Swell test requirements for lime stabilised materials

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Executive Summary

Limits are currently recommended in Advice Note HA 74/95 relating to the permitted amount of swell in standard samples of lime stabilised cohesive material. This is a requirement for determining the suitability of cohesive material (Class 7E), prior to its stabilisation as a capping layer within the Series 600 Earthworks of the Specification for Highway Works. The swell test is currently the prime indicator to the suitability of selected cohesive fills for achieving satisfactory lime stabilisation. The test indicates when the lime and any sulphates, or sulphides, in the fill react together to produce highly expansive products, thus causing excessive swell. It is essential that unsuitable cohesive materials are not stabilised as they would produce significant levels of swell within the pavement foundation, leading to premature pavement failure, resulting in high costs for pavement repair and subsequent traffic delays. This research project is required to validate or revise the swell limits currently given in HA 74/95, whilst ensuring that only suitable cohesive fills are permitted for lime stabilisation within the SHW.

A wide ranging review of published and unpublished data was carried out in the initial phase of the project; details covering the origin of the soaking test in the UK, and the relevant information from other national standards and guides, are presented in a summary of the literature review.

Following current British Standards testing methods and relevant clauses of the SHW, seven British soils were stabilised with quicklime, and subjected to a testing methodology aimed at providing data to assess the applicability of the swell test as an indicator to the suitability and acceptability of SHW Class 7E materials for lime stabilisation. CBR specimens of the stabilised materials were prepared, soaked, and monitored for swell for up to 400 days. The strength of the specimens was measured after 7, 28 day and long-term curing. CBR specimens of the stabilised materials, prepared at states of compaction well within the current UK requirements, resulted in strengths around or slightly higher than the current acceptability requirement. Contrary to experiences reported in lime stabilisation literature, Weald Clay was effectively stabilised with quicklime. For all the soils stabilised in the trial, swell values below the average upper limit of 5mm (HA 74/95) were recorded.

Problems with two test methods for lime stabilised materials were identified. It is recommended that the British Standard method for determining the CBR of cured lime stabilised specimens is amended to take into account potential failure and significant displacement of a cone of material within the surface being tested, and the British Standard method for determining the Initial Consumption of Lime is updated to reflect the possibility of achieving pH values for saturated lime solutions outside the currently stated acceptability range.

It is concluded that the currently specified laboratory tests for lime stabilisation of capping materials, including the swell test procedure, *are effective performance indicators for mix design and long-term durability*. It is recommended that the swell test procedure be retained in the UK specification in its current form. Also, the swell limits currently specified in the UK specification are considered to be appropriate for the typical range of British clays stabilised in the trial, and should not be altered.

1 Introduction

The swell test is currently the prime indicator to the suitability of selected cohesive fills for achieving satisfactory lime stabilisation. The test indicates when the lime and any sulphates, or sulphides, in the fill react together to produce highly expansive products such as ettringite or thaumasite, thus causing excessive swell. It is essential that unsuitable cohesive materials are not stabilised as they would produce significant levels of swell within the pavement foundation, leading to premature pavement failure, resulting in high costs for pavement repair and subsequent traffic delays.

Limits relating to the permitted amount of swell in standard specimens of lime stabilised cohesive material are currently recommended in Advice Note HA 74/95 (*Design and construction of lime stabilised capping*) (DMRB 4.1.6). Swell data are a principal requirement for determining the suitability of cohesive material (Class 7E), prior to its stabilisation as a capping layer within the Series 600 Earthworks of the Specification for Highway Works (SHW) (MCHW 1).

In the near future, HA 74/95 (DMRB 4.1.6) will be replaced with an Advice Note encompassing lime, cement, and lime and cement treatment of earthwork materials; it should be noted that items referred to as being part of HA 74/95 (DMRB 4.1.6) within this report will be reproduced in a broadly similar form in the replacement Advice Note.

This research project has been undertaken with the aim of either validating the swell limits currently given in HA 74/95 (DMRB 4.1.6), or ascertaining whether these limits need to be revised. The outcome of this work will assist in ensuring that only suitable cohesive fills are permitted for lime stabilisation within the SHW (MCHW 1).

2 Background to swell testing

The origins of the need for a soaking test, and the associated limiting swell values, are as follows. Stabilised materials which satisfy the specified criteria for strength requirements rarely give trouble, provided that they remain in a dry condition. In most cases, this is also true if the materials become saturated but, in certain instances, the material may contain components which either expand on contact with water or which, in the presence of water, may give rise to chemical reactions which lead to expansion. Tests carried out on the stabilised material in a dry condition may therefore give a false impression of the long-term durability of the stabilised material. This is why soaking tests were introduced but their introduction did not occur until the publication of the 1986 edition of the Specification for Highway Works (DOT, 1986). Before then, other methods were used to detect the presence of components which might give rise to expansion.

The main components of stabilised materials which are likely to give rise to problems of expansion when the stabilised material becomes saturated are expansive clay minerals and sulphates. In Great Britain, the possible presence of expansive clay minerals is not a serious problem but sulphates, usually calcium sulphate and less commonly the more soluble magnesium sulphate, may occur, sometimes in high concentrations (Bessey and Lea, 1953; Forster *et al.*, 1995). In the presence of excess water, these can react with the cementitious matrix of the stabilised material and cause expansion to occur. Water is an essential component of the reaction and, whilst the material remains dry, no reaction will occur. Quite small amounts of these sulphates in lime stabilised materials can give rise to considerable expansion if the moisture content of the material increases after it has been compacted. An indication of the degree of expansion that can occur is presented in Sherwood (1962).

Once the presence of sulphates was recognised as a potential problem, the Specification for Road and Bridge Works (SRBW) introduced a requirement that the sulphate content of cement stabilised cohesive materials should not exceed 0.25% (Clause 801.4 of the SRBW, DOT, 1975). The actual chemical determination of sulphate content is not difficult and the precision of the test is very good. The main problem lies with obtaining a representative sample and with the sampling errors that may arise with reducing several kilograms of the bulk sample down to the 10g test portion required for the test. For this reason, when the 1986 edition of the SHW was published, the requirement for determining the sulphate content for cement stabilised materials was omitted and instead a soaking test was introduced to detect the presence of expansive components. BS 1924 *Methods of test for stabilized materials* (BSI, 1953, 1957, 1967, 1975) and *Stabilized materials for civil engineering purposes* (BSI, 1990a) has long included two soaking tests. One (now Clause 4.3 of BS 1924: Part 2: 1990) is the *Determination of the effect of immersion on the compressive strength* and the other is a soaked California Bearing Ratio (CBR) test (Clause 4.5).

For cement stabilised materials, the 1986 edition of the SHW required that after immersion for seven days the test specimens should retain at least 80% of their compressive strength and *the specimens should not show any sign of cracking or swelling* (Clause 1036.2, DOT, 1986). The test specimens are either test cubes or cylinders which after curing for seven days, as required by the specification, can be handled with ease. When they are subjected to the BS 1924 immersion test it is therefore possible to detect any cracks in the test specimens that may have occurred as the result of sulphate attack. However, detecting cracking will be subjective and its relation to volumetric change will be uncertain.

When a strength specification was included for lime stabilised specimens, it was decided to specify the CBR test rather than the compressive strength test as the criterion for acceptance. In this test, the specimen remains in the mould and only the surface is visible. When a soaked CBR test is carried out, as specified in BS 1924 (BSI, 1990a), it is not possible to see whether any cracking has occurred. All that is known is the extent to which immersion has affected the CBR value and the degree of swelling that has occurred. These are likely to be good indicators of the *in situ* performance of lime stabilised capping.

As swelling is a characteristic of sulphate attack, it was suggested in CR 151 *Stabilized capping layers using either lime, cement or lime and cement* (Sherwood, 1992) that a limit for the amount of swelling that occurs during the soaking period should be specified. The suggested limit was an average of 5mm with no specimens to exceed 10mm. These values were not entirely arbitrary and were based on the figure of 0.25% that was set for the sulphate content in pre-1986 editions of the SHW, and the amount of heave that such a concentration of sulphates is likely to cause, as observed during laboratory investigations (Sherwood, 1962).

The current principal suitability requirements for SHW Class 9D lime stabilised capping materials (MCHW 1) are that the average CBR value, after 3 days curing and 4 days soaking, of each batch of test specimens prepared as described in HA 74/95 (DMRB 4.1.6) shall be 15% and no individual test specimen shall have a CBR of less than 8%. The average degree of swelling that occurs after monitoring the test specimens for 28 days shall be less than 5mm and no individual test specimen shall have a swell of more than 10mm. These requirements were incorporated within HA 74/95 (DMRB 4.1.6), following the publication of CR 151 (Sherwood, 1992).

As the potentially detrimental effects of sulphates on the lime stabilisation process have become widely recognised, tests for total sulphate content, expressed in terms of SO_3, and total sulphur content have gained further significance. In HA 44/91 (DMRB 4.1.1), the potential for expansion caused by a reaction between the clay fraction and sulphates in the soil is noted, and a maximum total sulphate value of 1.0% is advised, unless case histories or a prolonged trial indicate that a higher value is acceptable. In HA 74/95 (DMRB 4.1.6), this advice is expanded to reflect the possibility of sulphates being produced as a result of oxidation of sulphides. The test for total sulphate content provides a measure of the total amount of sulphate in a soil, whilst the test for total sulphur content provides a measure of the initial sulphate content plus the contribution to the sulphate content resulting from the oxidation of the sulphides (Sherwood, 1993). Providing the percentage total sulphur content is appropriately converted, comparisons can be made between the percentage sulphate in a soil, and the percentage of sulphate in the soil plus that formed by oxidation of sulphide. As migration of sulphates into lime stabilised capping could also cause the expansive reaction, HA 74/95 (DMRB 4.1.6) also advises assessing sulphate content of groundwater and any standing water.

3 Literature review

A wide ranging review of published and unpublished data was carried out at the outset of the project (see Snowdon and Steele, 1998). Specific information relating to swell values, with relevant specification requirements, the time for swell to cease, total sulphate contents and their relations for cohesive materials were sought. Identification of suitable soil types (SHW Class 7E, MCHW 1) for the laboratory trial was also a requisite.

The literature review yielded only limited relevant data relating specifically to swell values and sulphate contents. It was noted that in the USA, where each state has its own procedure for evaluating material suitability and mixture design, lime is primarily used to reduce swell from natural soils to a *reasonable* value (TRB, 1987). Unfortunately, no actual swell value that related to *reasonable* could be established from the literature. Apart from requirements for reducing swelling potential, by the addition of higher lime contents, and increasing unconfined compressive strength, none of the USA's specifications for mixture design has reference to a restriction in sulphate content for stabilised materials. In Brazil, a reduction in swell to approximately 6%, for a cohesive material, was reported by Mendes Fihlo (1975). This value could possibly be taken as indication to a *reasonable* value.

The South African (NITRR, 1986), Australian (NAASRA, 1986) and New Zealand (Dunlop, 1977) guides and specifications are very similar and reflect the experience gained in the UK and USA. Minimum increases in CBR, or compressive strength, are applied as the primary requirement for suitability and acceptance. A restriction on allowable sulphate content is only applied in the South African specification. The New Zealand specification only has a passing reference to the potential for sulphates causing swell, but mentions that no evidence of this type of reaction has been found in New Zealand soils (Dunlop, 1977).

A number of papers discussed the problems of swell associated with sulphates and pyrites (Abdi and Wild, 1993; Dubbe *et al.*, 1984; Hunter, 1988; Littleton *et al.*, 1988; Nixon, 1978; Wild and Abdi, 1993), but in the context of this study, the investigations employed various test methods and produced minimal relevant data. The most relevant data were presented in reports on previous TRL studies (MacNeil, 1995; MacNeil and Steele, 1993) and in papers and reports by Babtie Dobbie (1993), Ferris *et al.* (1991), Holt (1994), Mitchell and Dermatas (1992), Littleton (1990) and Burkart *et al.* (1999).

The only standard containing swell requirements for acceptability is the current draft CEN standard relating to the use of lime-treated mixtures. This includes limits for volumetric swelling, which are reproduced in the following table (CEN, 1997). These are presented as an alternative to the current SHW lime stabilisation requirements (HA 74/95, DMRB 4.1.6), which are also included in the CEN draft standard. The volumetric values equate to linear swells of 6.35mm (5%) and 12.7mm (10%) for samples compacted into standard BS 1377 CBR moulds. HA 74/95 (DMRB 4.1.6) has equivalent limits of 5mm and 10mm. Requirements relating to sulphates, sulphur, sulphides and other potentially expansive materials are as those given in HA 74/95 (DMRB 4.1.6).

Determination of volumetric swelling
The potential for swelling of the mixture shall be assessed as below, by the measurement of volumetric swelling, Sv, on cylinders subjected to immersion in water at elevated temperatures, in accordance with prEN00227420.

If Sv 5%, the soil/material is suitable for treatment
If Sv 10%, the soil/material is unsuitable
If 5% < Sv < 10%, the soil/material warrants further study

4 Testing regime

4.1 Testing methodology

The testing methodology was developed with the primary aims of enabling measurement of swell values, the time scale for the cessation of swell and to assess any long-term effects. Assessment of the Class 7E untreated material suitability, and the Class 9D lime stabilised material acceptability requirements, were undertaken following current British Standards testing methods and relevant clauses of the SHW (MCHW 1) and HA 74/95 (DMRB 4.1.6). A summary of the soil test methods used is presented in the unnumbered table below.

As it could not be guaranteed that any effects on swell performance would be representative of a natural material at a higher sulphate content, it was considered inappropriate to artificially increase the natural sulphate contents of any of the materials selected for the trial.

4.2 Class 7E cohesive soils

For the laboratory trial, samples of cohesive soils were sourced from areas with relatively high sulphate contents, as identified by Bessey and Lea (1953) and Forster *et al.* (1995). In total, seven cohesive soils, namely Mercia Mudstone, Oxford, Lower Lias, London, Gault, Weald and Kimmeridge Clays, were included in the test programme.

Particle size distributions are presented in Figure 1; six soils met the grading requirements for Class 7E (Table 6/2, MCHW 1), and the Mercia Mudstone was only fractionally outside the grading envelope at the upper end. Suitability data for plasticity, organic matter, total sulphate, total sulphur and Initial Consumption of Lime (ICL) are presented in Table 1. The data for all soils comfortably exceed the minimum plasticity requirement of 10% (MCHW 1). For organic matter content, HA 74/95 (DMRB 4.1.6) advises an upper limit of 2%, but also notes that some materials with organic matter contents greater than 2% can be satisfactorily stabilised with lime. Sherwood (1993) also noted that it is the type of organic compound rather than the total amount which is important. Two soils exceed the 2% advisory upper limit, Lower Lias Clay by 0.2% and Kimmeridge Clay by 3.3%.

The data for total sulphate content (Table 1), expressed as SO_3 and SO_4, showed a wide range of values; the measured

Test	*BS test reference*	*SHW Class 7E*	*SHW Class 9D*	*For suitability*	*For acceptability*
Particle size distribution	BS 1377: Part 2: 1990	✓	–	✓	–
Plasticity indices	BS 1377: Part 2: 1990	✓	–	✓	–
Organic matter	BS 1377: Part 3: 1990	✓	–	✓	–
Total sulphate content	BS 1377: Part 3: 1990	✓	–	✓	–
Total sulphur content	BS 1047: 1983	✓	–	✓	–
Initial Consumption of Lime	BS 1924: Part 2: 1990	✓	–	✓	–
Optimum moisture content (2.5kg rammer compaction)	BS 1924: Part 2: 1990	–	✓	–	✓
MCV calibration	BS 1924: Part 2: 1990	–	✓	–	✓
MCV compliance check	BS 1924: Part 2: 1990	–	✓	–	✓
Soaked CBR at 7 and 28 days and long-term	BS 1924: Part 2: 1990	–	✓	✓	✓
Swell	BS 1924: Part 2: 1990	–	✓	✓	✓

Table 1 Class 7E characterisation data

	Atterberg limits			*Chemical analysis*									
					Total sulphate content as SO_3 (SO_4)content								
Soil type	*Plastic limit (%)*	*Liquid limit (%)*	*Plasticity index (%)*	*Organic matter (%)*	*Soil (%)*		*2:1 water soil extract (g/l)*		*Total sulphate content*	*Total sulphur converted to total sulphur content (% SO_3)*	*Initial consump-tion of lime (%)*	*Clay fraction (%)*	*Activity (%)*
Mercia Mudstone	17	34	17	0.77	0.24	(0.29)	–	–	<0.04	<0.10	3.2	18	0.94
Oxford Clay	19	55	36	1.24	0.39	(0.47)	–	–	1.90	4.75	5.7	52	0.69
Lower Lias Clay	23	49	26	2.2	0.15	(0.18)	–	–	0.38 [2]	0.95	5.1	37	0.70
London Clay	24	66	42	1.1	0.66	(0.79)	1.79	(2.15)	0.38 [2]	0.95	1.9 [3]	55	0.76
Gault Clay [1]	28	74	46	1.0	1.29	(1.55)	1.55	(1.86)	0.52 [2]	1.30	5.5	63	0.73
				1.1	0.78	(0.94)	0.93	(1.12)	0.27 [2]	0.68			
				1.1	0.40	(0.48)	1.50	(1.80)	0.10 [2]	0.25			
Weald Clay	20	35	15	1.0	0.06	(0.07)	–	–	0.09 [2]	0.23	2.8	21	0.71
Kimmeridge Clay	28	62	34	5.3	0.61	(0.73)	2.03	2.76	1.04 [2]	2.60	6.0 [4] 7.5 [5]	56	0.61

[1] *Due to material variability, chemical tests undertaken on three sub-samples,*

[2] *Total sulphur content by external soil testing house's dry powder method,*

[3] *ICL value not achieved - value as reported by MacNeil (1995),*

[4] *ICL value not achieved - upper lime addition recommended in HA 74/95 reported,*

[5] *ICL value as reported by external soil testing house.*

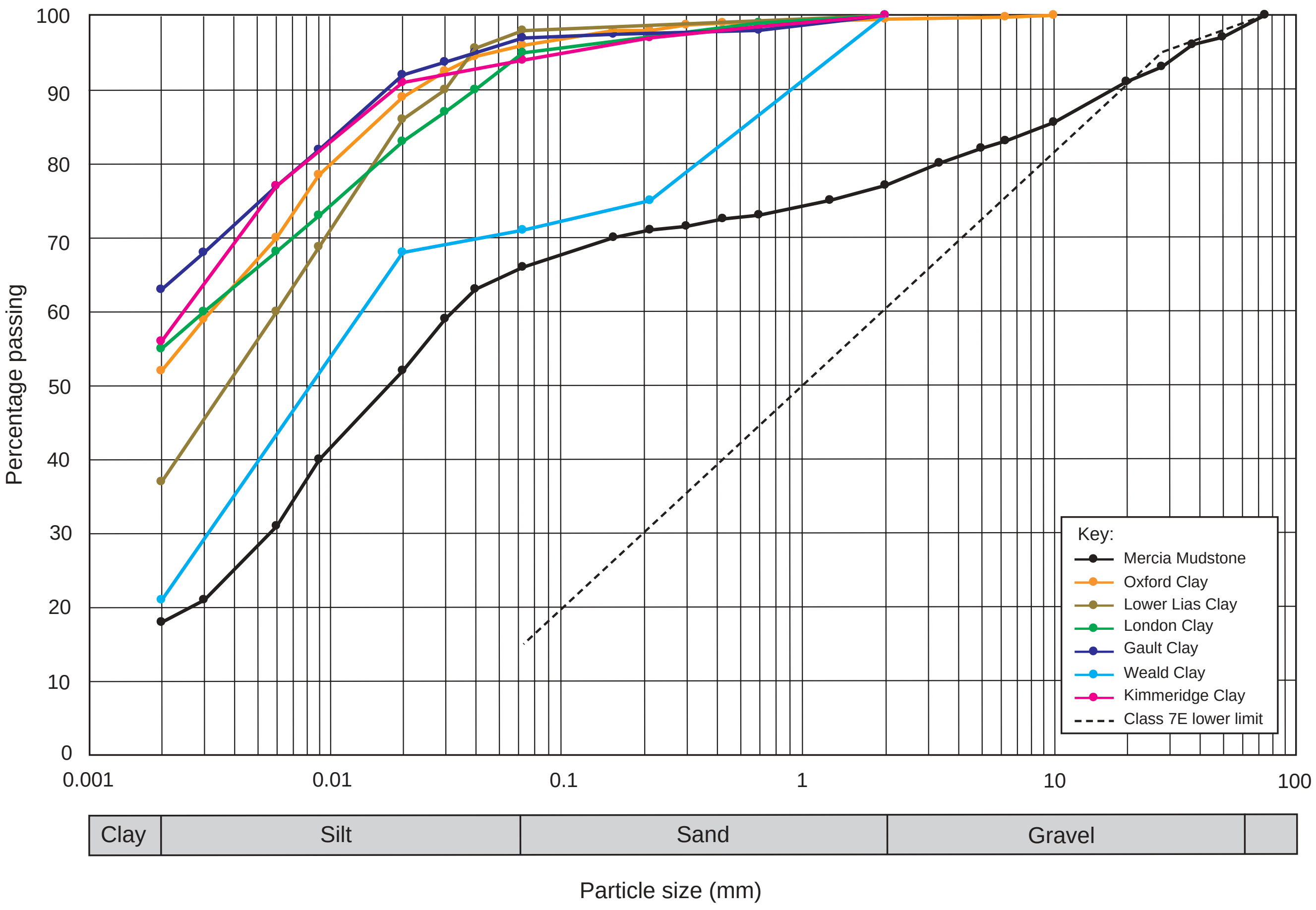

Figure 1 Particle size distribution for Class 7E cohesive soils

total sulphate values for three soil types were below the originally specified 0.25% upper limit, and the values for the other four soil types ranged between two and five times this value. The total sulphur content data showed a similarly wide range of values. The results of converting the total sulphur content data to equivalent total sulphate content data, as described in HA 74/95 (DMRB 4.1.6), showed broad agreement with the measured total sulphate content values for Mercia Mudstone, London, Gault and Weald Clays. This indicates that the sulphur in these soil samples occurred in the form of sulphates. For the other three soil types, the total sulphur contents produced equivalent total sulphate contents considerably in excess of the measured values. In descending order, the differences were: Oxford Clay 4.36%; Kimmeridge Clay 1.99%; and Lower Lias Clay 0.8%. It can be concluded that sulphur in these soils did not mainly occur in the form of sulphates, but as either sulphides or sulphur. From these analyses, it is evident that the soil types used in the trials encompassed a comprehensive range of the chemical characteristics that have the potential to play leading roles in expansive chemical reaction.

At the outset of testing, it was decided that, rather than undertaking a preliminary suite of CBR tests to develop a specific design mix for each soil type, i.e. to ascertain lime additions which would achieve the CBR requirements specified in HA 74/95 (DMRB 4.1.6), each material would be tested at one lime addition. Following current SHW procedures, this lime addition was taken as the ICL value plus 0.5% for each soil type in the test programme, with the exception of the London Clay, where previous testing had shown that a lime addition equal to the minimum addition of 2.5%, specified in HA 74/95 (DMRB 4.1.6), would result in stabilisation. As reported previously by MacNeil (1995), and Rogers *et al.* (1997), the ICL test can prove difficult to undertake in strict accordance with the test procedure detailed in BS 1924 (BSI, 1990a). The ICL test data are plotted in Figure 2, and the lime additions selected after interpreting the data are detailed in Table 1. Problems with the ICL test are further discussed in Section 6.1.

4.3 Sample preparation

Sample preparation was divided into two stages; the initial stage involved preparing and stabilising samples of each soil, to enable a 2.5kg rammer laboratory compaction curve and a MCV calibration to be generated, and the second stage involved preparing large stabilised samples of each soil at specific moisture contents, for use in preparing CBR test specimens.

During the initial preparation stage, for each soil type, a range of moisture content levels was prepared so that the resulting stabilised materials would have ranges of moisture content encompassing Optimum Moisture Content (OMC) and a range of MCVs on the wet leg of the MCV calibration.

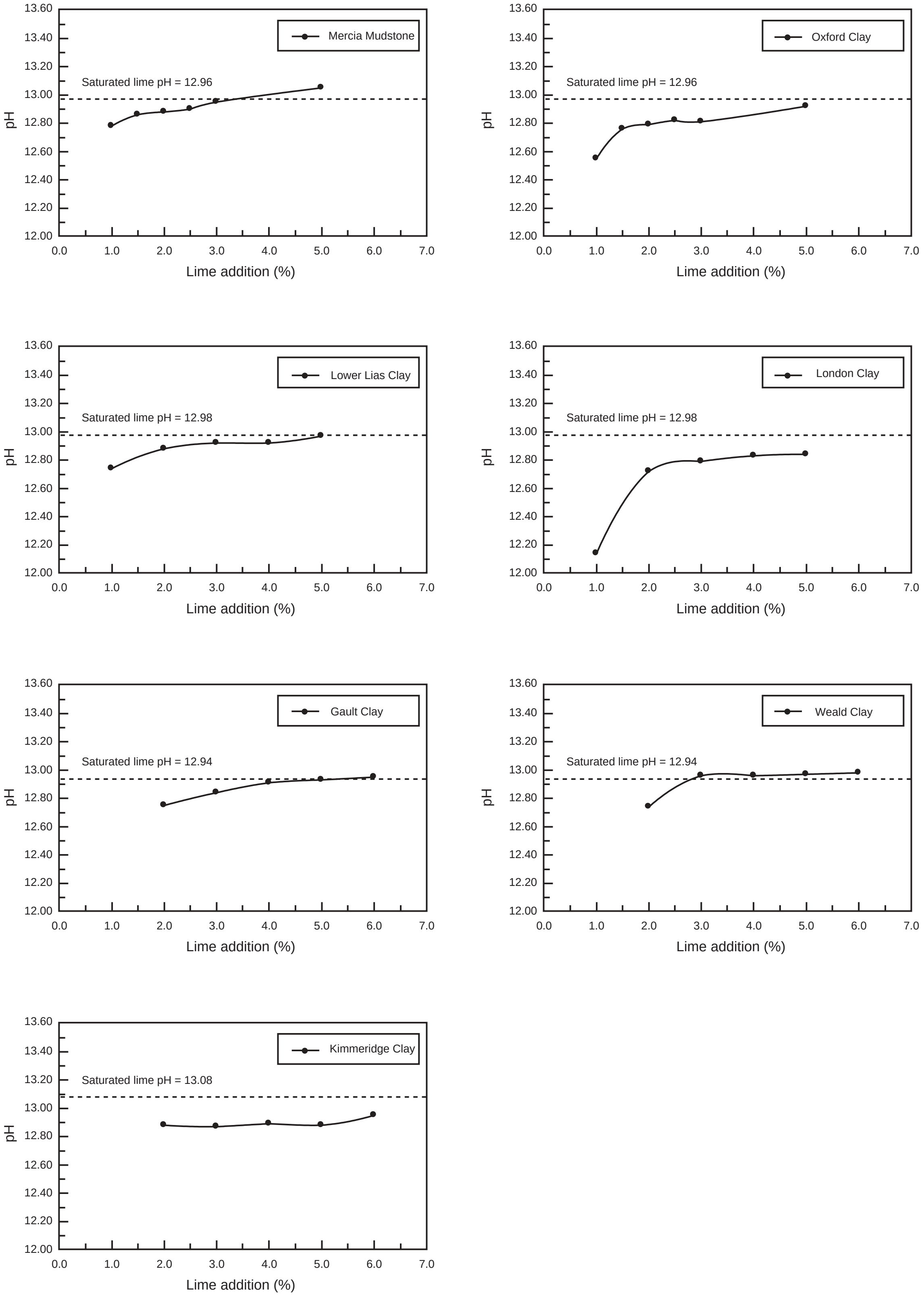

Figure 2 Initial Consumption of Lime (ICL) plots

The soil preparation procedures specified in BS 1377 (BSI, 1990) were followed. Batches of Class 7E soils were prepared and then placed in airtight plastic bags for a period of time to allow the moisture to equalise. The batches were remixed prior to the addition of SG60 quicklime. To achieve a uniform distribution of the lime throughout the soils, quicklime was added whilst the paddle mixer was operating. The Class 9D lime stabilised batches were then mixed further, sampled for moisture content and sealed in airtight bags for a period of time, commonly referred to as the mellowing period. For each stabilised soil, a nominal mellowing period of 24 hour lapsed prior to testing.

On completion of mellowing, samples were remixed, sieved through a 20mm sieve and then compacted in a 1-litre mould, using a 2.5 kg rammer. MCVs were also evaluated following the normal test procedures. To enable the generation of air void content data, particle density testing was undertaken on representative sub-samples, following the gas jar method set out in BS 1377. On completion of testing, the data were used to identify the OMC and the associated MCV of each Class 9D material.

During the second preparation stage, larger samples of each the Class 9D materials were prepared at moisture contents in excess of OMC, i.e. at moisture contents which, when compacted using the standard laboratory compactive effort, would result in compacted samples with air void contents below the upper limit of 5%, specified for lime stabilised capping in HA 74/95 (DMRB 4.1.6). Samples of the Class 7E soils were prepared at appropriate moisture contents, stabilised and mellowed following the procedures used in the initial preparation stage. For each Class 9D material, two sets of CBR specimens were made up for testing after 7 days, 28 days and long-term; in total, six CBR specimens of each Class 9D material were prepared using standard laboratory compaction. Material for each standard test specimen was compacted in a CBR mould in three layers using 62 blows per layer of the 2.5kg rammer.

To assess the effect of states of compaction on the swell potential of lime stabilised soils, additional pairs of CBR specimens of each Class 9D stabilised soil were prepared at higher air void contents. Measured quantities of the stabilised soils were compacted in CBR moulds using the 2.5kg rammer and an appropriate number of blows; a target of 10 to 15% air void content was selected to replicate a very poor state of compaction, and a target of 7 to 9% selected to replicate a state of compaction poorer than the state of compaction associated with the maximum 5% air void content requirement for lime stabilised capping, specified in HA 74/95 (DMRB 4.1.6). Pairs of CBR specimens of all seven stabilised soils were prepared at the high air void content, and pairs of CBR specimens of stabilised Gault and Kimmeridge Clays were prepared at the mid air void content.

On completion of preparation of the CBR specimens, the moulds were sealed top and bottom and allowed to dry-cure at room temperature. After 3 days, the specimens were placed in a water bath, at a temperature ranging between 18 and 20^{o}C, and allowed to soak until required for 7, 28 day or long-term CBR testing. During soaking, the swell of each sample was measured following the procedures specified in BS 1924 (BSI, 1990a) and HA 74/95 (DMRB 4.1.6).

To highlight the effect of the length of the dry-curing period on long-term swell and strength, a supplementary pair of stabilised Gault Clay CBR specimens were prepared using standard laboratory compaction, and dry-cured in sealed CBR moulds for approximately 50% of the total long term curing period, prior to being placed in the water bath and monitored for swell.

5 Results

5.1 Compaction

The results of laboratory compaction testing of the stabilised soils are presented in Tables 2a and 2b. As a rule of thumb, it is worth noting that the decrease in percentage moisture content resulting in the addition of quicklime to the Class 7E soils was very similar to the percentage lime addition. As with many lime stabilised materials, the classical, peaked standard compaction curves (Figures 3a and 3b) were not evident for any of the materials, and hence the moisture content acceptability data for the material being prepared for CBR testing were selected on the basis of achieving an air void content of less than 5%.

The MCV calibrations (Figures 4a and 4b) were used to convert the moisture acceptability data to a maximum limit of MCV for each stabilised material. Following preparation of the large stabilised samples of each soil, MCV compliance checks were undertaken to confirm that the materials were at MCVs below these limits. In agreement with advice in HA 74/95 (DMRB 4.1.6), which suggests that the MCV at OMC varies between 12 and 14, the MCVs of the stabilised materials, prepared at moisture contents slightly wet of OMC, ranged from 11.0 to 13.4.

For each Class 9D material, the dry densities and associated air void contents for each of the three pairs of CBR specimens prepared using standard laboratory compaction (Tables 3a, 3b, 3c and 3d) showed good agreement. The mean air void contents for the stabilised Lower Lias, London, Gault, Weald and Kimmeridge Clay specimens were within the 1 to 2% range. The mean air void content was slightly higher for the stabilised Mercia Mudstone specimens (2.8%) and slightly lower for the stabilised Oxford Clay specimens (0.12%). The dry densities and air void contents of the pairs of CBR specimens prepared to replicate a very poor state of compaction showed reasonably good consistency between pairs, and had a mean air void content of 13.6%. Likewise, pairs of CBR specimens prepared to replicate a state of compaction slightly poorer that the minimum requirement also showed good consistency between pairs, and had a mean air void content of 8.7%.

To summarise, the ‘standard’ CBR specimens were prepared at states of compaction considerably better than the minimum requirement specified in HA 74/95 (DMRB 4.1.6); the ‘mid’ CBR specimens were prepared at states of compaction which would be unacceptably poorer than

Table 2a BS1377 2.5kg rammer test and MCV data (24 hour mellowing)

Sample details		*Class 7E*	*Class 9D*					
Material	*Test level*	*Moisture content (%)*	*Immediate [1] moisture content (%)*	*MCV*	*Moisture content (%)*	*Dry density (Mg/m^3)*	*Particle density (Mg/m^3)*	*Air void content (%)*
Mercia Mudstone + 3.7% SG60 quicklime	1	20.9	18.4	15.0	18.3	1.714	2.70	5.1
	2	23.4	20.9	12.8	20.9	1.685		2.4
	3	25.3	22.7	11.0	22.4	1.658		1.4
	4	28.5	25.4	8.6	25.7	1.537		3.5
	5	30.1	27.1	7.2	26.8	1.540		1.7
Oxford Clay + 6.2% SG60 quicklime	1	33.0	27.8	14.4	27.8	1.485	2.62	2.1
	2	35.0	29.5	13.8	29.5	1.454		1.6
	3	37.5	32.1	11.9	33.0	1.408		-0.2
	4	40.1	33.7	11.5	33.7	1.360		2.3
	5	50.0	43.5	7.7	43.5	1.209		1.3
Lower Lias Clay + 5.6% SG60 quicklime	1	25.1	19.8	15.0	19.7	1.624	2.70	7.8
	2	29.1	25.1	13.8	25.1	1.553		3.6
	3	34.6	31.7	10.8	31.3	1.443		1.3
	4	39.6	37.4	8.2	37.6	1.306		2.5
	5	54.9	42.8	5.5	42.8	1.209		3.5
London Clay [2] + 2.5% SG60 quicklime	1	29.9	27.0	17.8	27.1	1.379	2.69	11.4
	2	34.2	31.2	15.4	31.1	1.345		8.2
	3	38.9	35.0	13.4	34.7	1.297		6.8
	4	44.2	39.9	11.9	39.9	1.262		2.7

[1] Moisture content sampled immediately after the addition of lime,
[2] Data as reported by MacNeil (1995).

Table 2b BS1377 2.5kg rammer test and MCV data (24 hour mellowing)

Sample details		*Class 7E*	*Class 9D*					
Material	*Test level*	*Moisture content (%)*	*Immediate [1] moisture content (%)*	*MCV*	*Moisture content (%)*	*Dry density (Mg/m^3)*	*Particle density (Mg/m^3)*	*Air void content (%)*
Gault Clay + 6.0% SG60 quicklime	1	33.0	29.6	15.5	29.2	1.358	2.65	9.1
	2	38.1	34.1	14.7	33.4	1.331		5.4
	3	52.8	46.6	10.3	47.0	1.167		1.1
	4	na	55.9	9.4	55.6	1.052		1.9
	5	na	56.9	9.0	56.4	1.046		1.5
Weald Clay + 3.3% SG60 quicklime	1	21.2	19.0	13.8	18.8	1.672	2.69	6.4
	2	25.5	23.0	11.5	22.9	1.637		1.7
	3	32.0	27.8	7.7	27.7	1.517		1.6
	4	na	33.5	5.2	33.3	1.393		1.9
	5	na	35.3	5.6	35.1	1.351		2.5
Kimmeridge Clay + 6.5% SG60 quicklime	1	27.5	22.4	13.4 [2]	21.5	1.408	2.65	16.6
	2	33.8	28.1	17.4	28.0	1.340		11.9
	3	39.8	33.3	14.5	33.2	1.329		5.7
	4	40.2	35.0	14.2	35.0	1.283		6.7
	5	49.9	43.8	10.7	44.1	1.189		2.6

[1] Moisture content sampled immediately after the addition of lime.
[2] On dry leg of MCV calibration.

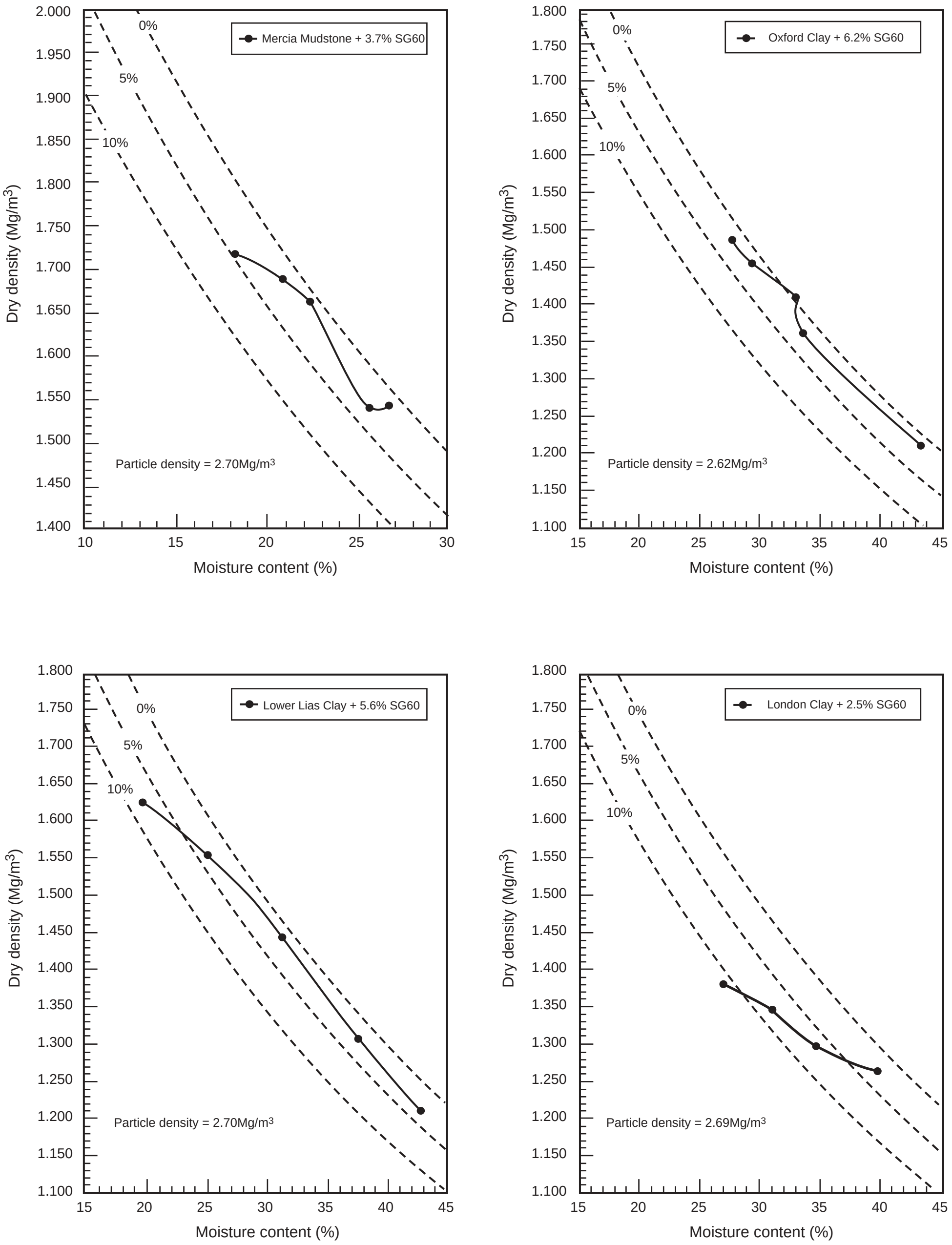

Figure 3a BS 1377 compaction curves for Class 9D materials (24hr mellowing)

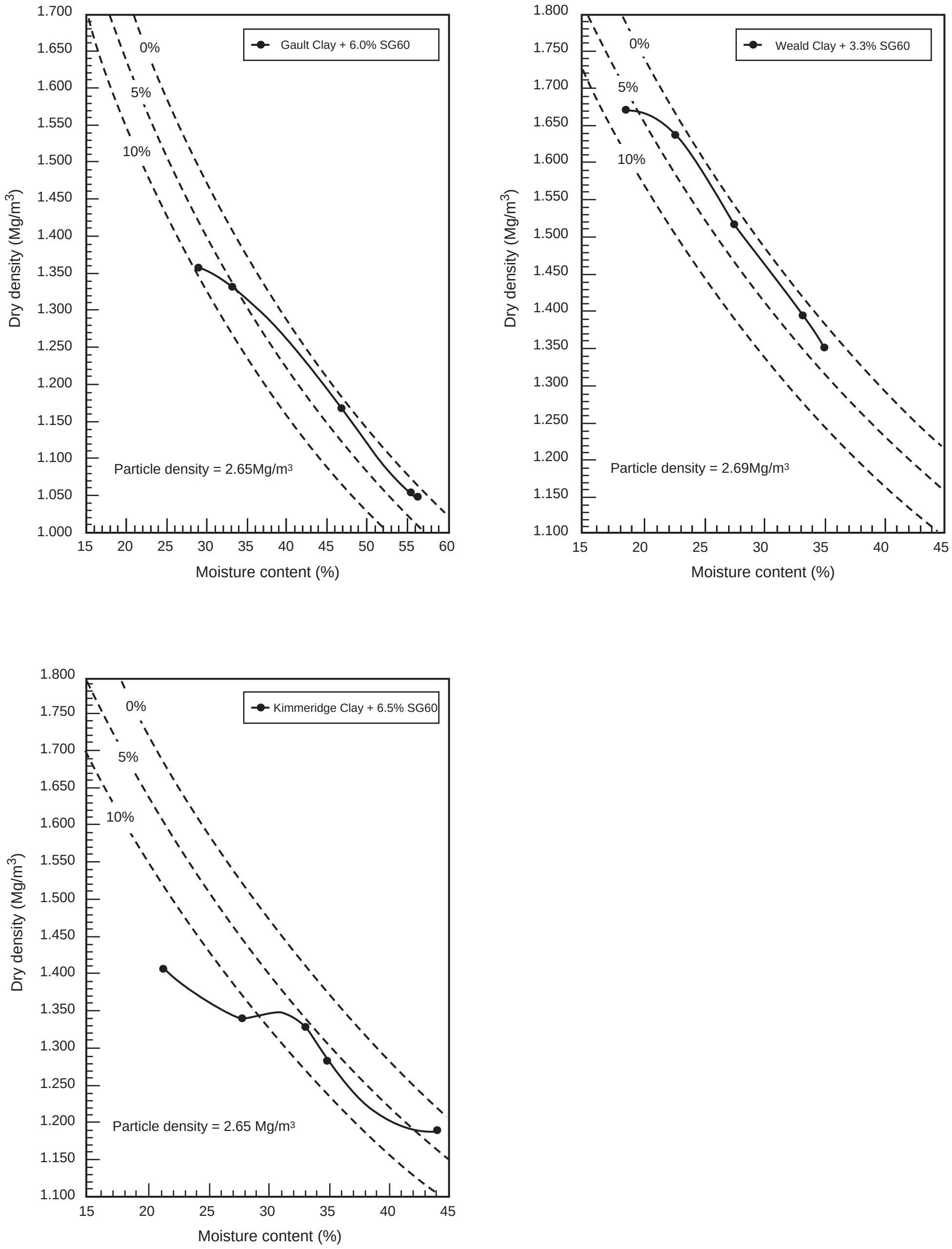

Figure 3b BS 1377 compaction curves for class 9D materials (24hr mellowing)

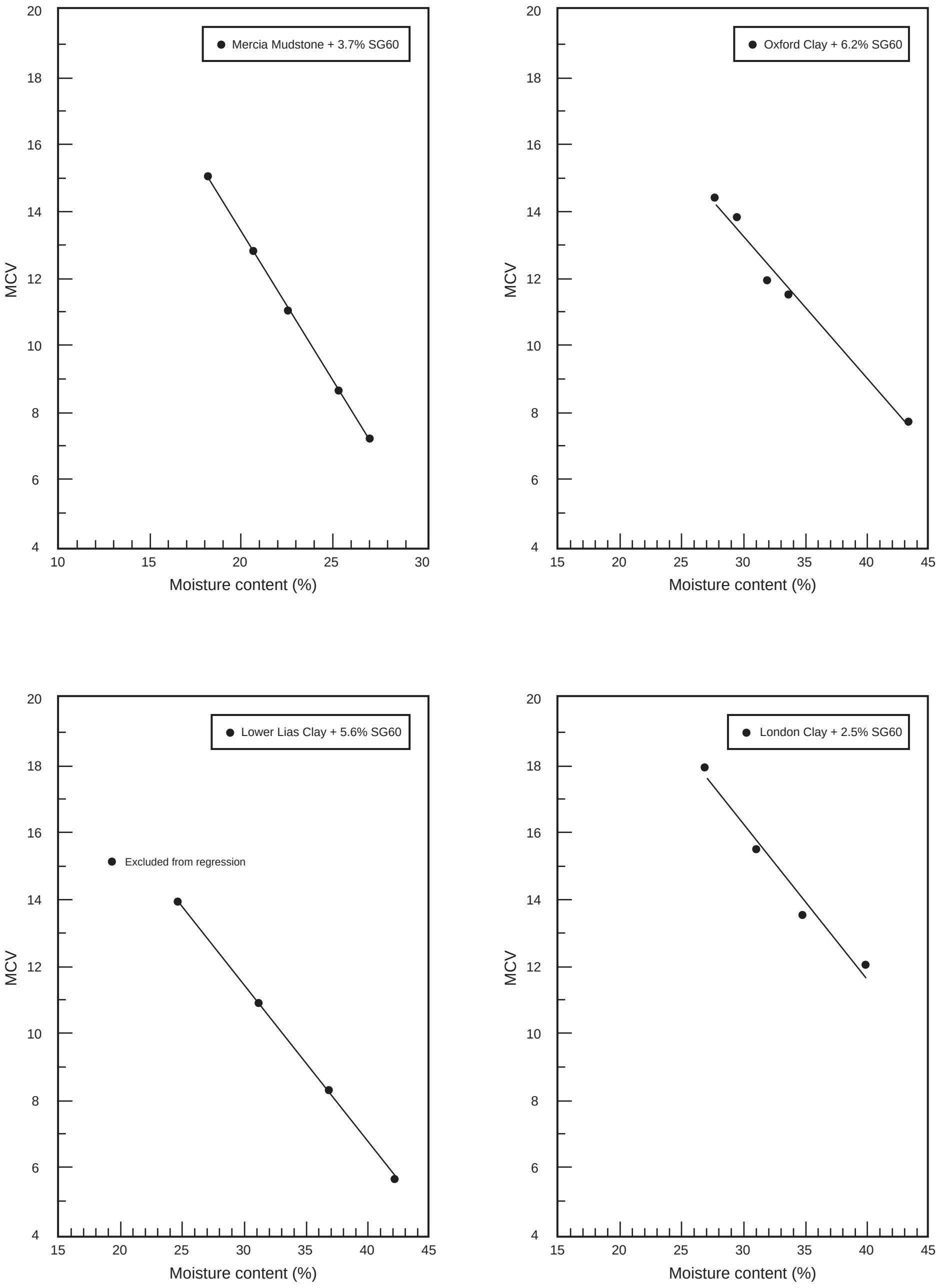

Figure 4a MCV calibrations for Class 9D materials (24hr mellowing)

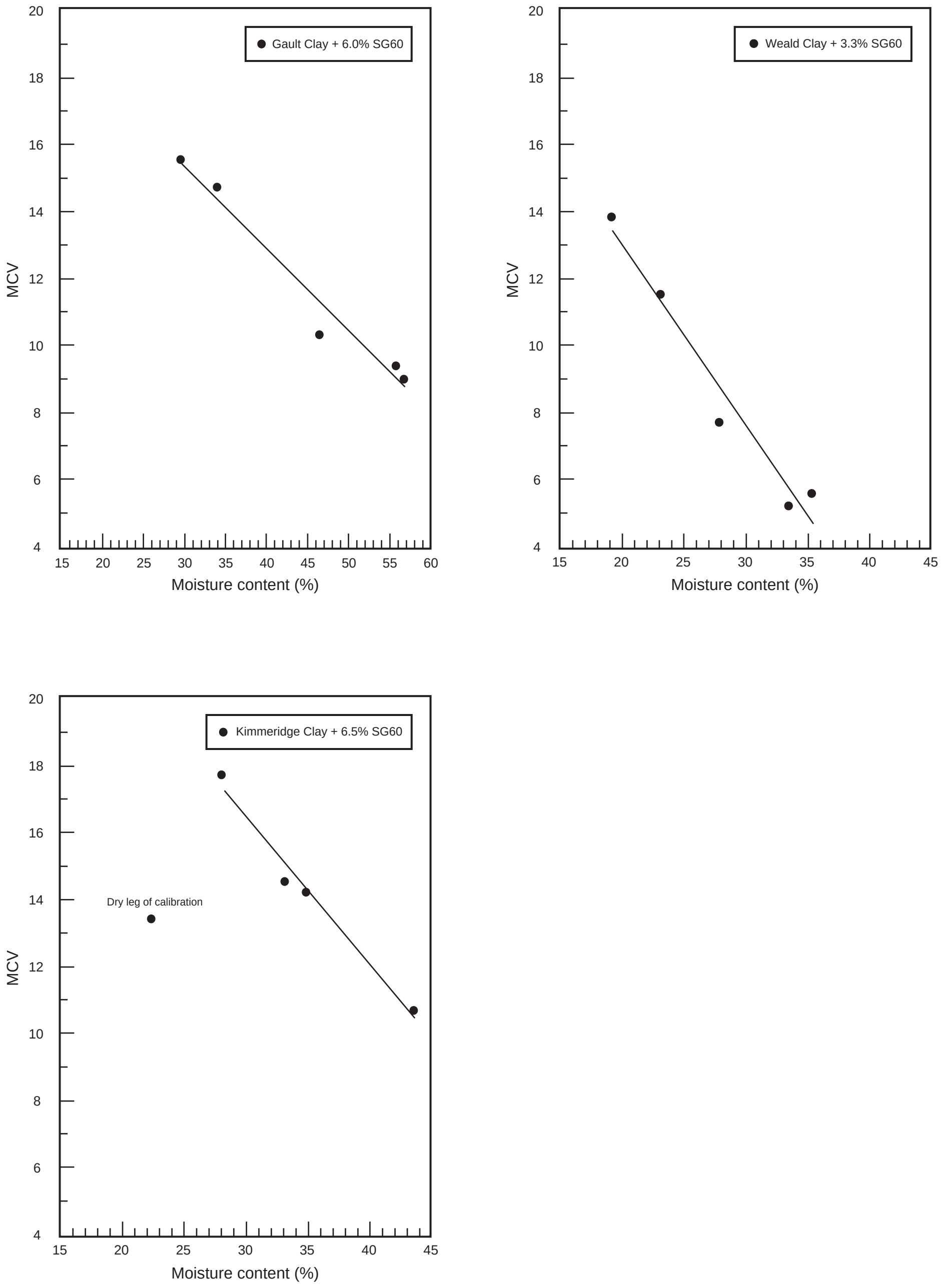

Figure 4b MCV calibrations for Class 9D materials (24hr mellowing)

Table 3a Sample preparation and CBR data

Sample details		*Sample preparation*						*CBR data*				
									Moisture content		*CBR*	
Material	*Sample ID*	*Class 7E moisture content (%)*	*Class 9D moisture content (%)*	*MCV*	*Moisture content (%)*	*Dry density (Mg/m^3)*	*Air voids (%)*	*Total curing time (days)*	*Top (%)*	*Base (%)*	*Top (%)*	*Base (%)*
Mercia Mudstone + 3.7% SG60 quicklime	MM/37/71	22.6	19.8	11.9	19.4	1.714	3.2	7	20.5	20.6	19	24
	MM/37/72					1.723	2.7		20.9	20.7	20	24
	MM/37/281					1.729	2.3	28	20.4	20.1	22	30
	MM/37/282					1.714	3.2		32.4	21.9	25	27
	MM/37/LT1					1.723	2.7	401	20.8	19.8	75	120
	MM/37/LT2					1.723	2.7		20.3	19.5	100	100
	MM/37/LTH1	22.7	–	–	19.8	1.515	13.9	189	24.0	25.3	29	23
	MM/37/LTH2					1.486	15.5		25.0	26.3	21	21
Oxford Clay+ 6.2% SG60 quicklime	OXC/62/71	37.6	31.5	12.7	31.5	1.420	1.1	7	32.1	31.4	16	17
	OXC/62/72					1.448	-0.8		31.5	31.5	16	17
	OXC/62/281					1.436	0.0	28	31.7	31.2	21	24
	OXC/62/282					1.433	0.2		32.0	31.2	20	24
	OXC/62/LT1					1.437	-0.1	401	31.5	31.0	75	120
	OXC/62/LT2					1.431	0.3		32.0	31.4	90	120
	OXC/62/LTH1	38.2	–	–	31.7	1.248	12.8	189	39.4	39.2	20	15
	OXC/62/LTH2					1.238	13.5		36.6	38.1	27	15

Table 3b Sample preparation and CBR data

Sample details		*Sample preparation*						*CBR data*				
									Moisture content		*CBR*	
Material	*Sample ID*	*Class 7E moisture content (%)*	*Class 9D moisture content (%)*	*MCV*	*Moisture content (%)*	*Dry density (Mg/m^3)*	*Air voids (%)*	*Total curing time (days)*	*Top (%)*	*Base (%)*	*Top (%)*	*Base (%)*
Lower Lias Clay + 5.6% SG60 quicklime	LL/56/71	32.0	27.4	11.0	27.3	1.535	1.3	7	27.6	27.5	11	13
	LL/56/72					1.526	1.8		27.2	26.7	13	14
	LL/56/281					1.528	1.7	28	26.9	26.8	18	20
	LL/56/282					1.527	1.8		27.6	26.8	17	20
	LL/56/LT1					1.527	1.8	234	27.7	27.7	55	65
	LL/56/LT2					1.519	2.3		27.8	27.2	65	65
	LL/56/LTH1	31.7	–	–	26.7	1.356	13.6	189	29.6	31.3	35	25
	LL/56/LTH2					1.343	14.5		29.6	33.3	28	19
London Clay + 2.5% SG60 quicklime	LC/25/71	39.9	37.2	12.3	37.3	1.319	1.8	7	36.9	36.1	15	20
	LC/25/72					1.327	1.2		37.1	36.3	14	21
	LC/25/281					1.334	0.7	28	37.0	37.0	16	26
	LC/25/282					1.300	3.2		36.0	32.5	17	27
	LC/25/LT1					1.319	1.8	234	38.8	37.7	12	30
	LC/25/LT2					1.320	1.7		38.5	37.7	18	35
	LC/25/LTH1	40.9	–	–	37.0	1.169	13.3	189	47.0	43.2	13	15
	LC/25/LTH2					1.153	14.5		49.8	44.6	8.5	16

Table 3c Sample preparation and CBR data

Sample details		*Sample preparation*						*CBR data*				
									Moisture content		*CBR*	
Material	*Sample ID*	*Class 7E moisture content (%)*	*Class 9D moisture content (%)*	*MCV*	*Moisture content (%)*	*Dry density (Mg/m³)*	*Air voids (%)*	*Total curing time (days)*	*Top (%)*	*Base (%)*	*Top (%)*	*Base (%)*
Gault Clay + 6.0% SG60 quicklime	GC/60/71	45.2	39.3	13.4	39.6	1.286	0.6	7	40.9	40.3	7.0	16
	GC/60/72					1.268	2.0		40.9	40.4	7.5	15
	GC/60/281					1.302	-0.7	28	42.5	40.7	14	18
	GC/60/282					1.275	1.4		44.2	40.0	8.5	20
	GC/60/LT1					1.257	2.8	182	43.9	40.6	15	50
	GC/60/LT2					1.266	2.1		44.4	40.3	20	50
	GC/60/LTM1					1.180	8.7	269	47.5	43.6	22	35
	GC/60/LTM2					1.195	7.5		50.5	44.4	27	40
	GC/60/LTH1					1.138	12.0	192	57.8	50.5	13	24
	GC/60/LTH2					1.152	10.9		51.8	54.0	14	24
	GC/60/LTD1					1.263	1.9	192[1]	40.7	40.0	50	24
	GC/60/LTD2					1.266	1.7		40.4	40.3	45	24

[1] *Dry cured for 101 days, wet cured for 91 days.*

Table 3d Sample preparation and CBR data

Sample details		*Sample preparation*						*CBR data*				
									Moisture content		*CBR*	
Material	*Sample ID*	*Class 7E moisture content (%)*	*Class 9D moisture content (%)*	*MCV*	*Moisture content (%)*	*Dry density (Mg/m³)*	*Air voids (%)*	*Total curing time (days)*	*Top (%)*	*Base (%)*	*Top (%)*	*Base (%)*
Weald Clay + 3.3% SG60 quicklime	WC/33/71	24.7	22.1	11.7	22.0	1.651	2.4	7	22.0	22.3	20	21
	WC/33/72					1.645	2.7		22.2	23.6	17	21
	WC/33/281					1.673	1.1	28	22.5	22.5	28	25
	WC/33/282					1.659	1.9		22.3	22.3	28	28
	WC/33/LT1					1.670	1.2	182	22.4	21.7	50	65
	WC/33/LT2					1.670	1.2		23.0	22.0	50	60
	WC/33/LTH1	24.7	–	–	21.7	1.458	14.1	189	26.0	27.3	17	13
	WC/33/LTH2					1.462	13.9		41.7	27.1	13	16
Kimmeridge Clay + 6.5% SG60 quicklime	KC/65/71	44.5	38.0	12.0	38.2	1.287	2.2	7	38.9	38.4	10	15
	KC/65/72					1.290	2.0		38.4	37.7	12	17
	KC/65/281					1.291	1.9	28	39.9	38.2	12	30
	KC/65/282					1.287	2.2		39.5	38.2	14	24
	KC/65/LT1					1.305	0.9	182	38.8	38.0	50	65
	KC/65/LT2					1.288	2.1		39.3	37.5	35	65
	KC/65/LTM1					1.190	9.6	183	40.7	44.1	40	28
	KC/65/LTM2					1.198	8.9		44.7	44.6	30	30
	KC/65/LTH1					1.130	14.1	183	46.0	47.8	24	18
	KC/65/LTH2					1.137	13.6		48.7	46.7	17	19

current requirements; and the ‘high’ CBR specimens were prepared at states of compaction which would be wholly unacceptable in terms of current requirements.

5.2 Strength

The 7-day, 28-day and long-term CBR data are presented in Tables 3a, 3b, 3c and 3d. With the exception of the CBRs for the stabilised Gault Clay specimens, all 7-day CBRs were in excess of the minimum 8% value specified in HA 74/95 (DMRB 4.1.6). In terms of achieving the design requirements of an average CBR of greater than 15% at 7 days, the lime additions applied to the Mercia Mudstone, Oxford, London and Weald Clays met this criterion. For capping mix design purposes, slightly higher lime additions would be required to guarantee average 7-day CBRs greater than 15% for the Lower Lias, Gault and Kimmeridge Clays. This is not particularly significant, as the lime additions used in the trial were based on the ICL value of each soil plus 0.5%. Lime additions required to meet the strength criteria would normally be derived from a more comprehensive suite of laboratory CBR tests.

For all materials, the CBR data are plotted in Figures 5a and 5b. For the standard CBR specimens (labelled soil initials/lime addition/curing period and mould number), which comprise the first six twin bars on each plot, the results show an increase in strength over the long-term curing period. In particular, the increase in the long-term CBR for stabilised Mercia Mudstone and Oxford Clay were dramatic, and the increases for stabilised Lower Lias, Weald and Kimmeridge Clays were appreciable. The increase in long-term CBR for both the stabilised Gault and London Clays were only modest.

In general terms, the data for the long-term CBR specimens prepared at mid and high air void contents (labelled M and H, respectively) tended to be slightly higher than the standard 7-day CBRs, typically equivalent to the standard 28-day CBRs and significantly less than the standard long-term CBRs. Generally, the long-term CBRs of the specimens prepared at mid air void contents were marginally higher than those of specimens prepared at high air void contents.

The CBR data for the stabilised Gault Clay CBR specimens which were dry-cured for an extended period (LTD1 and LTD2 in Table 3c) were broadly similar to the equivalent specimens which were cured in the standard manner. The only notable difference was that the top surfaces of the extended dry-cured specimens produced higher CBRs; this is consistent with improved bonding taking place during dry-curing, resulting in a more durable material, which did not suffer significant water ingress during soaking.

5.3 Swell

For each Class 9D material, swell plots for individual CBR specimens are presented in Figures 6 to 12. Long-term data were recorded for a nominal 6 month period. When variations in the long-term swell rate were observed, recording was extended to in excess of 12 months.

The average swell values for each pair of CBR specimens are summarised in Table 4. Significantly, none of the 62 specimens tested had a swell value in excess of the 10mm upper limit specified in HA 74/95 (DMRB 4.1.6), and only one specimen (GC/60/LTH1) had a swell value in excess of the upper average limit of 5mm quoted in HA 74/95.

A comparison of 7-day with 28-day swell data for standard compaction indicates that swelling was continuing up to 28 days. Similarly, a comparison of 28-day with the long-term swell data shows that, with the exception of the Kimmeridge Clay, swelling continued to occur well beyond the standard test periods of 28 and 56 days (HA 74/95). Specimens of Lower Lias, London, and Weald Clays showed increases in swell rates beyond the standard test periods, and specimens of Mercia Mudstone, Oxford and Kimmeridge Clays showed small and consistent decreases in swell rates beyond the standard test periods. However, in absolute terms, the differences between the 28-day and the long-term swell data were all small.

In terms of non-standard compaction, all long-term Gault and Kimmeridge Clay specimens prepared at ‘mid’ air void contents swelled considerably more than the equivalent specimens prepared at standard air void contents. With the exception of the Mercia Mudstone, all pairs of long-term specimens prepared at ‘high’ air void contents also swelled considerably more than the equivalent specimens prepared at standard air void contents.

Table 4 Swell summary data

	Average swell (mm)					
Class 9D	*7 days*	*28 days*	*Long-term (standard air void content)*	*Long-term (mid air void content)*	*Long-term (high air void content)*	*Extended dry cure long-term (standard air void content)*
Mercia Mudstone	0.12	0.40	0.63	–	0.47	–
Oxford Clay	0.29	0.33	0.66	–	2.01	–
Lower Lias Clay	0.19	0.27	0.42	–	0.79	–
London Clay	0.41	0.55	0.83	–	2.70	–
Gault Clay	0.60	2.49	2.96	3.90	4.98	0.87
Weald Clay	0.14	0.29	0.62	–	0.50	–
Kimmeridge Clay	0.90	1.54	1.05	2.75	3.87	–

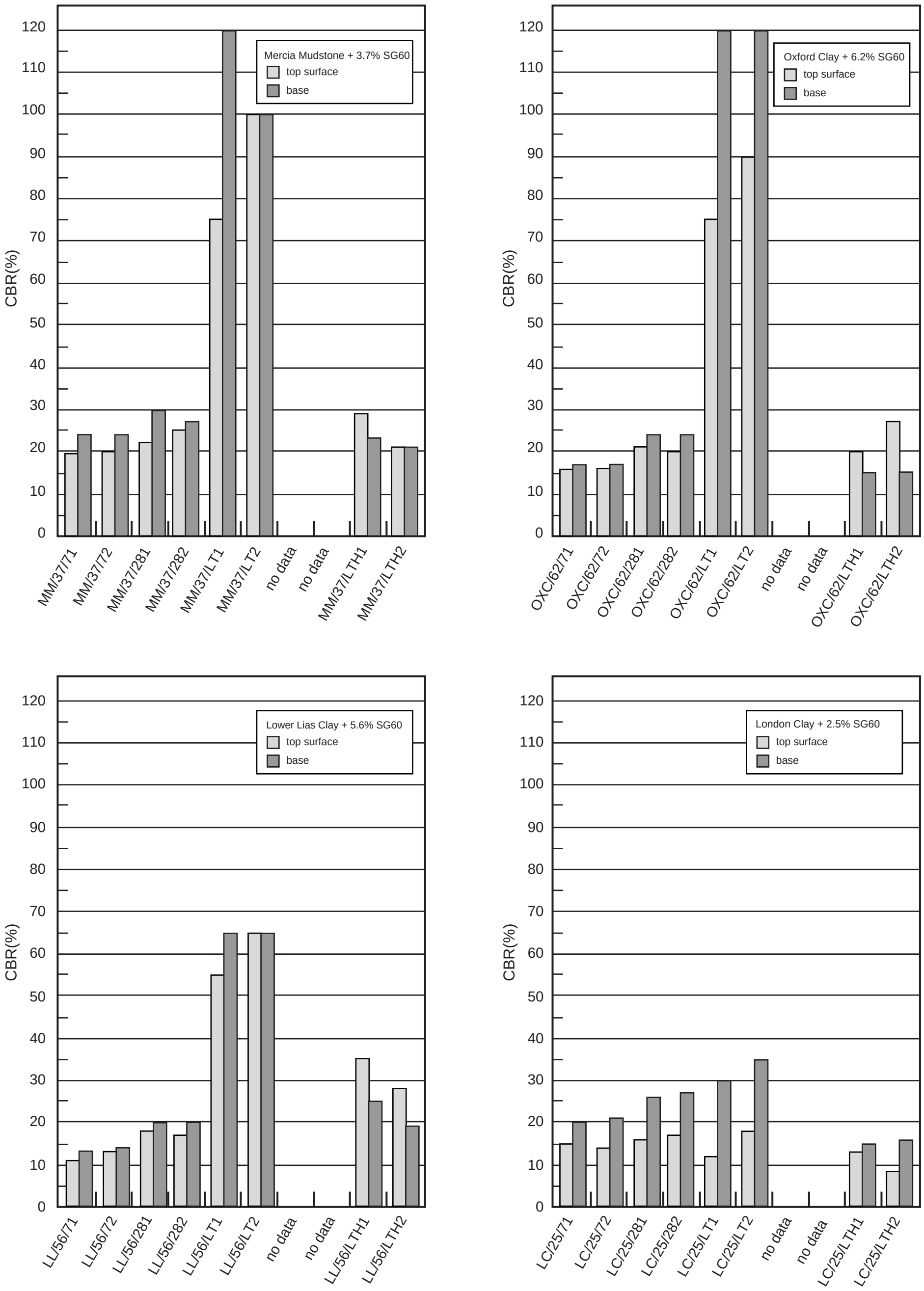

Figure 5a CBR data plots for Class 9D materials

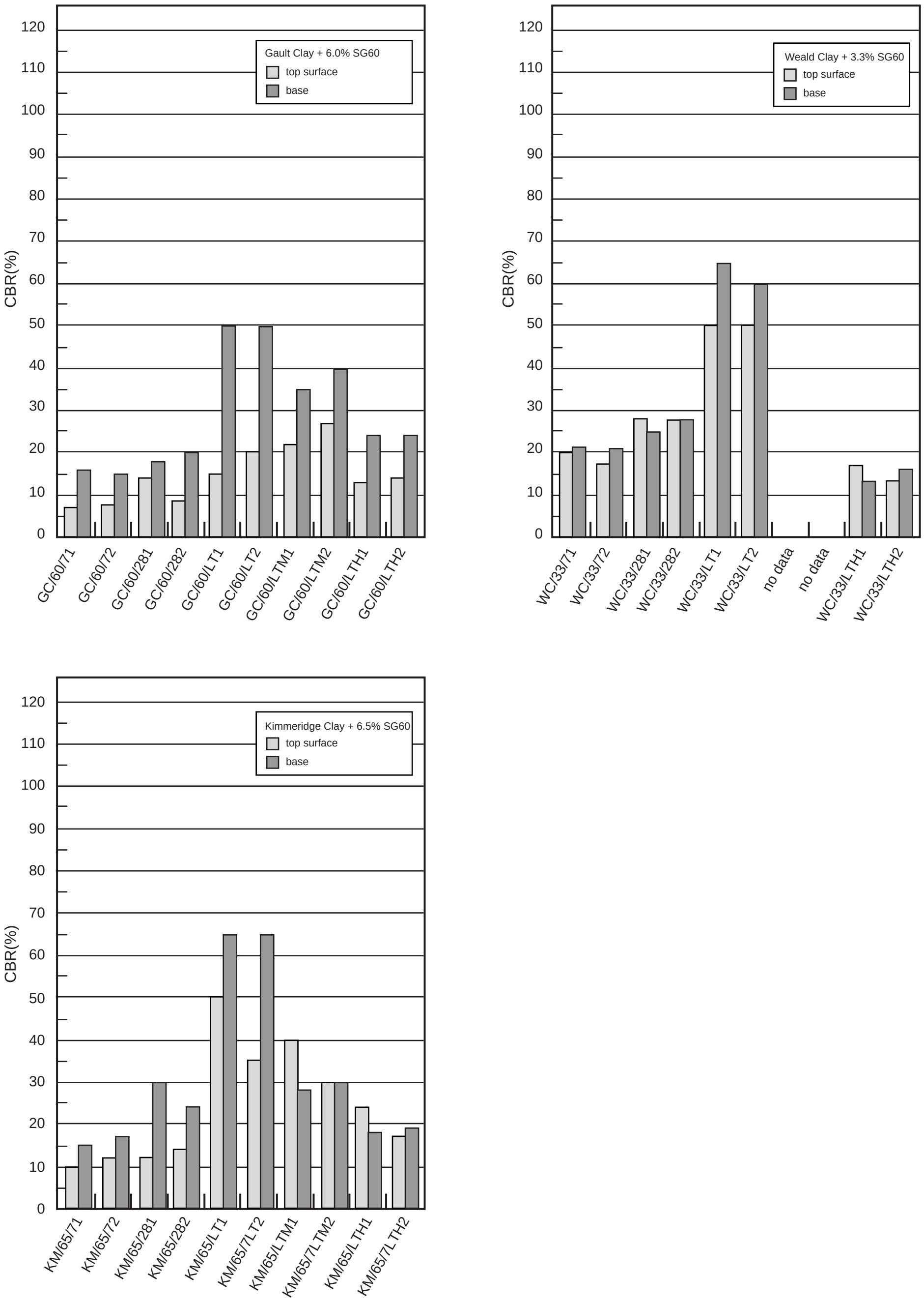

Figure 5b CBR data plots for Class 9D materials

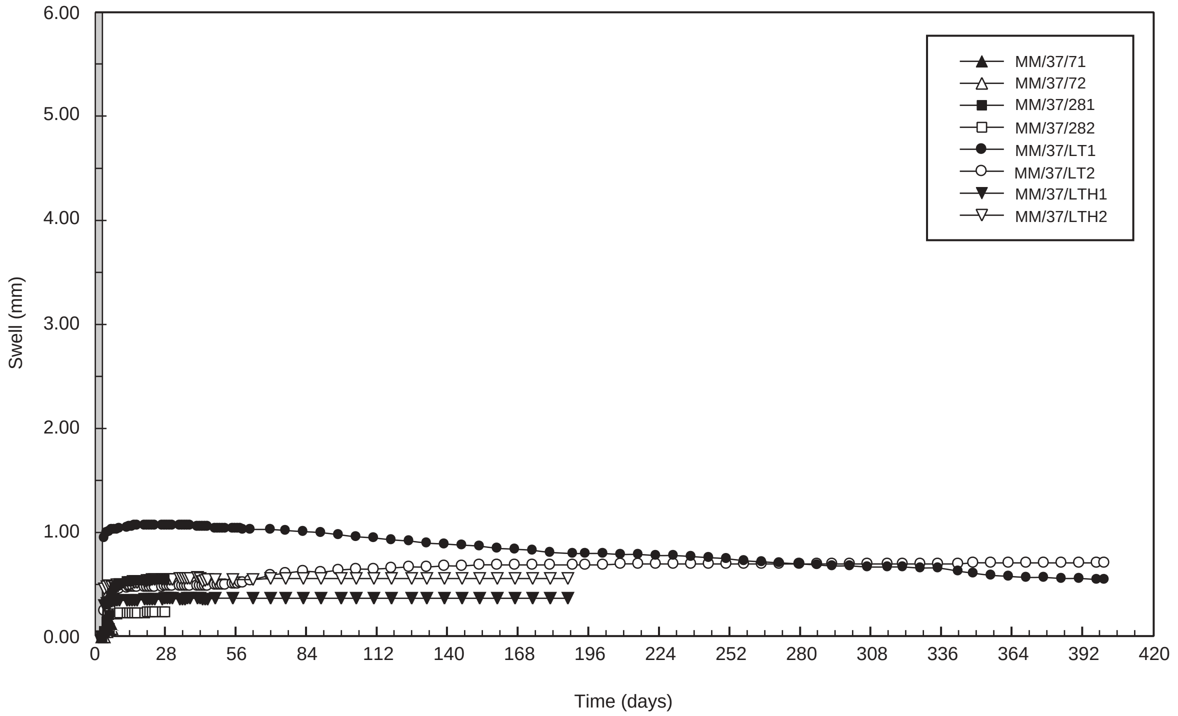

Figure 6 Swell plot for Mercia Mudstone + 3.7% SG60

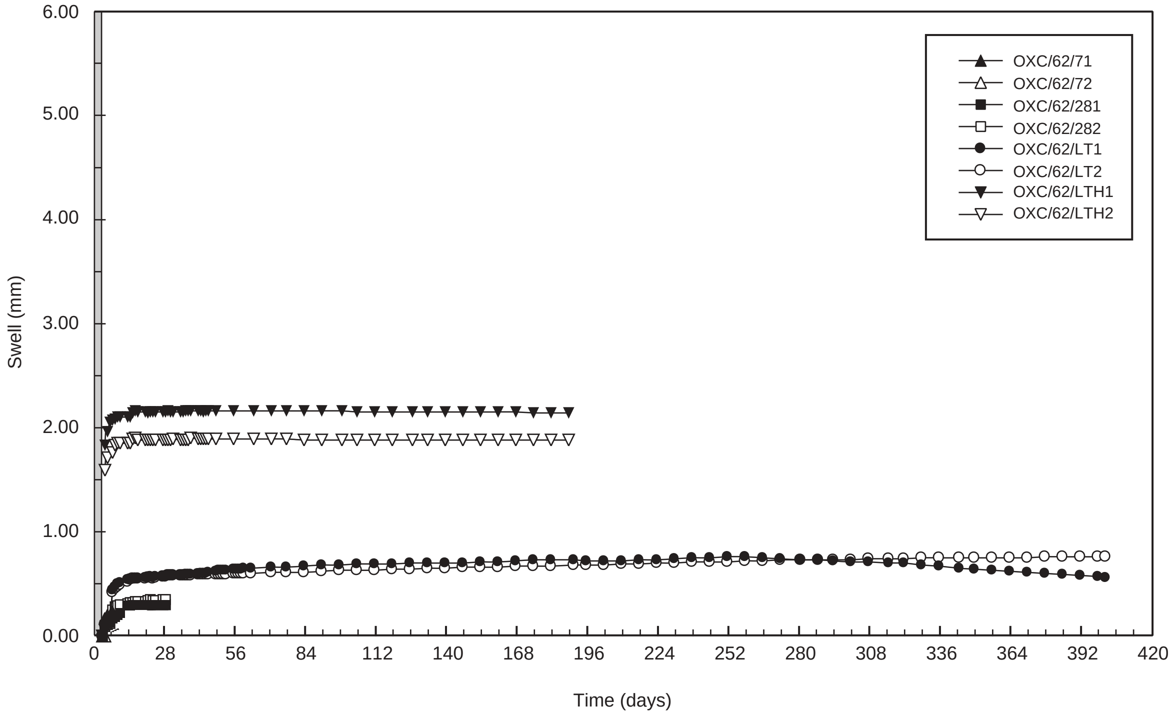

Figure 7 Swell plot for Oxford Clay + 6.2% SG60

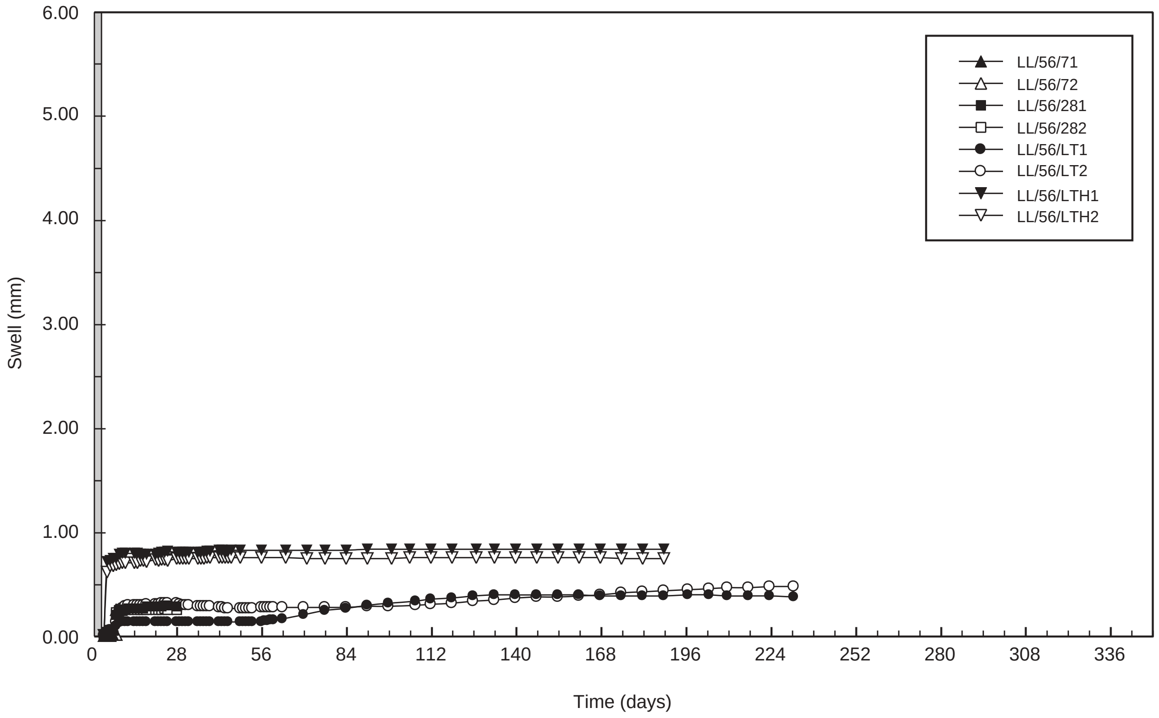

Figure 8 Swell plot for Lower Lias Clay + 5.6% SG60

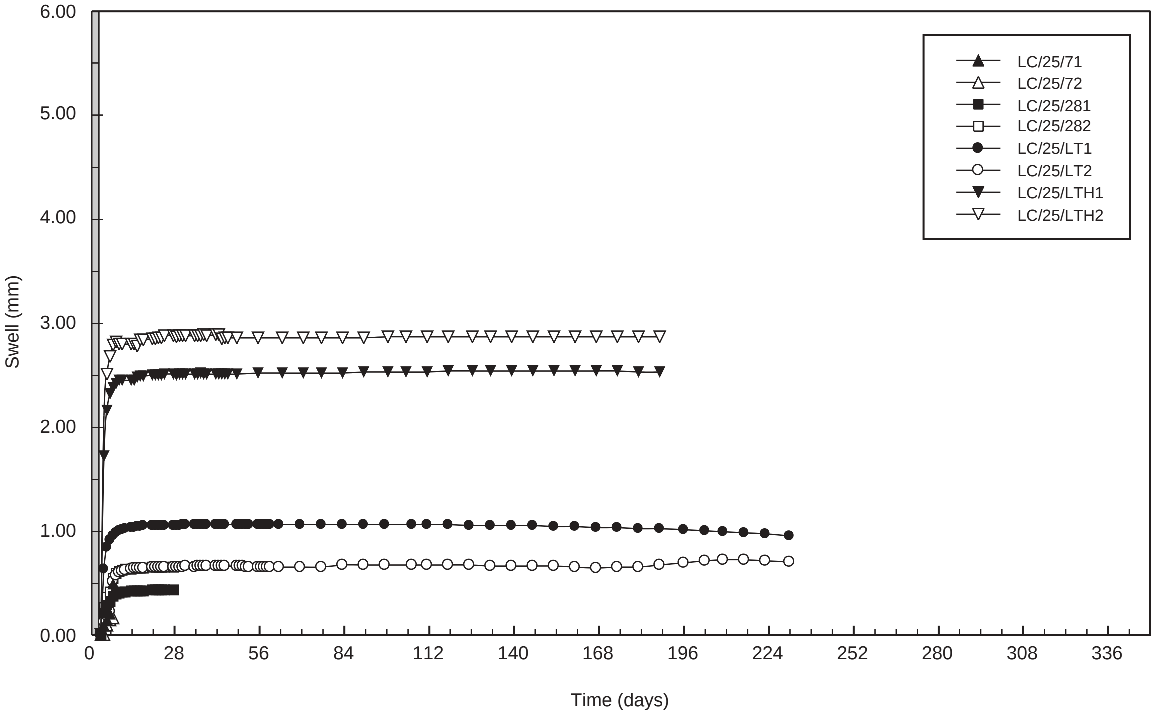

Figure 9 Swell plot for London Clay + 2.5% SG60

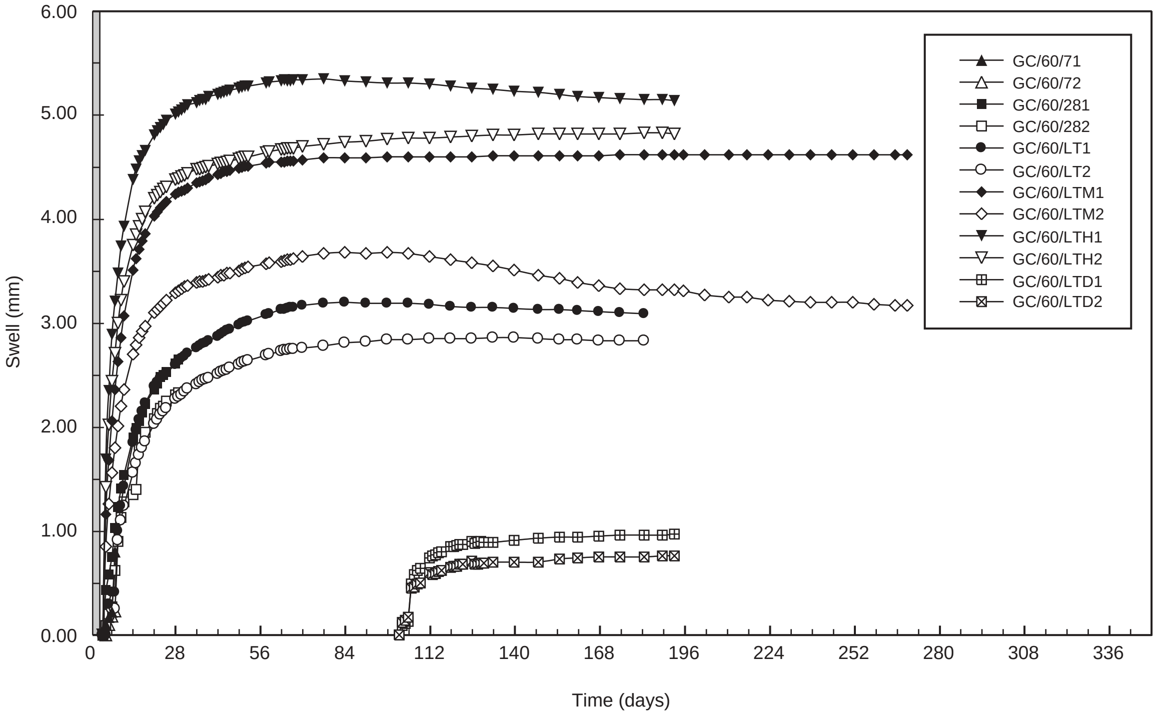

Figure 10 Swell plot for Gault Clay + 6.0% SG60

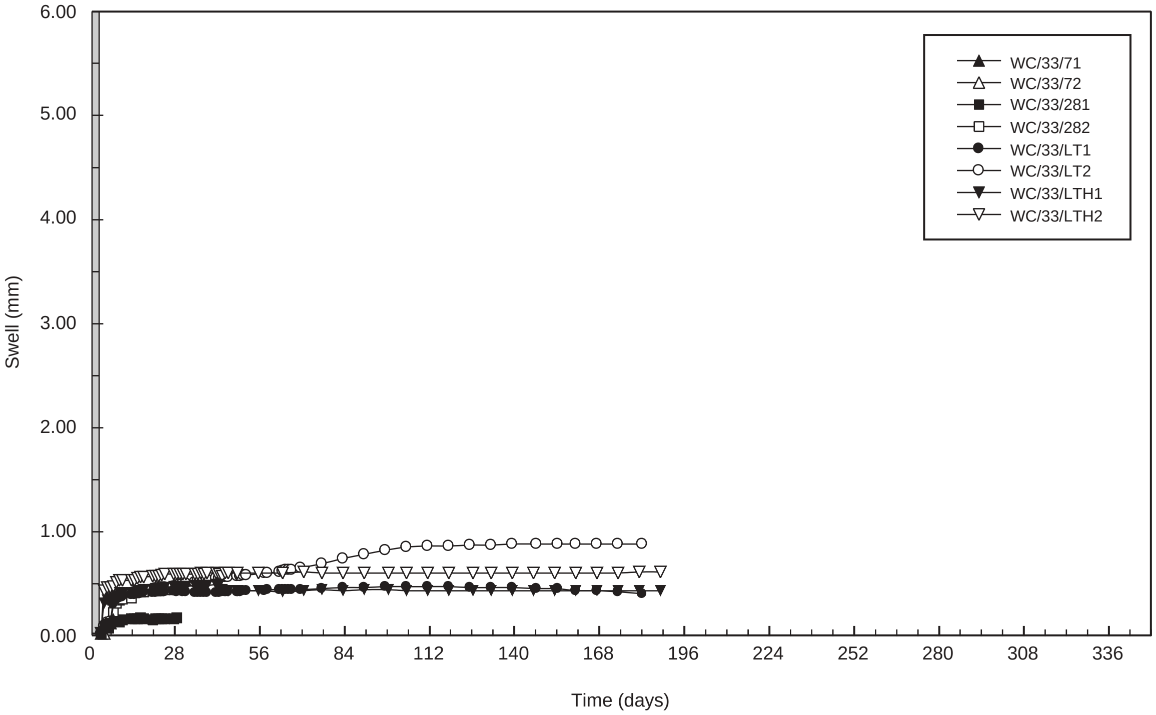

Figure 11 Swell plot for Weald Clay + 3.3% SG60

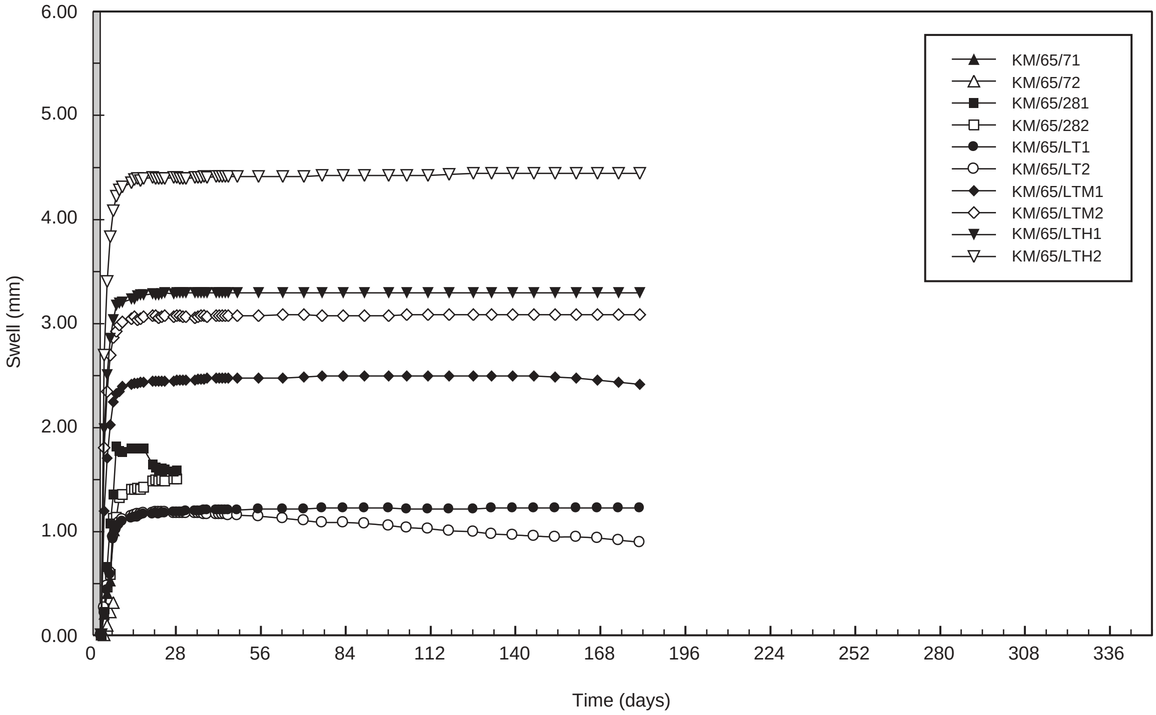

Figure 12 Swell plot for Kimmeridge Clay + 6.5% SG60

A summary of the swell and air void content data is presented in Figure 13. The lines of best fit (geometric or linear) highlight two distinct swell behaviours of the Class 9D materials. The long-term swell behaviour of the lime stabilised Mercia Mudstone, Lower Lias and Weald Clays was not significantly influenced by an increase in air void content. However, the long-term swell behaviour of the lime stabilised Oxford, London, Gault and Kimmeridge Clays were significantly influenced by air void content. Of all Class 9D materials tested, Gault Clay was by far the most susceptible to long-term swell.

Confirmation that dry-curing produces a more durable material is highlighted by an average swell value of 0.87mm for the Gault Clay specimens dry-cured for an extended period, compared to an average swell of 2.96mm for the equivalent standard specimens.

6 Discussion

6.1 ICL testing

According to BS 1924 (BSI, 1990a), the Initial Consumption of Lime value of a soil gives an indication of the minimum amount of lime needed to be added to a material to achieve a significant change in its properties. Samples of a soil are mixed with water and different proportions of lime, and the pH of the samples are compared to the pH of a saturated lime solution. The lime addition that results in a pH value equivalent to that of a saturated lime solution is termed the ICL value of the soil.

For acceptance of the pH measurement system, BS 1924 (BSI, 1990a) requires the pH of saturated lime solutions to be within the range 12.35 to 12.45 at 25°C. However, during the tests, the pH values of three saturated lime solutions ranged from 12.94 to 13.08, as measured using a pH measurement system calibrated using pH 10.00 and 12.00 buffers. Previous experience has shown that pH values between 12.4 and 13.0 can be recorded for saturated lime solutions.

As the test aims to ascertain the lime addition which results in a test sample having a pH value equivalent to a saturated lime solution, the measured pH values of saturated solutions of the industry standard SG60 powdered quicklime used in the trials were applied as the defining criteria for the ICL test. It is recommended that BS 1924 (BSI, 1990a) is updated to reflect these findings.

6.2 Development of strength

In general, the additions of quicklime used to stabilise the seven soils used in the trial resulted in Class 9D materials which, when prepared at states of compaction well within the current requirements set out in HA 74/95, resulted in strengths around, or slightly higher than, the acceptability requirement of an average CBR of 15% at 7 days, with no individual test specimen having a CBR less than 8%.

The long-term CBRs of the Class 9D specimens prepared using standard compaction were in excess of the corresponding 28-day CBRs. With the exception of the Class 9D London Clay specimens, which showed only small increases over the long-term curing period, the increase in strength over the long-term curing period ranged from two to four times the 28-day CBRs. This indicated that, for all of the Class 9D materials, the stabilisation reaction continued well beyond the standard suitability and acceptability test period of 28 days. It is interesting to note that, whilst the soaked 28-day CBR test

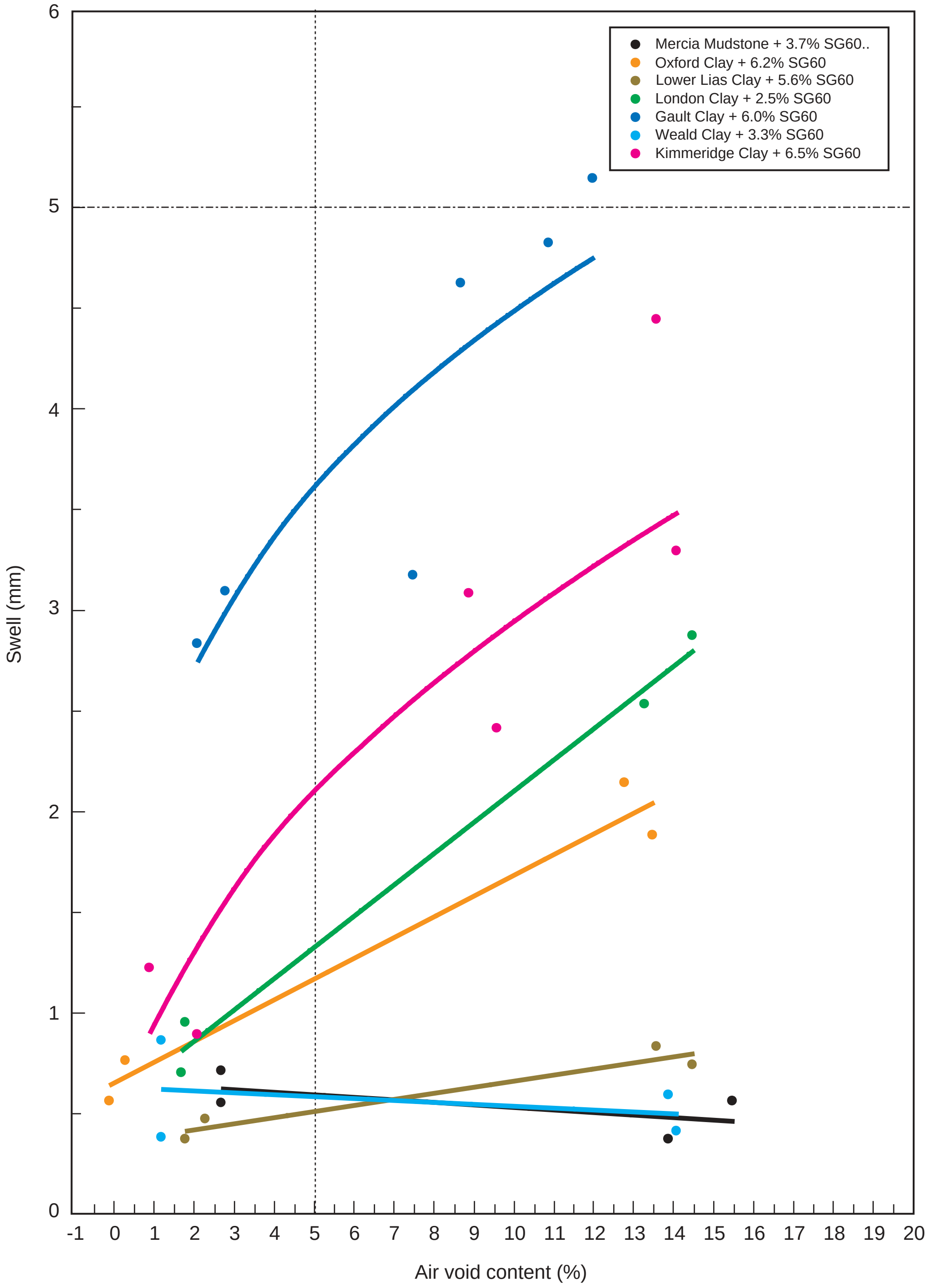

Figure 13 Air void content versus swell

is performed with the aim of verifying the long-term strength and durability of the Class 9D materials, the values obtained from the test underestimate the measured long-term strength gains by a considerable degree. Dumbleton (1962) also reported similar findings for the same seven soil types used in this trial. However, both the 7 and the 28 day tests are important, as they indicate pessimistic strengths which are likely to be achieved during the early stages of the stabilisation reaction, i.e. those applicable during construction of a stabilised capping layer and subsequent layers in a pavement structure. As it is unlikely that Class 9D materials would be inundated with water during construction, the dry *in situ* CBRs would probably comfortably exceed the minimum strength requirement, even with the application of the lime additions used during this trial.

Unsurprisingly, the specimens prepared at poorer states of compaction did not show the long-term strength gains of the specimens prepared using standard compaction. However, it is a significant feature of lime stabilisation that these poorly compacted specimens achieved reasonable CBR values at the end of the long-term curing period.

One particular issue encountered during CBR testing has not been previously reported in the literature on lime stabilisation. During loading of a number of the Class 9D specimens, a bearing capacity type of failure occurred within the surface being tested. The failure (see Figure 14) extended up to a depth of approximately 20mm below the surface and appears similar in shape to the mechanisms shown in standard texts (see, for example, Terzaghi and Peck, 1948). The result of this failure is shown in a CBR plot reproduced in Figure 15. The failure typically resulted in the force at 2.5mm being recorded as approximately twice the force at 5mm. This effect was particularly evident on Class 9D long-term specimens of Oxford, London, Gault and Kimmeridge Clays. As the work done was being used to displace failed material, rather than penetrate the sample, it could be argued that the 'residual' strength data for the 5mm penetration should be discounted from the CBR assessment of these specimens.

6.3 Swell potential

Swell potential of expansive soils is widely recognised to be fundamentally governed by clay mineralogy (Nelson and Miller, 1992). With respect to lime stabilisation, many texts discuss the contribution of the main clay minerals such as the kaolinite group, the mica-like group (including illites) and the smectite group (including the highly expansive montmorillonites) to the swelling reaction (see Section 3). In general, it is concluded that kaolinite rich clays tend to be unreactive, illite rich clays tend to be active, and montmorillonite rich clays tend to be highly active. Skempton (1953) defined the activity of a clay as:

$$\text{Activity } A_c = \frac{\text{Plasticity index}}{\text{\% by weight finer than } 2\mu\text{m}}$$

and suggested $A_c < 0.75$ for inactive clays, $0.75 < A_c < 1.25$ for normal clays, and $A_c > 1.25$ for active clays. In terms of the clay minerals, Bowles (1984) quoted the following activities:

Kaolinite	0.4 - 0.5
Illite	0.5 - 1.0
Montmorillonite	1.0 - 7.0

Details of activity data for the seven cohesive soils used in the trials are presented in Table 1. The values for A_c range from 0.61 for Kimmeridge Clay to 0.94 for Mercia Mudstone, and suggest that the mica-type group dominate the soils being tested, with a likely contribution from the kaolinite group. This is in good agreement with published data on the composition of mudrock formations (Cripps

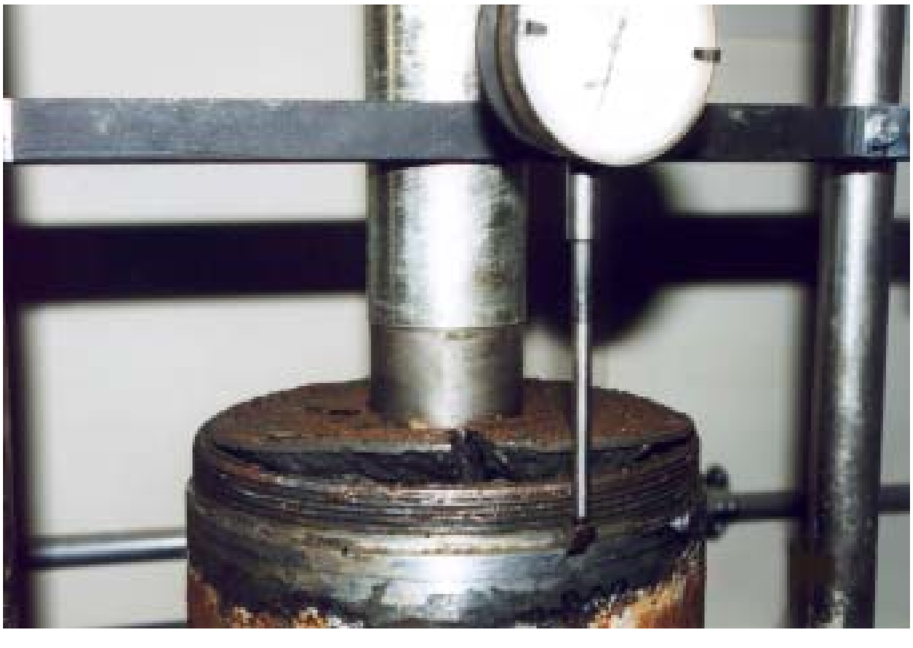

Figure 14 CBR test showing failure surface

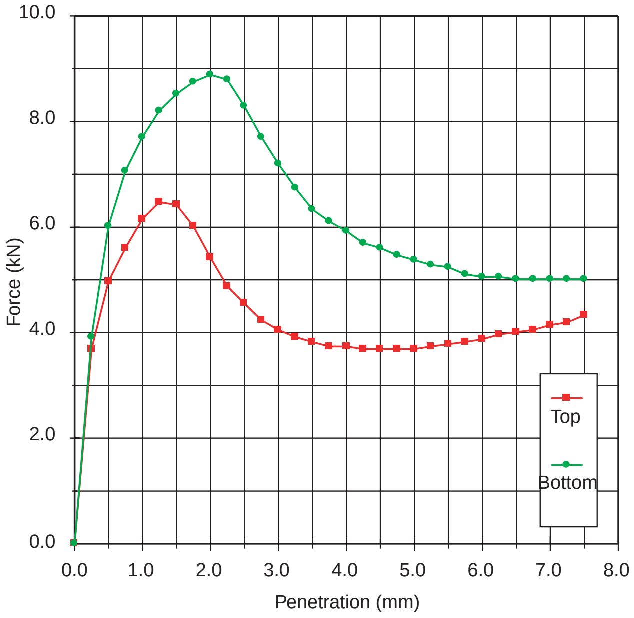

Figure 15 CBR plot for failing specimen

and Taylor, 1987), reproduced in Table 5, and X-ray diffraction analysis of London Clay (MacNeil and Steele, 1993), reproduced in Table 6.

In Clause 3.8 of HA 74/95 (DMRB 4.1.6), soils which have been successfully stabilised with lime are detailed, as are those which do not stabilise well, due to what various authors attribute to be the presence of kaolinite, though a degree of ambiguity is attached to this claim. In particular, Weald Clay is highlighted as reacting poorly with lime. This is clearly not supported by the strength data generated for the 7-day, 28-day and long-term CBR specimens in this trial, which indicate the following order for improvement in bearing capacity, for what can be regarded as minimum lime additions for stabilisation of the recovered samples of each soil:

Soil type	*Improvement in bearing capacity*
London Clay	Lowest
Gault Clay	
Kimmeridge Clay	↕
Lower Lias Clay	
Weald Clay	
Oxford Clay	
Mercia Mudstone	Highest

Table 6 X-ray diffraction analysis of London Clay (MacNeil and Steele, 1993)

	Mineralogical constitution		
Soil	*Kaolinite (%)*	*Illite*	*Illite-Smectite* [1]
London Clay	14	29	57

[1] *Illite-smectite mixed layer mineral > 90% smectite composition*

During soaking, specimens of Class 9D Mercia Mudstone, Oxford, London, Gault and Kimmeridge Clays experienced small degrees of shrinkage. This is considered to be analogous to shrinkage in concrete, but in the absence of a program of X-ray diffraction analysis, this was not further investigated.

Trends in the swell data (Figure 13) indicate that, for all the soils stabilised in the trial, air void contents well in excess of the minimum 5% required for lime stabilised capping result in swell below the average upper limit of 5mm (HA 74/95, DMRB 4.1.6). However, data from previous TRL research on lime stabilisation of London Clay (Figure 16) show that swell can easily approach and exceed this limit at air void contents above 5%. Indeed, one sample of London Clay stabilised with 2.5% SG60 quicklime, mellowed for 48 hours and compacted to a 4.1% air void content, produced a swell of 9.97mm, which is just within the maximum permissible swell of 10mm for any individual sample (HA 74/95).

It is concluded that the swell limits currently specified in HA 74/95 (DMRB 4.1.6) are appropriate for the typical range of British clays stabilised in this trial. In terms of the requirements in the current specification, any attempt to reduce the limits would potentially reduce the range of British clays which could be regarded as suitable for stabilising with lime, even though previous experience would highlight successful stabilisation. An increase in swell limits would potentially increase the variability of stabilised materials used as capping, with an associated risk of increases in instances of differential swell or settlement. It is probable that either of these alterations to the current specification would result in increased construction costs.

6.4 General comments

The high degree of consistency between the chemical analysis data for the Class 7E soils (Table 1) and the Class 9D swell data is noteworthy. However, care must be taken in

Table 5 Composition of mudrock formations (after Cripps and Taylor, 1987)

	Mineralogical constitution			
Soil	*Kaolinite*	*Illite*	*Smectite*	*Pyrite*
Mercia Mudstone	Minor	Major	Minor(localised)	–
Oxford Clay	Minor	Major	Minor(localised)	Minor
Lower Lias Clay	Minor	Major	Minor(localised)	Minor(localised)
Gault Clay	Present	Major	Present	–
Weald Clay	Present	Major	Minor	Minor(localised)
Kimmeridge Clay	Present	Major	Minor	Minor

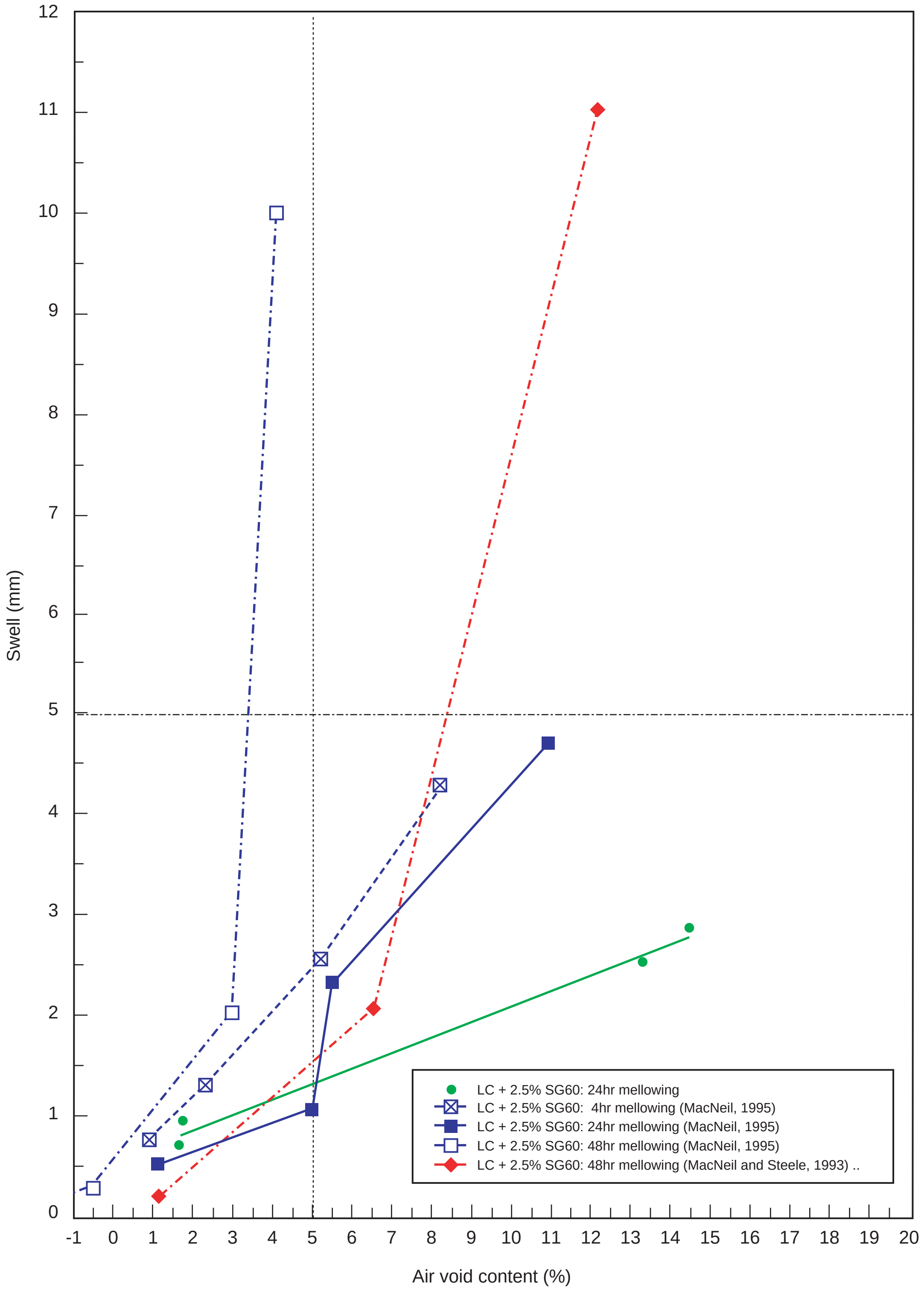

Figure 16 Air void content versus swell for lime stabilised London Clay

interpreting the data. In particular, some gypsum crystals were observed in the Class 7E Gault Clay sample and contributed to the highest total sulphate content (Table 1). Whilst the Class 9D Gault Clay produced the highest average swell, it must also be noted that, due to the presence of expansive clay minerals (see Table 5), the untreated Gault Clay would also have had the highest swell potential.

As discussed by Burkart *et al.* (1999), where gypsum is the only sulphate-bearing mineral in a lime treated soil, and the gypsum concentration is known, it is possible to determine the amount of ettringite which may be produced by using the following ratio:

lime : gypsum : ettringite = 1.00 : 3.07 : 7.45

For example, if water was available to a subgrade soil treated with 6% lime and containing 1.0% fine-grained gypsum, a maximum of 2.4% ettringite would develop. The reaction would consume 0.3% lime, leaving 5.7% lime still available for the cementitious reaction. In contrast, if the lime addition was 6% and the gypsum content was 18.4%, the ettringite formed would be 44.7%, both the lime and gypsum would be totally consumed, and no cementitious products would be created.

The lime-sulphate expansive reaction is relatively complex, and due to contributions of other variables, including clay mineralogy and associated swell potential, sulphate type and content, sulphide content and potential for oxidation, chemical composition of groundwater, lime addition and long-term pH regime, temperature and state of compaction, it would be erroneous to conclude that the likely degree of swell of a lime stabilised soil is solely related to the measured total sulphate content of the untreated soil. However, from the following ranking of data generated in the trial, it is evident that the swell test was effective at identifying the contribution of total sulphate content of the Class 7E soils to the resulting swell of the Class 9D materials.

Sulphate content (Table 1)	*Long-term swell (Table 4)*	
Weald Clay	Lower Lias Clay	Lowest
Lower Lias Clay	Weald Clay	
Mercia Mudstone	Mercia Mudstone	
Oxford Clay	Oxford Clay	
Kimmeridge Clay	London Clay	
London Clay	Kimmeridge Clay	
Gault Clay	Gault Clay	Highest

From the review of published literature, it is evident that only a few problems have been encountered when using the swell test to assess the swell potential of lime stabilised material. In particular, Snedker (1996) reported on an investigation of swell problems encountered with lime stabilisation of Middle and Lower Lias Clays, during construction of the M40. It was found that the swell test ‘proved to be unsatisfactory in reproducing either the degree of swell or the [very wet] condition of the lime stabilised material in the field.’ Snedker suggested that, as full testing programmes to obtain representative results can be expensive, it may be better to assess risk by desk study work, or to minimise testing to total sulphur and total sulphate tests, in combination with knowledge of soil mineralogy. It is worth noting that both the stabilisation and the subsequent investigation of the failure were undertaken prior to the publication of HA 74/95 (DMRB 4.1.6), and that the knowledge and experience gained from the failure of the M40 lime stabilised capping was incorporated in the Advice Note, particularly in the sections covering Ground Investigation Strategy and Execution of the Ground Investigation.

It is likely that research on sulphate testing for structural backfills (Reid *et al.*, 2001) will result in improvements to the test methods for the determination of sulphur compounds, detailed in the current specification. The work, which has examined the potential for oxidation of sulphides to sulphates in relatively free draining backfill, does not propose any alterations to the limits currently specified for lime stabilised capping materials.

Clause 6.1 of HA 74/95 (DMRB 4.1.6) states that:

> *‘It is essential to set limits on the material properties required for Class 7E... and Class 9D..., both to allow the selection of suitable material and to give assurance of good long-term performance of the pavement structure.’*

From the work undertaken as part of this project, no data have been generated or identified to suggest that the currently specified laboratory tests for lime stabilisation, including the swell test procedure and the associated suitability limits, provide anything other than effective performance indicators for mix design and long-term durability. Accordingly, it is recommended that the swell test procedure is retained in the UK specification in its current form.

7 Conclusions

A laboratory test programme to assess the swell potential of seven lime stabilised British clays has been completed. Following current UK test procedures, CBR specimens of the stabilised materials were prepared, soaked, and monitored for swell for up to 400 days. The strength of the specimens was measured after 7, 28 day and long-term curing. The following points comprise the main conclusions of the study:

1. A wide ranging review of published and unpublished data yielded only limited relevant data relating specifically to swell values and sulphate content limits for lime stabilised soils.
2. Quicklime additions of the Initial Consumption of Lime + 0.5% resulted in stabilised materials which, when prepared at states of compaction well within the current UK requirements, resulted in strengths around or slightly higher than the current 7-day CBR acceptability requirement.
3. Contrary to unsuccessful experiences reported in lime stabilisation literature, Weald Clay was effectively stabilised with quicklime.

4 The long-term swell behaviour of lime stabilised Mercia Mudstone, Lower Lias and Weald Clays was not significantly influenced by an increase in air void content. However, lime stabilised Oxford, London, Gault and Kimmeridge Clays were all significantly influenced by air void content. Of all stabilised materials tested, Gault Clay was by far the most susceptible to long-term swell.

5 The British Standard method for determining the CBR of cured lime stabilised specimens should be amended to take into account potential failure and significant displacement of a cone of material within the surface being tested.

6 The British Standard method for determining the Initial Consumption of Lime should be updated to reflect the possibility of achieving pH values for saturated lime solutions outside the currently stated acceptability range.

7 The currently specified laboratory tests for lime stabilisation of capping materials, including the swell test procedure, are effective performance indicators for mix design and long-term durability. It is recommended that the swell test procedure be retained in the UK specification in its current form.

8 The swell limits currently specified in the UK Advice Note on lime treatment are considered to be appropriate for the typical range of British clays stabilised in the trial, and should not be altered.

8 Acknowledgements

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Abstract

Limits are currently recommended in Highways Agency Advice Notes relating to the permitted amount of swell in standard samples of lime stabilised cohesive material. This is a requirement for determining the suitability of cohesive material, prior to its stabilisation as a capping layer within the Series 600 Earthworks of the Specification for Highway Works.

This report describes the investigation of seven British soils which were stabilised with quicklime, and subjected to a testing methodology aimed at providing data to assess the applicability of the swell test as an indicator to the suitability and acceptability of materials for lime stabilisation. Specimens of the stabilised materials were prepared, soaked, and monitored for swell for up to 400 days. For all the soils stabilised in the trial, swell values below the average upper limit of 5mm (HA 74/95) were recorded.

Related publications

TRL447 *Sulfate specification for structural backfills* by J M Reid, M A Czerewko and J C Cripps. 2001 (in production)

TRL424 *Detailed chemical analysis of lime stabilised materials* by J D McKinley, H Thomas, K Williams and J M Reid. 1999 (price £25, code E)

TRL306 *Laboratory trial mixes for lime-stabilised soil columns and lime piles* by A H Brookes, G West and D R Carder. 1997 (price £25, code E)

TRL305 *Review of lime piles and lime-stabilised soil columns* by G West and D R Carder. 1997 (price £25, code E)

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