCV (or reduction in moisture content); increase in CBR; reduction in PI	9E

CBR – California bearing ratio. LL – liquidity limit. PI – plasticity index. pfa – pulverised-fuel ash.

It is worth spending time studying Table B1 since, when digested, it provides useful guidance on how to use lime and/or cement depending on soil type. At the same time, however, through its use of an unwieldy classification system, it complicates the process for specification and compliance purposes. At decision time, adequate long-term strength and durability is the requirement for capping performance and this is judged using the soaked CBR test, irrespective of the exact soil type, treating agent used and thus exact classification. This unnecessary complication with the classification system is further complicated when coal fly ash and ggbs are added to the matrix.

Depending exactly what soil type is concerned and thus capping class sought, HE testing is summarised in Table B2:

- on the untreated material – to determine suitability prior to stabilisation
- on the treated material.

The actual notes that accompany the tables in HA 74 are useful and are also included here.

Table B2: Soil tests for suitability and design[24]

Soil property	Defined and tested to	Relevant	Note/guide
To determine soil suitability			
Plasticity tests	BS 1377-2:1990[52]	All except 7G/9C	Thus not fly ash
Particle size distribution	BS 1377-2:1990[52]	All except 7G/9C	Thus not fly ash
Uniformity coefficient	Note 1	Just 7F/9B	Just cohesive with cement
Organic matter	BS 1377-3-1990[53]	All except 7G/9C	Thus not fly ash
Moisture content for untreated soil	BS 1377-2:1990[52]	6E/9A, 6R/9F, 7G/9C	For granular and fly ash
MCV for untreated soil	BS 1377-4:1990[54] (in Scotland, DMRB 4.1.7 SH7/83[55])	7E/9D, 7F/9B, 7I/9E	Just cohesive materials
Water-soluble sulfate, oxidisable sulfides, TPS	TRL Report TRL447, Test Nos. 1, 2 and 4[38]	All	–
Initial consumption of lime	BS 1924-2:1990[46]	Just 7E/9D	For lime-only treatment
On treated soil			
CBR	BS EN 13286-47:2012[43]	All	–
Swelling	BS EN 13286-47:2012[43]	All	–
MCV for stabilised soil	BS EN 13286-46:2003[35]	7E/9D , 7F/9B, 7I/9E	Just cohesive materials
Moisture content for stabilised soil	BS EN 13286-2:2010[42]	6E/9A, 6R/9F, 7G/9C	For granular and fly ash
OMC for stabilised soil (2.5 kg test)	BS EN 13286-2:2010[42]	7E/9D, 7F/9B, 7G/9C, 7I/9E,	Cohesive and fly ash
OMC for stabilised soil (4.5 kg test)	BS EN 13286-2:2010[42]	6E/9A, 6R/9F	Granular only
Frost susceptibility	BS 1924-2:1990[46]	All	If used in the frost zone
Impact lump dry density of chalk	Clause 634 MCHW-1[3]	6E/9A, 6R/9F	Just chalk

Note 1: The uniformity coefficient is defined as the ratio of the particle diameters D60 to D10 on the particle size distribution curve where:
D10 = particle diameter at which 10% of the soil by weight is finer
D60 = particle diameter at which 60% of the soil by weight is finer.

Note 2: IDD – impact lump dry density.

Note 3: Limits on moisture content, or MCV, are applied primarily to ensure ease of handling of the untreated material.

Note 4: Additional sulfate and sulfur testing may be required on exposure of formation level in cuttings.

Note 5: MCV is the preferred method of moisture control for cohesive materials. The MCV limits will ensure that an adequate state of compaction is achieved, and the limits are independent of changes of plasticity with time. The operator must ensure that the MCVs recorded are on the correct calibration leg, ie the 'wet' leg.

Note 6: Moisture content is the preferred method of moisture control for granular materials. If moisture content is to be used as the alternative to MCV for cohesive materials then the moisture content values required for acceptability must be directly related to the material properties at the time of compaction.

Table B3: Earthworks improvement to HA 74[24]

Treating agent	Process	Material	Initial class	Primary purpose of constituent	Resultant class
Lime	Improvement	Unsuitable granular	U1A	Reduction in moisture content (or increase in MCV)	1A, 1B, 1C
Lime	Improvement	Unsuitable cohesive	U1A	Increase in MCV (or reduction in moisture content); reduction in PI	2A, 2B, 2C, 2D, 2E
Lime	Improvement	Unsuitable chalk	U1A	Reduction in moisture content	3

B2 Earthworks improvement

The HE approach is summarised in Table B3. Firstly, it should be noted that HE restricts improvement to lime only. Secondly, and as with capping, the process is complicated by the resultant classification after treatment with lime into subclasses of Class 1 and 2 when Class 1 and 2 alone would suffice. Thirdly, considering the fact that lime is just being used as a drying agent without any requirement or expectation for long-term strength or strength gain, the current approach fails the use of other potential drying agents like coal fly ash.

Appendix C:
Actual use of hydraulically treated soil under house foundations

C1 Introduction

There is history, albeit comparatively recent, of the use of hydraulically treated soils for fill directly under residential properties. The practice has been ongoing for nearly 10 years and is known to have employed to date:

- lime, cement and coal fly ash
- purpose-made stabilisation equipment including rotovators and spreaders
- strict and thorough controls before, during and after construction.

This section provides a general review of this use.

C2 Overview of soil treatment

Where carried out, the overlying development has consisted in the main of two- and three-storey terraced, detached and semi-detached dwellings with both timber-frame and cavity masonry construction.

In all cases, the house foundations above the treated soil were designed by appropriately qualified civil/structural engineers and generally comprised reinforced concrete foundations together with suspended ground floor slabs. Giving details of the foundations used on NHBC sites may infer that these foundation types represent the accept norm, which is not the case.

Generally, the treated soil was required to provide a minimum allowable bearing capacity of 75–100 kPa for foundations, with maximum settlements not exceeding 25 mm and a tilt limit of 1:750.

C3 Soil treatment

In general terms, treatment was carried out to enable soft cohesive made and natural ground to remain on site. In all cases, the soft ground was removed down to firm natural deposits at the base of excavation for subsequent treatment.

The soils treated generally comprised natural and weathered glacial till and sandy clays of low to medium plasticity. This included clays of low to medium compressibility and thus low volume-change potential such as glacial till with minor deposits of alluvial sand and gravel.

Actual processing of the work involved:

- removal of poor soil down to firm natural soil of adequate bearing capacity
- transport of the poor soil to a ‘mixing area’
- treatment using conventional powder spreaders and mechanical rotovators consisting generally of a minimum of 2% treating agent (either lime alone, lime–cement blend or cement–coal fly ash blend) up to a maximum of 5% treating agent
- lime with the more cohesive soils, and cement, or lime or cement with coal fly ash, where the soils were less cohesive and more granular
- excavation from the mixing area and transport of the treated soil to the point of use
- placement as fill in layers 250–300 mm maximum thickness compacted to minimum 95% relative compaction (either BS heavy 4.5 kg or light 2.5 kg rammer) and 5% maximum air voids using conventional roller compaction (in some instances additional compaction was carried out using rolling dynamic compaction at 1.25–1.5 m depth intervals)
- overall depths of placed treated fill varied from 2 m to 5 m constructed as podia with 1:1 side slopes and crest extending some 2 m beyond house foundations.

C4 Investigation and testing

Where recorded, preliminary geotechnical investigation and testing generally consisted of:

- trial pits – generally one at the location of each house or unit
- on the soil recovered from trial pits and elsewhere, testing for:
  - particle size
  - liquid and plastic limits
  - moisture content
  - acid-soluble sulfate and TPS (includes sulfides)
  - pH.
- in each trial pit, hand-vane shear tests to determine the necessary depth of excavation of poor soil
- on the treated mixture, laboratory compaction tests to determine OMC and maximum dry density.

Quality control during treatment generally consisted of checks on:

- moisture content, organic matter, grading, plasticity, sulfates, pH of soil before treatment
- treating agent spread rates using collecting trays
- pulverisation of mixture
- checks to confirm depth of layer treatment
- MCV tests.

Post-compaction validation tests and results generally consisted of:

- in situ density and moisture content measurement using nuclear density gauge; one, where recorded, for every 250 m^3 of treated soil placed
- plate-bearing tests carried out, at a frequency where recorded of one per 1000 m^2 or one every third or sometimes every fifth dwelling using a 600 mm-diameter plate loaded to 100–125 kPa on the surface of each 1.5 m depth of placed treated soil
- settlement monitoring for up to six months to meet overall settlement requirements. Where recorded, six-month settlements were generally less than 1 mm.

Where treatment was used to stabilise foundations for access roads, CBR testing formed part of the testing.

Appendix D:
Performance properties for hydraulically treated soils

With regard to sub-base, capping and earthworks fill in road schemes, there is considerable published information on mechanical performance properties such as CBR and compressive strength required for and used for design purposes. There are less data for those mechanical performance properties that might apply to treated structural fill under housing.

Although outside the scope of the guidance in this report, which has considered treatment as a means of making a soil fit for purpose rather than for enhancement beyond its normal optimum non-treated strength, for completeness and for confidence this appendix provides data on shear strength, effective stress parameters, coefficient of volume compressibility and safe or allowable bearing pressures.

It would not be unusual, even with modest amounts of lime, eg 2–3%, and depending on the exact type and plasticity of the clay, to realise effective stress values of at least:

- 100 kN/m^2 for c′ (cohesion referred to effective stress)
- the natural drained value of typically 25–35° for φ (angle of shearing resistance referred to effective stress).

In BRE Digest 471[28], soft ground is defined as soil that has shear strength of 20–40 kPa and very soft ground as soil that has shear strength of < 20 kPa. With hydraulically treated ground, however, it would be rare for that same very soft or soft soil when treated not to realise shear strengths of 100 kPa. Such shear strengths are achievable with modest treating agent contents of 2–3%. Indeed, with not much higher treating agent contents and depending on the soil type, values in excess of 1000 kPa are not unknown.

In the absence of shear strength testing or results, test evidence shows that shear strength can be taken as ~30% of the unconfined uniaxial compressive strength, R_c. Thus for a treated soil during the mixture design process that achieves R_c category $C_{0.4/0.5}$ in accordance with BS EN 14227-15, it would have a shear strength of 30% of 0.4 MPa; in other words 120 kPa.

Soaked strengths with hydraulically treated soils are also generally good. It is common with stabilised soils for highway pavement use, and it is stressed here with the very onerous pavement use rather than earthworks use, to require the strength of water-immersed specimens to attain 80% of non-immersed strengths. It is not suggested here that this is necessarily the target for treated fill under housing, but with modest stabiliser, contents ratios of 70%+ are usually readily achievable for hydraulically treated soils.

With regard to compressible soils and soils with high potential for shrinkage and swelling, it is known that when hydraulically treated those soils have significantly reduced settlement and heave characteristics. Test data show that m_v, the coefficient of volume compressibility for highly plastic clays, can be reduced following treatment to values ~0.1 m/MN. Such values are more associated with hard clays than plastic clays, which can have m_v values > 0.3 m/MN, even approaching 2 m/MN.

It is probable that this characteristic can also be examined by comparing plasticity properties before and after treatment. Treatment realises a marked increase in plastic limit with a corresponding marked fall in PI. It is not unusual for PI to reduce by 20 points and quite plastic soils see their PI fall to < 20, even as low as 10. The fall in plasticity is usually a function of the type of soil. However, depending on the percentage of added lime, it is possible to render many cohesive soils non-plastic and thus remove completely their potential for shrinkage and swelling.

Some of the parameters discussed above and the values achieved are time-related. Some properties like immediate bearing index improvement and plasticity reduction are realised immediately. Strength characteristics like shear strength and compressive strength, although usually significant by seven days, will continue to develop with time, with values doubling by 28–90 days and even quadrupling by one year and later. This needs to be recognised with testing and makes the time of test difficult to decide for some parameters. A pragmatic balance is required here. Bearing in mind that it would be unusual to have the luxury of more than two months to carry out investigation and testing for soil treatment, test ages beyond 28 days would be difficult. This timescale, however, should be sufficient and can be aided where time is short or where ultimate properties are sought, by accelerated curing techniques employing 40°C testing.

The data discussed above are a summary of findings from a myriad of technical documents[32, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65], which are listed in the references. It is suffice to say here, however, that the summary is a generalised summary and that parameters will vary from one soil to another. The summary is meant to be illustrative and should not be viewed as indicative for any site without confirmation laboratory testing for the soil, stabilisers and conditions in question.

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The guidance is intended to inform developers, engineers and other building professionals considering the use of soil stabilisation and wanting to learn more about the subject and its application. It also suggests a regime of validation and testing to support the review of suitability and appropriateness of the technique.

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ISBN 978-1-84806-464-5