A COMPARISON OF 3 SWELL/STABILITY TESTS ON CLAY SOILS TREATED WITH LIME, CEMENT AND GGBS

BRITPAVE Soil Stabilisation Task Group:- Project Report

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Summary

This report reviews the test methods used to assess the potential for treated/stabilised soils to swell or disintegrate because of the presence of sulfates or sulphides in the soil. It also reports the results of a laboratory test program which compared three of these test methods, i.e.:

- BS EN 13286-47: 'CBR swell test'
- BS EN 13286-49: 'accelerated, unconfined, expansion test'
- A loss of strength on immersion test

Three clays were used for this comparative test program:

- a highly plastic, but 'zero sulfate' glacial clay
- a Lias clay with medium sulfates
- a London clay with low sulfate but high sulfide

The binders were:

- unstabilised without binder
- stabilised with 2% lime
- stabilised with 2% lime and 2% Portland cement
- stabilised with 2% lime and 2% GGBS

It was found that:

- All three tests detected potential problems with the medium sulfate clay.
- There was no evidence that the European accelerated test is better at detecting the potential for sulfide-induced expansion than the CBR swell test. The European accelerated test is carried out at 40°C, which raises concerns about its ability to replicate reactions that occur only at low temperatures.
- The loss-of-strength-on-immersion test was the most severe of the three tests and may be overly severe for evaluating mixtures with lower binder contents
- All three test methods showed an enhanced resistance to sulfate-disruption for the specimens where the binder was 2% lime + 2% GGBS.

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1. Introduction

Stabilising soil with lime and/or cement is an effective method of converting weak soil into a useable construction material. It is widely used in the construction of highway pavements, car/ lorry parks, foundations for floor slabs and the remediation of contaminated land. However, the presence of sulfates in the soil, can potentially cause expansion problems [1] because in wet conditions, calcium (from the lime or cement) can react with alumina (a primary constituent of clay) and sulfate to produce calcium-aluminate-sulfate-hydrate minerals, which have very large expansion potentials, up to as much as 250%.

The potential for stabilised soils to swell is usually measured by compacting a mixture of soil and binder, into a circular mould and then immersing the mixture, still in the mould, in water at a temperature of 20^oC. The mould constrains the specimen horizontally and the linear expansion in the vertical direction is measured. This test method is referred to as the "CBR Swell Test" and was originally set out in BS 1924: Part 2:1990 [2]. In 2005, BS1924-2 was withdrawn and replaced by a European Standard, BS EN 13286-47: 2004 [3].

Over the last 20 years, some concerns have been expressed that the CBR Swell Test may not fully replicate the conditions encountered in the field and may underestimate the potential for swell. These concerns were first raised during extensive investigations of problems encountered during the construction of the Banbury section of the M40 in the late 1980's, where there was expansion of the lime stabilised capping layer. The initially 250mm thick stabilised layer heaved by up to 50mm. Snedker [4] has reported the problems and subsequent investigations and attributes the problems to the presence of sulfides in the form of pyrites (iron sulfide), which, after the construction processes, oxidised to sulfate and reacted to produce expansion. Although chemical testing had been carried out prior to testing, it had only measured the total sulfate and no testing was carried out for sulfide. Subsequently, designers of soil stabilisation have recognised the importance of sulfides. Highways Agency publication HA 74/95 [5] was a key document, published in 1995, which was written in the light of the M40 case and provided extensive guidance on the assessment of sulfates <u>and sulfides</u> in materials stabilised for use in highway construction.

About ten years after the problems with the M40, the report [6] from the Thaumasite Expert Group, set up to investigate sulfate-related deterioration in concrete, highlighted the extent to which disturbance of a soil can induce pyrites to oxidise and significantly increase the sulfate level. This oxidation would be accelerated during soil stabilisation operations by both the pulverisation process and the use of lime and/or cement, which increases the pH level and thereby decreases the chemical stability of the pyrites [7]. The Expert Group report also identified a mechanism of sulfate attack which differed from conventional sulfate attack where gypsum and ettringite are formed. This alternative attack, which produced mainly thaumasite, only occurred in cold wet conditions, required as source of carbonate and attacked concrete to produce a wet pulpy mass. Longworth, who was a member of the Thaumasite Expert Group, noted [8] that investigations on the M40 soil stabilisation problems had found that ettringite, initially formed during summer months, was converted to thaumasite by exposure to cold winter conditions. Based on experience with sulfate reactions in cementitious materials, he suggested that 20^oC is too high a temperature to reproduce the thaumasite type of sulfate reactions, because thaumasite only forms readily at temperatures between 5°C and 15°C. In his view, a procedure is called for that includes testing at temperatures that are more typical of UK ground conditions, which for much of the year are less than 10°C.

Others have also suggested [1,9,10] that the conditions for oxidation of pyrite and/or the development of swell realised in the field, are not fully replicated using the BS EN 13286-47 CBR swell test because both the protection offered by the CBR mould and the method of soaking employed, hinder the access of water and air. Various alternative tests have been proposed, often based on measuring the strength lost by specimens following immersion in water. For over 50 years the Highways Agency Series 800 [11] has included a test, originally for soil cement, where the strength of immersed specimens is required to be greater than 80% of the strength of non-immersed specimens (the test details have changed over the years). Others have adapted this test procedure to assess the stability of stabilised, sulfate-containing fine-grained soils, e.g. Kennedy used a variation [12] utilising specimens prepared in MCV moulds, in trials for a number of road schemes, including projects on the A130, A421 and A505, involving stabilisation of chalks and clays. Another alternative test procedure is the European accelerated test: BS EN 13286-49 [13], which specifies an unconfined swell test, where the material is completely immersed in water at 40°C and the volumetric expansion is measured rather than the linear swell.

As well as selecting a test method, appropriate acceptability limits have to be determined. The European Standard for 'Soil treated by lime' [14] contains a requirement that the average CBR swell value should not exceed 5 mm and no individual value should exceed 10 mm. This is the same test and limits, as recommended in the Highways Agency Advice Note HA74/07[15], except that the European Standard requires the water to be continually aerated. The European Standard for 'Soil treated by lime' [14] also contains limits for specimens tested using the BS EN 13286-49 'European accelerated test'. It requires that the volumetric expansion should not exceed 5%, subject to a note that "*where the volumetric swelling is greater than 5 % but does not exceed 10 %, the use of the mixture is generally not possible; however a complementary study can be made according to experience at the place of use*".

It is not easy to relate the linear swell measured on specimens constrained in CBR moulds to the volumetric expansion measured in the European accelerated unconfined test. In the CBR swell test, linear expansion is measured on a 127mm high CBR mould sample and the 5mm limit equates to 3.9% linear expansion and the10mm limit to 7.8% linear expansion. If the specimen in the CBR mould was fluid and flowed freely out of the mould (like toothpaste squeezed from a tube) then 5mm linear expansion would equate to 3.9% volume expansion. However, if the CBR mould was fully restraining all horizontal expansion and the measured 5mm expansion was only the expansion in the vertical direction, then this would equate to 12% unrestrained volumetric expansion. Notman [9] reported that when extruding the CBR specimens after testing, considerable force was required to overcome the specimen's adhesion/frictional resistance against the internal surface of the CBR mould. This was measured as between 16 and 20 kN. Such a force would undoubtedly prevent the specimen squeezing out like toothpaste and significantly reduce the measured expansion. Because of the complications of the constraint, it is not simple to relate linear expansions to volumetric.

Subsequent to the problems on the M40, various investigations have been carried out into the applicability of swelling tests for stabilised soils. In 2001, MacNeil and Steele, [16] reported on CBR swelling tests carried out with seven cohesive soils taken from around the UK. The acid soluble sulfate content of the soils ranged from 0.07 to 1.55 % SO4, and total potential sulfates contents from <0.1 to 5.7 % SO4. The soils were stabilised with between 2.5% and 6.5% of quicklime (determined as the ICL (Initial Consumption of Lime) for the soil + 0.5%). None of the 62 specimens tested had a swell value in excess of 10 mm, the upper limit stated in HA74/07, and only one specimen (a Gault clay with 0.8% acid soluble SO4), had a swell in excess of the upper 5 mm average swell value. From the CBR swell results, the Report inferred that all of the soils were "suitable" for stabilisation and concluded that no data had been generated to suggest that the CBR swell test procedure and associated limits, provide anything other than effective performance indicators for mix design and long-term durability; it recommended that the swell test procedure be retained in the UK specification in its current form. As pointed out by Notman [9], this is despite the soils tested containing up to 5.7% total potential sulfate and HA/74 suggesting that the upper limiting value of TPS should not exceed 1% and warning that there is evidence that, for some materials, values as low as 0.25% may cause swelling (17). In the absence of any corroborating evidence of the suitability of the soils, it would appear that whilst the Report had not generated any data that the CBR swell test was not an effective performance indicator, arguably it had not actually generated any data to confirm that it was an effective indicator.

Notman [9, 10] compared the performance of three laboratory methods for comparing the swell performance of stabilised soils. They were the CBR swell test (BS 1924-2: 1990), the European accelerated unconfined test (BS EN 13286-49: 2004) and a loss of strength upon immersion test [11] He concluded that the test most likely to pass a material as being suitable was the CBR swell test, whereas the loss of strength on immersion test, with a limit of $\leq$ 80%, was the most difficult to satisfy. He recommended further investigation to establish the most suitable test.

Buttress et al [18] compared the European accelerated test with the CBR swell test (the older BS1924-2:1990 version) They used a kaolin and a montmorillonite clay, artificially spiked with various proportions of sulfate (gypsum) and stabilised with lime. Surprisingly the CBR swell test showed only 4.8mm expansion for the kaolin clay, when it had been spiked with 5% SO4. In their tests the relative severity of the test seemed to vary with the clay type, with the European accelerated test showing more expansion for the kaolin clays spiked with sulfate than the CBR swell test, whilst for the spiked montmorrilonite clays the reverse was apparent. The European accelerated test failed the stabilised kaolin clay without any sulfate.

In 2004, significant heave occurred in the stabilised soil capping layer, during construction of the A10 Wadesmill Bypass. It has been suggested by Notman [9] that a contributory factor may have been the failure of the CBR swell test to pick up the potential for swelling. However, subsequent investigations [19] found that high levels of sulfates and sulfides (up to 4.3% SO4) were present sporadically in the glacial tills, used in the capping layer and sub base, but this was missed by both the pre-contract site investigation carried out for the HA and the comprehensive pre-construction checking undertaken by the contractor. There is no evidence to suggest that inadequacies in the CBR swell testing procedure contributed to missing the potential for expansion.

The differences in opinion about the most suitable test method to assess the swelling potential of stabilised soils, are noted in the BRITPAVE publication ‘Guidelines for Best Practice for the Stabilisation of Sulfate-bearing Soils’ [1]. In order to compare the effectiveness of different test methods for detecting sulfate/sulfide swell and disintegration in stabilised soils, the BRITPAVE Soil Stabilisation Task Group embarked on an experimental programme of research. The principle aims were:

- to check the validity of concerns that the BS EN 13286-47: ‘CBR swell test may not fully detect the potential for sulfate/sulfide swelling, due to the CBR mould restricting the access for air and moisture and also restraining the specimen against lateral expansion.
- to assess which tests can give a reliable indication of the potential for swell, in the shortest period of time.

2. Experimental

Testing was carried out on three samples of clay:

1) **a highly plastic, but ‘zero sulfate’ glacial clay**, which would not be liable to sulfate-swell but could expand due to water-uptake. This clay was included to differentiate between sulfate-expansion and swelling due to ‘plasticity’.
2) **a Lias clay with medium sulfates**, which would potentially exhibit sulfate expansion and disintegration. Czerewko et al [21] have carried out detailed investigations on clay samples from the same source.
3) **a London clay with low sulfate but high sulfide**, which might not swell in the CBR test because of lack of oxygen access to oxidise the sulfide to sulfate.

Their plastic and liquid limits were determined in accordance with BS1377-2:1990 and their initial consumptions of lime in accordance with BS1924-2:1990. Their moisture condition values were determined in accordance with BSEN13286-46:2003, after addition of 2% lime

The following binders were used:

1) unstabilised without binder
2) stabilised with 2% lime (CaO)
3) stabilised with 2% lime and 2% Portland cement
4) stabilised with 2% lime and 2% GGBS (ground granulated blast furnace slag)

GGBS was included because it is one of the risk mitigation measures, which has been shown to inhibit expansive sulfate reactions. The Californian Bearing Ratios were measured in accordance with BSEN 13286-47:2012.

Three test methods were employed to measure sulfate expansion/disruption:
1) **BS EN 13286-47: ‘CBR swell test’:** The mixtures were mellowed for 48 hours after adding lime. Subsequently, where required, cement or GGBS was added and the specimens were immediately moulded and then immersed in water. Swelling was monitored during 56 days of soaking

2) **BS EN 13286-49: 'accelerated, unconfined, expansion test':** The specimens were stored at 20ºC and >90% RH for 72 hours, then fully immersed for 7 days in water at 40°C, prior to the measurement of expansion.
3) **A loss of strength on immersion test:** This followed a procedure developed by Kennedy [12] which was based on the MCHW clause 880 method [11] for assessing cement bound granular materials. The specimens were prepared in MCV moulds and then immediately extruded from their moulds and sealed to prevent evaporation (by wrapping in cling film and placing in closed plastic bags). The strengths of specimens which had been cured sealed for 7 days and then immersed in water for 21 days were compared with the strengths of control specimens, which had been cured sealed for 28-days. Comparisons were also made for specimens with extended curing (a) 7-day sealed + 49-day immersed vs 56-day 'sealed' (b) 7-day sealed + 84-day immersed vs 90-day'sealed'

It proved impractical to carry out strength testing or accelerated-expansion testing on specimens without binder.

3. Results

The results of the tests on the clays are shown in Table 1 and the results of the CBR strength tests in table 2.

Table 1: Properties of clays

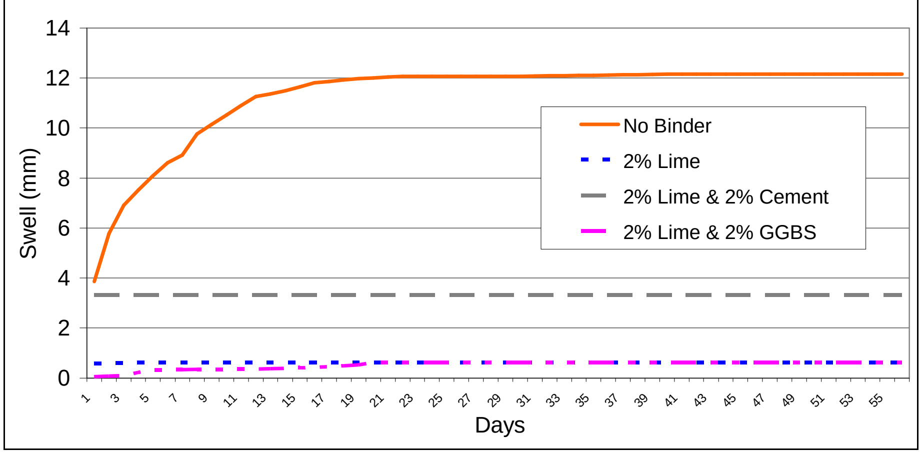
	Sulfates (average values)			Plastic limit	Liquid limit	MCV	ICL
Clay	WS	AS	TPS				
Low-sulfate, low sulfide Glacial clay	65 mg SO4/l	<0.1 %SO4	<.01 %SO4	18%	50%	10.5	3.4%
Medium-sulfate, low-sulfide Lias Clay	1,450 mg SO4/l	0.5 %SO4	0.7 %SO4	22%	57%	11	3.5%
Low-sulfate, high-sulfide London clay	800 mg SO4/l	0.1 %SO4	1.6 %SO4	22%	53%	11	3.4%

Table 2: CBR strength tests (after 56 days of immersion)

Clay	Binder	CBR at 2.5mm penetration	
		Top	Bottom
Low-sulfate, low sulfide Glacial clay	None	0.4	2.1
	2% lime	18	36
	2% lime+ 2% cement	22	57
	2% lime + 2% GGBS	18	17
Medium-sulfate, low-sulfide Lias Clay	None	0.4	3.5
	2% lime	5	26
	2% lime+ 2% cement	13	99
	2% lime + 2% GGBS	35	40
Low-sulfate, high- sulfide London clay	None	0.5	4.0
	2% lime	14	27
	2% lime+ 2% cement	20	105
	2% lime + 2% GGBS	37	39

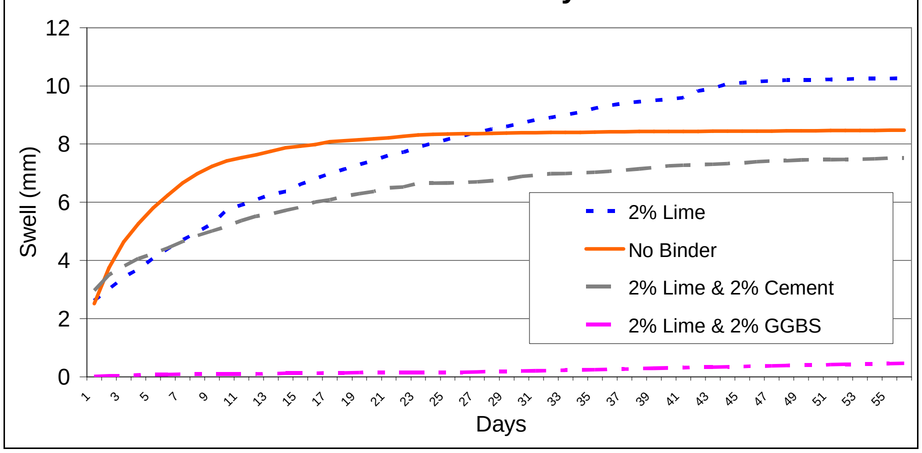
Figures 1 to 3 show the CBR expansion against time. For the low-sulfate, low-sulfide clay, without binder (Fig.1), the expansion was 12 mm. As expected, the addition of binder to stabilise the soil, substantially reduced the expansion, although it is noticeable that with 2% lime and 2% cement there was a significant initial expansion (~ 4mm) during the first day of immersion.

Figure 1: CBR Swell of Low Sulfate and Low Sulfide Clay



With the medium sulfate clay, (Fig.2) the samples, which had been stabilised with 2% lime, expanded by about 10mm and the samples with 2% lime + 2% cement expanded by about 8mm. The expansion increased steadily between 1 and 56-days and was typical of what would be expected as a result of sulfate-induced swell. The sample stabilised with 2% lime + 2% GGBS did not expand (<1mm).

Figure 2: CBR Swell of Medium Sulfate and Low Sulfide clay



The low-sulfate, high sulfide clay also showed expansions (Fig.3). The samples stabilised with 2% lime expanded by about 2mm and the samples with 2% lime + 2% cement expanded by about 6mm. With this clay, these expansions took place within the first 3 days and no subsequent expansion was noted, which is not typical of sulfate expansion. The sample stabilised with 2% lime + 2% GGBS did not expand (<1mm).

Figure 3: CBR Swell of Low Sulfate and High Sulfide Clay

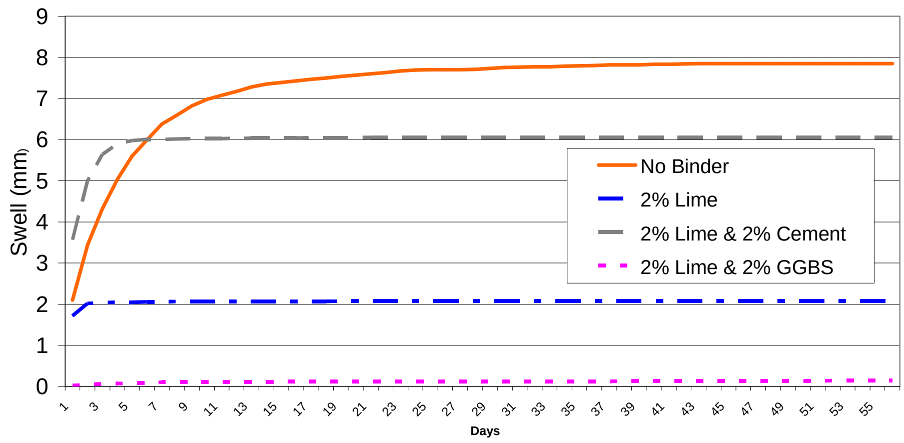


Table 3 shows the 56-day CBR swell, the European accelerated expansion and the loss=of-strength upon immersion at 28-, 56- and 91days.

Table 3: Expansion and loss-of-strength tests

Clay	Binder	CBR Swell @ 56 days (mm)	EN Accel' Test (vol %)	Compressive strength (N/mm^2)					
				28-day		56-day		91-day	
				air	soak	air	soak	air	soak
Low Sulfate & Low Sulfides	2% lime	0.6	1.5	0.5	0.2	0.5	0.2	1	0.5
	2% lime + 2% cement	3.3	4.3	1	0	1.1	0.5	1.5	1
	2% lime + 2% GGBS	0.6	2.0	0.4	0	0.2	0.2	0.5	0
Medium Sulfate & Low Sulfides	2% lime	10.3	8.0	0.6	0	0.5	D*	0.5	D*
	2% lime + 2% cement	7.5	7.1	1.1	0	1	D*	1.8	D*
	2% lime + 2% GGBS	0.5	3.3	0	0.5	0.6	0	0.3	n/t*
Low Sulfate & High Sulfides	2% lime	2.1	4.2	0.6	0	0	0	0.5	0
	2% lime + 2% cement	6.1	3.5	1.1	0	1	0.5	1.2	0.6
	2% lime + 2% GGBS	0.4	2.0	0.4	0.6	0.5	0.2	1	0.2
D* = disintegrated under soaking n/t* = no specimen									

Table 4 assesses the results in Table 3 against bandings based on the pass/fail limits, which are generally applied for the three tests, i.e.:

- CBR immersed swell should be less than 5mm
- European accelerated expansion should be less than 5%
- 28-day strength on immersion should be greater than 80% of the non-immersed strength

Table 4: Assessment of expansion and loss-of-strength results

		CBR Swell @ 56 days (mm)	**EN Accelerated Test (vol %)**	**28-day soaked/ unsoaked strength**
Assessment used for test results	*Pass*	< 3mm	< 4%	Soaked strength > 90% of unsoaked
	???	3 to 7mm	4 to 7%	Soaked strength 70% to 90% of unsoaked
	Fail	> 7mm	> 7%	Soaked strength < 70% of unsoaked
Clay	**Binder**			
Low Sulfate and Low Sulfides	2% lime	*Pass*	*Pass*	**Fail**
	2% lime + 2% cement	*???*	???	**Fail**
	2% lime + 2% GGBS	*Pass*	*Pass*	**Fail**
Medium Sulfate & Low Sulfides	2% lime	**Fail**	**Fail**	**Fail**
	2% lime + 2% cement	**Fail**	**Fail**	**Fail**
	2% lime + 2% GGBS	*Pass*	*Pass*	*Pass*
Low Sulfate & High Sulfides	2% lime	*Pass*	???	**Fail**
	2% lime + 2% cement	???	*Pass*	**Fail**
	2% lime & 2% GGBS	*Pass*	*Pass*	*Pass*

Comparing the CBR swell test and the European accelerated test in Table 4:

- Both detected significant but "just acceptable" swell for 2% lime + 2% cement with the low-sulfate, low-sulfide clay. It may be that this binder content was too low to fully stabilise this high-swell clay.
- Both clearly "failed" the medium-sulfate, low-sulfide clay stabilised with 2% lime or 2% lime+ 2% cement. However, when this clay was stabilised with 2% lime + 2% GGBS both tests showed much lower expansions and a "pass".
- With the low-sulfate, high-sulfide clay, the CBR swell test failed this clay, when stabilised with 2% lime + 2% cement. The European accelerated test showed significant but "acceptable" expansions for both 2% lime and for 2% lime + 2% cement. Once again, stabilisation with 2% lime + 2% GGBS showed significantly less expansion than with other binders.

4. Discussion

It should be noted that the binder contents were selected to be on the low side of what might be used in practice, and the lime contents were less than the initial consumption of lime requirement (Table 1).

The medium-sulfate clay contained 0.5% acid soluble SO_4, which is around the minimum level expected to produce deleterious sulfate expansion, in practical applications [1]. When this clay was stabilised with 2% lime or 2% lime+ 2% cement, the CBR swell test detected a gradual expansion (see Figure 2) consistent with sulfate heave and the expansions at both 28- and 56-days were somewhat in excess of the normal limit of 5mm. These mixtures also somewhat exceeded the 5% limit in the European Accelerated test and lost all strength when subjected to the loss-of-strength-on-immersion test. This clay appears to have been particularly appropriate for the present study, with a medium, but still potentially detrimental sulfate content. All three tests classified it as “failing” when stabilised with 2% lime or 2% lime + 2% cement. In contrast, all three tests classified it as “passing” when it was stabilised with 2% lime + 2% GGBS, consistent with the ability of GGBS to resist sulfate-expansion [Ref]

With the low-sulfate, high-sulfide clay, the CBR swell test detected an initial (but not continuing) expansion over the first few days, which was sufficient to “fail” this clay when stabilised with 2% lime + 2% cement. When stabilised with 2% lime, there was a smaller initial expansion which gave a “pass” result. With both 2% lime and 2% lime + 2% cement, the European accelerated test detected expansions, which were just less than the 5% limit. From the tests on this clay, there was no evidence to support the suggestion [1] that the European accelerated test might be more able to detect potential expansion associated with sulfides, compared to the CBR swell test. Mixtures of this clay with 2% lime and 2%lime + 2% cement lost most of their strength when subjected to immersion and also failed this test. Once again, when this clay was stabilised with 2% lime + 2% GGBS, the expansions were much reduced and “passes” were achieved for all three tests, including the loss-of-strength-on-immersion test.

When the control clay (low-sulfate, low-sulfide) was stabilised with 2% lime + 2% cement there was a significant expansion, just less than the limiting values, in both the CBR swell test and the European accelerated test. This probably indicates that this binder content was too low to fully stabilise this high-swell clay.

The loss of strength on immersion test was the most severe of the tests and failed all of the combinations of clays and binders, except for the sulfate/sulfide containing clays stabilised with lime+GGBS, where the soaked strength was slightly greater than the unsoaked strength. This can be attributed to the activating effect of sulfate on the strength development of GGBS [21] and with GGBS as binder, the presence of sulfate may well have a beneficial rather than a deleterious effect. It should be noted that the loss of strength on immersion test would normally only be used for sub-base and base applications, and not capping.

As reported in the Introduction, it has been suggested [8] that testing at even 20^{o}C may be too high to fully induce the thaumasite form of sulphate expansion. The European accelerated test is undertaken at 40°C and cannot be expected to replicate chemical reactions which only occur at lower temperatures [15].

5. Conclusions

- All three tests detected the potential for sulfate problems with the medium sulfate clay.
- There was no evidence that the European accelerated test is better at detecting the potential for sulfide-induced expansion than the CBR swell test. The European accelerated test utilises a temperature of 40^{o}C, which raises concerns about its ability to replicate reactions that occur only at low temperatures.
- The loss-of-strength-on-immersion test was the most severe of the three tests and may be overly severe for evaluating mixtures with lower binder contents.
- All three test methods showed an enhanced resistance to sulfate-disruption for the specimens where the binder was 2% lime + 2% GGBS.

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