SCI LECTURE PAPERS SERIES

SIMULATING SULFATE ATTACK OF MORTAR AND CONCRETE ABOVE AND AGAINST GROUND

WH Harrison
Glebe Research Services, Glebe House, Hartwell, Aylesbury,
Bucks HP17 8QG, UK

ISSN 1353-114X
LPS 122/2000

Key words *mortar, concrete, sulfate attack, laboratory simulation studies*

SUMMARY

Wherever sulfate ions can come into contact with set Portland cement there is the potential for reaction and the ultimate destruction of the cementitious bond. The reaction may also produce an expansion resulting in structural stresses.

Certain well defined conditions where sulfate attack is almost inevitable can be identified in the field but, despite the often alarming results obtained by accelerated laboratory tests, the problem remains defiantly absent for most uses of concrete and mortar.

The art in testing cement bound products and constructions for sulfate resistance is therefore to match the test procedure with the field performance such that the acceleration required for reasonably rapid assessment does not distort the performance and establishes the degree of acceleration achieved.

This paper is about simulating sulfate attack under controlled and repeatable conditions so that not only the liability of different types of mortar or concrete to attack can be assessed and their relative performance determined but that the test procedure should accelerate, whilst not substantially altering, the type of degradation that occurs in the field. For mortar exposed above ground, a small scale laboratory test of this type has been developed.

For concrete, a possible explanation of the low failure rate of concrete completely buried in sulfate soils is advanced but needs further investigation before an improvement in the present simple simulation test involving the immersion of concrete cubes in sulfate solutions can be introduced.

INTRODUCTION

Mortar and concrete made with Portland or Portland-based cements are well known to be vulnerable to attack by water-borne sulfate. The rate of attack is generally attributed to the mineralogical composition of the cement, the permeability of the product in which they are used and the concentration of the sulfate.

Under certain circumstances, sulfate attack of mortar and concrete in the UK has led to large repair bills but it is equally true to say that considering the large volumes of concrete and mortar used and the presence of sulfate salts in many UK natural soils, in wastes used as fill and in some fired-clay bricks, the overall failure rate is very low.

This paper is about simulating sulfate attack under controlled and repeatable conditions so that not only the liability of different types of mortar or concrete to attack can be assessed and their relative performance determined but that the test procedure should accelerate, whilst not substantially altering, the type of degradation that occurs in the field. It also shows where protective barriers against the ingress of sulfate-bearing water are needed irrespective of the composition of the cement and of the specification of the mortar or concrete. A possible explanation of the low failure rate in sulfate soils is advanced but needs further investigation.

WHERE SULFATE ATTACK IS FOUND IN UK

The main sources of sulfate which affect mortar or concrete are some natural soils, fill material generated from some types of industrial wastes and some types of fired clay bricks. The sources are more specifically defined in BRE Digest 363(1). In Figure 1, a distinction has been made between exposure of mortar and concrete to these various sources against or above ground. Further sub-divisions are shown for exposure against ground when one face of the mortar or concrete is open to air, and above ground when exposure is internal or external.

Figure 1. Exposure to sulfate source related to position in building

MORTAR IN WALL OR FLOOR

Against Ground	
In contact with: Sulfate soil or fill and/or Normal sulfate clay bricks	(i) One face has access to air.
	(ii) No faces have access to air.
Above Ground	
In contact with: Normal sulfate clay bricks	(iii) Internal exposure
	(iv) *External exposure*

CONCRETE IN WALL OR FLOOR

Above Ground	(i) No normal sources of sulfate
Against Ground	
In contact with: Sulfate soil or fill	(ii) One face has access to air
	(iii) *No faces have access to air*

Note: Where a simulated exposure test is recommended text is shown in italic.

SULFATE ATTACK OF MORTAR

The various types of exposure identified in Figure 1 are described below with comment on the need and availability of a simulated test procedure. The types of exposure for which a test is considered necessary are shown in italics in Figure 1.

(i) Mortar in contact with sulfate soil with one face open to the air

This type of exposure will be in the form of a retaining wall. The wall could be retaining sulfate-bearing soil; it could be built with sulfate-containing bricks; it could also be saturated for most of its life and subjected to a hydrostatic head. Sulfate will have every opportunity to build up in the mortar as any water containing sulfate, derived either from the bricks or from the retained soil, that is lost from the open face by evaporation will leave its sulfate behind. Whilst some may remain on the surface as efflorescence and be subsequently washed further down the face by rain, much will accumulate in the mortar bed.

Fed by sulfate from a retained reservoir, there is no limit to the concentration of sulfate that can build up in the mortar so it is not surprising that the mortar in garden retaining walls often shows signs of distress due either to pressures generated by crystallization or expansive sulfate attack further aggravated by frost action. In more substantial brick retaining walls such as bridge abutments, the recommended protective measures will have been taken. These will include the use of a low permeability mortar made with a sulfate-resisting cement, low porosity, low sulfate bricks and, more importantly, the rear of the wall protected by the provision of drainage and preferably some form of waterproof barrier.

Simulation Test:

It would not be too difficult to set up a laboratory test to simulate this type of exposure - a plug of mortar in a tube subjected to a head of sulfate solution - but it is predictable that the requirements for the mortar would be to formulate it to be as impermeable as possible.

(ii) Mortar in contact with sulfate soil with no face open to the air

The difference between this exposure and that of a retaining wall is that the only mechanism operating to encourage sulfate to enter the mortar is by diffusion of the sulfate ions in a continuous water phase between the groundwater or the sulfate in the pore water of some types of fired clay bricks and the pore water in the mortar. However, since many mortars have a fairly porous matrix it would seem that this process would be a common occurrence. It cannot surely be assumed that the recommendations for mortar composition in British Standards is always observed and yet as far as I have been able to establish no failures have been reported in completely buried brickwork.

Simulation Test:

The lack of field failures hardly justifies a mortar test procedure to simulate this type of exposure but, as proposed later in this paper, there is a need to further investigate the reason for this remarkable resistance to the diffusion process.

(iii) Mortar not in contact with sulfate soil – internal exposure

Occasional problems have arisen in walls where leaks have provided the water and gypsum plaster contributed to the sulfate source but, in the main, the only vulnerable walls are those of bathrooms or washrooms with inadequate waterproof finishes or those suffering from rising damp.

Simulation Test

No mortar test required as failures are due to design, construction or maintenance faults.

(iv) Mortar not in contact with sulfate soil – external exposure

The principal source of sulfate affecting mortar out of contact with the ground is that contained in some fired-clay bricks. Above ground, the relatively uniform temperature and moisture content conditions of the soil are lost and, in external walls, mortar, which has a much higher porosity than concrete, is continually subjected to changes in moisture content and temperature. It also undergoes progressive carbonation which increases its resistance to sulfate attack. The rate of carbonation will depend primarily on the porosity and moisture content: carbonation will practically cease during very dry or very wet weather and, as water is needed both for the sulfate to migrate from the bricks and for reaction to take place, continuously wet mortar will be highly vulnerable to attack.

The effect of freezing, whilst it can be destructive under some circumstances on its own, can be quite devastating in combination with sulfate.

The field performance of different mortar formulations in external walls built with sulfate-containing bricks varies with the type of construction. Failures are rarely reported in walls between dpc and eaves unless there is a building detail fault but between dpc and the ground, at the top of gable end walls, parapets, chimneys and free-standing walls, there is a long history of mortar failures. These take the form of expansion of the brickwork or erosion of the external face of the mortar joint.

Simulation test:

A test for mortar should simulate the conditions of sulfate entering mortar from brick, intermittent wetting and drying and a capability for introducing freeze-thaw cycles. The rating of various standard mortar formulations would need to be judged by comparison with that of their known field perfomance so that new mortar types could be assessed. An accelerated laboratory test of this type was developed at BRE in the 1980's and is at present under consideration for inclusion in European Standards (CEN).

The test specimens of mortar are formed between bricks rather than moulded and the subsequent test procedure designed to submit the mortar to the severest of exposure conditions experienced in the field. Full details of the method were published in Masonry International(2).

Some results of testing small tablets of mortar made using a Portland cement with a very high C_3A content, a range of sand types and mix formulations [corresponding to Mortar Designations (ii),(iii) and (iv)] and the effect of initial brick suction are shown in Figures 2,3 and 4.

Fig 2
(click for enlargement 50k)

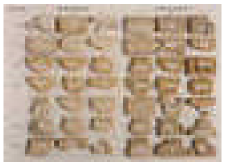

Fig 3
(click for enlargement 46k)

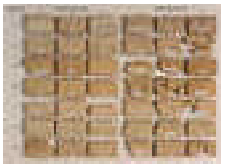

Fig 4
(click for enlargement 46k)

The problem with laboratory testing for mortar durability is that any particular test wil1 only give a comparative performance of different materials when tested in that test regime. By trying to simulate site practice in specimen production as well as simulating the method by which sulfate enters the mortar from the brick (and , in the case of frost action, freezing from the outer face), the comparative performance after 25 cycles was found to relate well to their known comparative performance in the field. Exposure panel tests on new mortar products over several years have given similar comparative performance to the laboratory tests.

SULFATE ATTACK OF CONCRETE

(i) Concrete out of contact with the ground

Reaction products of sulfate attack have been identified in the structural concrete of bridges subjected to surface erosion by chloride-based de-icing salts suspected of containing sulfate as an impurity. However, there have been no reports of attack of concrete above ground due to sulfate alone so no simulation test is needed.

(ii) Concrete in contact with sulfate soil with one face open to the air

Probably the main source of verified cases of sulfate attack of concrete is concrete floors laid directly on a sulfate-containing hardcore or fill. The hard, gritty, granular nature and cheapness of such wastes from old slag heaps and red shale from self-ignited coal spoil tips led to their wide usage. Depending on the water availability under the floors, the concrete starts to expand causing humping and doors to jam generally after 5 to 10 years. Now, some forty years on, although the practice has long since ceased, the legacy lingers on in the form of the occasional failure usually due to a leaking pipe reawakening any sulfate laying dormant. This mode of failure is similar to that described for mortar in retaining walls. Sulfate water enters the concrete at the lower face next to the fill and water only leaves by evaporation at the top face, hastened if the building above is heated. If the concentration of sulfate is low and the quality of the concrete high, it will take much longer for expansion to take place but in most house floors the quality of the concrete is not particularly high. Even so, it is only those properties under which water tends to collect for some reason that have problems. Today there are sufficient safeguards built in to the requirements for ground floors to ensure that these problems are not repeated and there is no demand for an accelerated test.

The same sort of situation arises with basements, retaining walls, pipes, tunnels and culverts as all will have a face from which water can evaporate. The quality of concrete for pipes, tunnels and culverts is very high and they really only need protection against unusually high sulfate levels. Similarly, there are few basements where dampness of the internal faces due to water penetration would be tolerated. The water barriers needed to prevent such dampness would, at the same time, prevent sulfate entering the concrete. Retaining walls of all types do need to be designed to prevent any sulfate in the retained soil from accumulating in the concrete.

There is no particular need to investigate various concrete compositions to resist this type of exposure when the requirement is clearly for a low permeability concrete made with a sulfate-resisting cement and with appropriate design of the structural features to provide some drainage and/or surface protection.

(iii) Concrete in contact with sulfate soil with no face open to the air

Concrete foundations surrounded on all sides by sulfate-bearing soil is a common type of exposure. It would also include piles, trenchfill and the concrete plinth on which strip foundation walls are built. Despite the apparent risk of sulfate attack of all these foundations, remarkably few cases are reported. Analysis of samples of concrete from foundations which have caused cracking in the structure above ground, sometimes does reveal the presence of ettringite but in many cases the movements can be attributed to geotechnical causes rather than expansion due to sulfate attack.

In all the above uses, the faces of cast concrete in contact with the soil have had no opportunity to be carbonated by exposure to air. Such exposure, even for a matter of hours, has been shown to impart a remarkable increase in the resistance of the concrete to sulfate attack and precast concretes of all types benefit from this effect.

Despite the dearth of failures of completely buried concrete (and mortar as indicated above) there is a need for an accelerated sulfate attack test for the following reasons:

- The present recommendations to combat sulfate attack of comp1ete1y buried concrete may be too conservative
- How are new concrete formulations best assessed?
- Are the new recommendations, designed to combat the recently diagnosed failures due to the formation of thaumasite, appropriate?

TESTS CURRENLY USED TO ASSESS SULFATE RESISTANCE OF CONCRETE

Most tests start with moulded specimens and compare their performance in various sulfate solutions. Loss of strength due to sulfate attack compared with similar specimens stored in water is the usual method of assessment. There is no fundamental reason for not using this basic method for testing concrete which will be buried in the ground but there are an almost infinite number of variations arising from the choice of solution strength, sulfate salt, cement type, cement content, water/cement ratio, size of specimen, shape of specimen, temperature of storage, duration of test, method of curing, time of curing. etc.

For specification purposes there is also a need to assess individual types of cement to classify them as sulfate resistant or not and possibly, in the future, the degree of sulfate resistance they provide. The prime practical current requirement however is for the concrete, irrespective of its composition, to be resistant to serious attack for at least 100 years.

The problem in devising a fair simulation test is therefore to decide how best to accelerate the attack without overlooking any possibility that the very means used to accelerate the process actually produces a form of attack unlike that which will ever befall the concrete in practice.

The most important parameters to get right in my view are the strength of the sulfate solution and the shape of the specimen. To these must now be added the temperature of the solution since storage at 20^0C for all previous tests had not revealed the potential for some cement/aggregate combinations to react to form thaumasite at temperatures below 15^0C.

The final specimens of a long-term (30 years) field and laboratory test at Northwick Park, Harrow have yet to be excavated but the published results at 5 and 15 years already reveal some interesting facts in relation to sulfate concentration and specimen shape. Various types and uses of concrete were simulated on site including cast-in-situ piles, precast units in the form of cylinders and wall panels forming a basement. Over 40 different mixes were represented and, for each mix, batches of 100mm cubes were cast and stored in solutions of magnesium sulfate at 0.42% $S0_4$ and 1.8% SO_4 in the laboratory. The mean sulfate concentration in the groundwater on site was 0.31% SO_4

(i) Effect of shape of test specimen

When the cubes in the laboratory solutions were attacked by sulfate, the 8 corners were always the first to crack and crumble and the attack would progress towards the centre. In general, the centres of the six faces of the cube were the last parts of the surface to show cracking. After 15 years, few of the cylindrical field specimens had shown any visible attack and most had increased in strength. The first attack was always round the edges of the end faces of the cylinders and this progressed towards the centre of the specimen from each end. The curved faces were not attacked except for the appearance of a white deposit in and around surface imperfections. There is a possibility that using specimens with vulnerable corners and edges not only accelerates attack on concrete but stimulates action which is never reproduced in the field. In this case, any extrapolation from the laboratory tests on cubes could be misleading.

(ii) Effect of sulfate concentration

Both the sulfate concentrations in the laboratory storage tanks were higher than the field groundwater so some acceleration of the attack would be expected. In fact, although many of the cubes in the solutions were severely attacked after five years, the cylinders from the same mixes in the field test were unattacked after 15 years.

(iii) Simulation of sulfate attack by cube immersion

The question whether a short-term cube test can predict the long-term performance in the field has not been satisfactorily answered by the results to date. The solution tests certainly produce an accelerated result and provide a comparison between different concrete mixes. Also, the comparatively small effects in the field test reflect the overall good performance of foundation concrete in the UK. However, no link between the two has been established and there is some evidence to show that both the shape of the test specimens and the strength of the laboratory solutions may need further consideration before a simple immersion test is accepted as a satisfactory simulation of field exposure. It would seem that one of the solutions should be matched in $S0_4$ concentration to that in the pore water of the concrete under test.

SULFATE PENETRATION BY DIFFUSION

It is clear from all the papers relating to the hydration of cement that all the $CaS0_4$ added to cement during its manufacture reacts to leave a very low concentration of $S0_4$ in the pore water.

For concretes completely buried in the ground, the only mechanism by which sulfate in the groundwater will be induced into the surface layer of the concrete is by diffusion. There would therefore be a concentration difference between the pore water and the groundwater depending only on the amount of sulfate in the latter.

In the studies of alkali silica reactions many papers contain analyses of the pore water in cement pastes. Most report them soon after setting and hardening but two papers(3,4) reported re-examination after several months. Whilst their main interest was in $(OH)^-$ and K^-, $S0_4^=$ was also reported. Conversion of the results from the units used in the papers to the more familiar units used in BS 5328(5) is shown in Table 1 and compared with the limits for Classes 2 and 3 in BS 5328 and with saturated gypsum solution. A further paper(6), looking at the effects of electrochemical chloride extraction on the chemical properties of hydrated cement pastes, reported the concentration of sulfate ions in the pore water of control specimens after 8 weeks. This is also included in Table 1.

Table 1. Concentration of $S0_4$ in pore fluid after 2 to 3 months

$S0_4$ in pore fluid expressed as in		*$S0_4$ Limits in Groundwater in BS 5328*	
Reference Paper	BS 5328	Class2	Class 3
Ref(3) 0.01 – 0.02M	0.96 – 1.92 g/l		
Ref(4) 27 mmole/l	2.6 g/l	0.4 – 1.4 g/l	1.5 – 3.0 g/l
Ref(6) 18 – 30 mmole/l	1.7 - 2.9 g/l		

(Saturated calcium sulfate solution contains 1.4 g/l $S0_4$)

It is more difficult to express the pore water from concrete than from cement pastes and mortars but if these high pore water concentrations of sulfate were also true of concrete then there would be little attack from groundwater sulfate until the concentration was at least around that associated with saturated gypsum. The $S0_4$ concentration in the pore water a few months after hydration of the cement may vary with the type of cement and presence of carbonate in the aggregate and further investigation could provide guidance in designing a better simulation test for establishing the resistance of concrete to sulfate attack of any sort.

Midgley(7) reported a change in composition of the ettringite phase several months after hydration. He found that 95% $C_3A.3CaS0_4.aq$ changed to a solid solution composition of 75% $C_3A.3CaS0_4.aq$: 25% $C_3A.3Ca(OH)_2$. aq. This could release sulfate to the pore water.

CONCLUSIONS

1. In assessing the risk of sulfate attack on mortar or concrete the exposure conditions should be divided into two categories. For those where sulfate can continually build up within the mortar or concrete, the remedy lies in external prevention measures and/or means of achieving very low permeability: for the conditions where seasonal changes in moisture and temperature cause sulfate movement or where the movement is conditional on a sulfate concentration difference between the pore water in the mortar or concrete and that in moisture present in some adjacent source of sulfate, a simulated laboratory test is required to test resistant formulations.

2. A simulation test for mortar has been devised and shown to work well for the UK. It is under consideration as the basis of a European Standard.

3. For testing of concrete in sulfate solutions, one of the solutions should be matched in $S0_4$ concentration to that in the pore water of the concrete under test.

4. In order to better simulate sulfate attack on completely buried concrete foundations, concrete in sulfate solutions in the laboratory should be presented to the solution in a more realistic way.

5. Better simulation of field exposure in laboratory testing of concrete for sulfate attack, would produce a reduced rate of sulfate penetration into test specimens. This would reflect field observations that attack on well made concrete completely buried in sulfate-bearing ground is a fairly rare event.

REFERENCES

1. BRE Digest 363. Sulfate and acid resistance of concrete in the ground. Construction Research Communications Ltd. London.
2. Laboratory scale tests on building mortars for durability and related properties. Harrison W.H. and Gaze M.E. J.Brit.Mas.Soc., Masonry International, 3, 1. 1989.
3. Pore solution chemistry and alkali aggregate reaction. Nixon P.J. and Page C.L. Concrete durability. Katherine and Bryant Mather lnternational Conference, Atlanta (1987) p. 1837.
4. Pore solution composition and chloride binding capacity of silica-fume cement pastes. Page C.L. and Vennesland 0. Materiaux et constructions. 16, No.91, (1983) Table II.
5. British Standard for Concrete BS5328 Part 1:1997 Guide to specifying concrete, Table 7.
6. Effects of electrochemical chloride extraction on chemical and mechanical properties of hydrated cement paste. Bertolini L, Yu S.W. and Page C.L. Advances in cement research, 1996, 8, No.31, July , Fig 11, p.98.
7. The composition of ettringite in set Portland cement. Midgley H.G. and Rosaman D. Fourth international symposium on the chemistry of cement. Washington D.C. (1960) Paper 111—52.