Communities and Local Government

Sulfate damage to concrete floors on sulfate-bearing hardcore

Identification and remediation

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Executive Summary

This document gives guidance on sulfate-attack damage to houses from the past use of sulfate-bearing hardcore and infill material.

Background to the guidance

Sulfate-bearing hardcore, derived from colliery spoil and other industrial by-products, was included in the construction of hundred of thousands of domestic properties in the period 1945 – 1970 as support for concrete floor slabs. The legacy has been a continuing occurrence of damage to floor slabs and abutting walls as sulfate from the hardcore has attacked the overlying concrete. Remediation of such damage is rarely covered by household insurance, as the cause is deemed to be a latent construction defect. Thus, in most cases, owner-occupiers have had to pay (typically £10-20k) out of their own pockets for repair. The situation has promoted a blight of numerous housing estates where cases have occurred, since prospective buyers and professionals concerned with house purchase and mortgages have naturally been very cautious when dealing with properties that may have sulfate attack. In some cases the only way to remove such blight has been the expenditure of government funds to remediate properties en masse.

The overall aim of this project is to provide authoritative guidance to local authorities, professionals and homeowners who are concerned with damage to houses and other dwellings caused by sulfate attack to floor slabs resulting from past use of sulfate-bearing hardcore.

Preparation of this document has required discussions with numerous professionals who are stakeholders in problems arising from sulfate-bearing hardcore. Their views have been diverse and sometimes times conflicting, typically reflecting differences in practice according to regional location. As a consequence, to be nationally acceptable, the guidance necessarily includes several options for procedures for investigation, assessment and remedial measures. As clearly stated, in the introduction to this document, it remains the responsibility of the professionals involved with a particular property to decide which of the options to utilise. Their actions will rightly be based on local experience and housing market constraints. Each dwelling will need to be considered on its own merits.

Outline of the guidance document

Sections 1 to 5 provide information on the mechanism of sulfate attack and where it is most likely to be found. Key points made are:

- For deleterious sulfate attack to occur in a ground floor slab, the concrete must be of a type susceptible to sulfate attack and it must be in direct contact with hardcore that contains a substantial amount of sulfates and moisture. No deleterious level of sulfate attack has been found where an intervening damp-proof membrane separates the concrete from the hardcore.
- Domestic buildings constructed from the early 1970s onwards are unlikely to have concrete floor slabs that will be affected by sulfate attack owing to a general recognition of problems arising from sulfate-bearing fills and adoption of appropriate design and construction measures.

Sections 6 to 8 provide information on the diagnostic procedures of sulfate attack and the assessment of the potential for further damage. Guidance is given on:

- The mechanism of damage, including how expansion of the sulfate-attacked concrete causes doming of the floor slab and pushes out walls below DPC.
- How to confirm the cause of damage by laboratory examination of concrete and hardcore.
- What factors to take into account when assessing risk – the likelihood of a further development of sulfate attack, compounded by the seriousness of the consequences.

Section 9 discusses the options for carrying out remedial works following sulfate attack, including the need to comply with recently introduced Building Regulations concerning insulation of floors and the provision (in some areas) of measures to prevent ingress of radon gas.

Section 10 outlines the environmentally correct procedures for disposal of wastes resulting from removal of hardcore and sulfate-attacked concrete.

Contents

1. Introduction

This guidance deals with damage to houses caused by sulfate attack to concrete floor slabs and oversite concrete that are placed directly on hardcore (fill) containing reactive sulfates.

Sulfate-bearing hardcore, derived from colliery spoil and other industrial by-products, was included in the construction of many thousands of domestic properties in the period 1945–1970, as support for concrete floor slabs, without the use of a separating damp-proof membrane. The legacy has been a continuing occurrence of damage to floor slabs and abutting walls as sulfate from the hardcore has reacted with the overlying concrete resulting in cracking, expansion and deformation. Figure 1 shows typical damage to a floor slab in a house built in the 1950s.

The aim of this guidance is to provide an understanding of the problem and to recommend a toolkit of techniques which professionals dealing with affected houses can use to identify sulfate attack and deal with any consequent problems or damage. It remains the responsibility of the professionals involved with each particular property to decide which of these techniques to utilise, to prioritise the criteria for assessment of current and possible future damage, and to decide which remedial measures to employ, if indeed any. Their actions will be based necessarily on local experience and housing market constraints.

This guidance does not cover the expansion of hardcore and consequent building damage resulting from the self-expansion of metaliferous slags[1] or of geological materials containing the potentially reactive mineral pyrite.[2] Both of these problems are (briefly) dealt with in BRE Digest 276: Hardcore.[3]

Figure 1: Distortion and cracking of a concrete floor slab caused by sulfate attack. Damage is greatest in front of the fireplace where water, carrying sulfates from underlying hardcore, has been drawn through the slab by heat from the fire.

2. What are sulfates and sulfate attack?

Sulfates are salts in which the negatively charged ion (anion) SO_4^{2-} forms a compound with a metal positively charged ion (cation) such as Ca^{2+}. In hardcore we are concerned primarily with sulfates that are readily soluble in water and which can therefore be readily transported to react with concrete. Such sulfates include gypsum (calcium sulfate, $CaSO_4$), epsomite (magnesium sulfate, $MgSO_4$), and Glauber's salt (sodium sulfate, Na_2SO_4). Sulfate-bearing materials which have been used in the past as hardcore in domestic properties include burnt colliery spoil (red ash or red shale), furnace bottom ash (black ash), blastfurnace slag, oxidised pyritic shales, and demolition debris containing gypsum plaster. Geographical occurrence of these materials is discussed in Section 5.

The amount of soluble sulfates present in the material is a vital factor in determining the potential for sulfate attack on concrete. Unfortunately, it may be difficult to get representative values of soluble sulfates in some materials because of their inherent variability. A suggested procedure for existing hardcore is detailed in Section 7.

Where a concrete slab overlies moist sulfate-bearing hardcore without an effective intervening waterproof membrane, the sulfates in hardcore may migrate into the concrete where they react with constituents in the cement matrix. Two sulfate attack mechanisms have been identified as affecting concrete slabs and oversite concrete:

Box 1: What is hardcore?

Hardcore is fill material used in building construction to raise ground levels and provide a dry, firm and level base on which to cast a concrete ground floor slab or 'oversite' concrete beneath suspended floors. To avoid subsequent problems, materials for hardcore should be granular, free-draining and consolidate readily. The hardcore should be well-compacted in layers of appropriate thickness. Materials should also be chemically inert and not physically affected by water. Unfortunately, some of the materials and placing procedures used in the past have not met these requirements and there has been consequent damage to buildings. The principal problems have been chemical attack by hardcore materials on concrete, settlement due to poor compaction, and swelling or consolidation resulting from changes in moisture content and/or chemical instability. An overview of hardcore is given in BRE Digest 276:1992.[3]

(i) Conventional or ettringite form of sulfate attack

In this type of attack, sulfates and water react with the tricalcium aluminate found in Portland cement to form a calcium sulfo-aluminate hydrate ($3CaO.Al_2O_3.3CaSO_4.31H_2O$) known as ettringite. This type of sulfate reaction has long been known and most published guidance on sulfate attack has addressed this mode. The formation of ettringite can be destructively expansive since it has a solid volume greater than the original constituents and typically grows as myriad acicular (needle-shaped) crystals that can collectively generate high internal stresses in the concrete.

To produce deleterious amounts of ettringite the reaction requires the presence of:

- a significant concentration of water-soluble sulfates
- concrete which contains a substantial content of calcium aluminate hydrates, as is the case in concrete made with most Portland cements
- wet conditions.

Incoming sulfate ions may also react with calcium hydroxide $Ca(OH)_2$ in the cement matrix of concrete to form gypsum (calcium sulfate dihydrate, $CaSO_4.2H_2O$). This reaction product also has a greater solid volume than the original constituents and in some cases can contribute to degradation of the concrete. If magnesium ions accompany the sulfates, they may also react with calcium hydroxide, producing brucite (magnesium hydroxide, $Mg(OH)_2$) which because of its low solubility precipitates out of solution, also leading to an increase in solid volume. Magnesium ions may also attack calcium silicate hydrates, the principal bonding material in set concrete.

Laboratory tests show that the first effect of the conventional form of sulfate attack is to increase the strength and density of the concrete as the reaction products fill the pore space. When it is filled, further ettringite formation induces expansive internal stresses in the concrete which, if greater than the tensile strength of the concrete, will expansively disrupt the affected region. This cracking together with white crystalline accumulations are the characteristic signs of the conventional form of sulfate attack.

(ii) The thaumasite form of sulfate attack (TSA)

This form of sulfate attack was first recognised in the UK in the 1990s and has since been found in several floor slabs and in oversite concrete. The reaction product is the mineral thaumasite which is a calcium silicate carbonate sulfate hydrate, ($CaSiO_3.CaCO_3.CaSO_4.15H_2O$).

Deleterious levels of TSA require the following:

- a significant concentration of water-soluble sulfates
- concrete which contains calcium silicate hydrates, as mostly derived from cementitious calcium silicate phases in Portland cements
- a source of carbonate, generally from a limestone aggregate
- a pH of 10 or higher, such as found in non-carbonated concrete
- persistent wetness
- low temperature (generally below 15°C).

Since the calcium silicate hydrates provide the main binding agent in Portland cement, this form of attack weakens the concrete as well as causing some expansion and, in advanced cases, the cement paste matrix is eventually reduced to a mushy, incohesive mass.

Further details of the chemistry of sulfate attack and factors contributing to its occurrence may be found in BRE Special Digest 1 SD1:1965).[4]

3. Factors that contribute to deleterious sulfate attack

The principal chemical factors required for sulfate attack identified in Section 2 are discussed here in terms of the likelihood of their occurrence. Additionally, other contributing factors are discussed which play a significant role in determining the likelihood of sulfate attack and its severity.

Factors inherent in hardcore

- The types of sulfate in hardcore are important. For sulfate attack to occur in floor slabs, sulfates must be carried into the concrete by interstitial water. Four sulfate compounds are both water-soluble and common in geological materials, namely: calcium sulfate, magnesium sulfate, sodium sulfate and potassium sulfate. Calcium sulfate is the most prevalent, but the least soluble (giving a maximum dissolved concentration of about 1400 mg SO_4 per litre of water) and because of that it is the least harmful to concrete.

  The other sulfates are much more soluble and potentially harmful to concrete since they can approach the concrete in large concentrations. Of these, magnesium sulfate can be particularly harmful as the magnesium cations from this can themselves contribute to destruction of concrete.

  The respective contributions of the four sulfate compounds are taken into account in the 2:1 water/solids extract test for sulfates[4] which caps the amount of calcium sulfate extracted, whilst allowing full extraction of the other more soluble sulfates.

- The total amount of sulfates in the hardcore is a significant factor. This depends on the concentration of sulfates in a unit volume of hardcore and the overall thickness of the hardcore. If a large reservoir of sulfates is present sulfate attack can be progressive over many years as sulfate in water in contact with the concrete is replenished. The acid-soluble sulfate test for fill materials addresses this factor.[4]

- The degree to which the sulfates are bound within the hardcore material is relevant. In some materials, such as blastfurnace slag, a substantial proportion of the sulfate may be locked in fused granules and be inaccessible for solution by interstitial water. In other materials, such as burnt colliery spoil, it is more readily soluble.

- The general inhomogeneity of hardcore derived from waste materials is a factor to be borne in mind when investigating it for sulfates. Sulfate contents can be expected to have varied substantially in the originally deposited hardcore and may have been changed subsequently by flow of interstitial water through the hardcore.

  Figures 2 and 3 show sulfate contents measured by the Building Research Establishment (BRE) in burnt colliery spoil (red shale) hardcore sampled at depths below a concrete floor slab in two rooms (kitchen and lounge) of a house in Stoke on Trent. Total amounts of sulfate in the material, as determined by acid extraction (Figure 2) on handful sized samples, vary erratically from 1.3 to 2.25 per cent SO_4, reflecting the original variability of the hardcore . In contrast, water-soluble sulfates by 2:1 water/solids extraction on the same samples (Figure 3) show profiles with depth that have undoubtedly been influenced by upward passage of water through the hardcore. This extract test is weighted in favour of the more soluble sulfates (those of magnesium, sodium and potassium which are potentially more harmful to concrete) and it is evident that these have been drawn upwards so that concentration increases with proximity to the concrete slab. Moreover the two rooms give substantially different results, presumably reflecting different water migration regimes. The lower values in the kitchen area (and particularly the topmost result measured just below the overlying concrete slab) may also indicate that here there has been a depletion owing to migration of sulfates into the overlying concrete.

Overall, the variability of results (some 70%), demonstrates the inappropriateness of evaluating the potential for future sulfate attack using just one or two test results on a house as the sole criterion.

- The presence of a substantial proportion of fines in the hardcore will promote upward flow of sulfate-bearing water by capillary action.
- The presence in some types of hardcore of pyrite (iron disulfide) that can oxidise as a result of exposure to air, water and bacteria, leading to the formation of additional sulfates.[4] Hardcore of this category includes incompletely or unburnt coal mine spoil and some quarried rocks such as the Cleveland Ironstone formation.

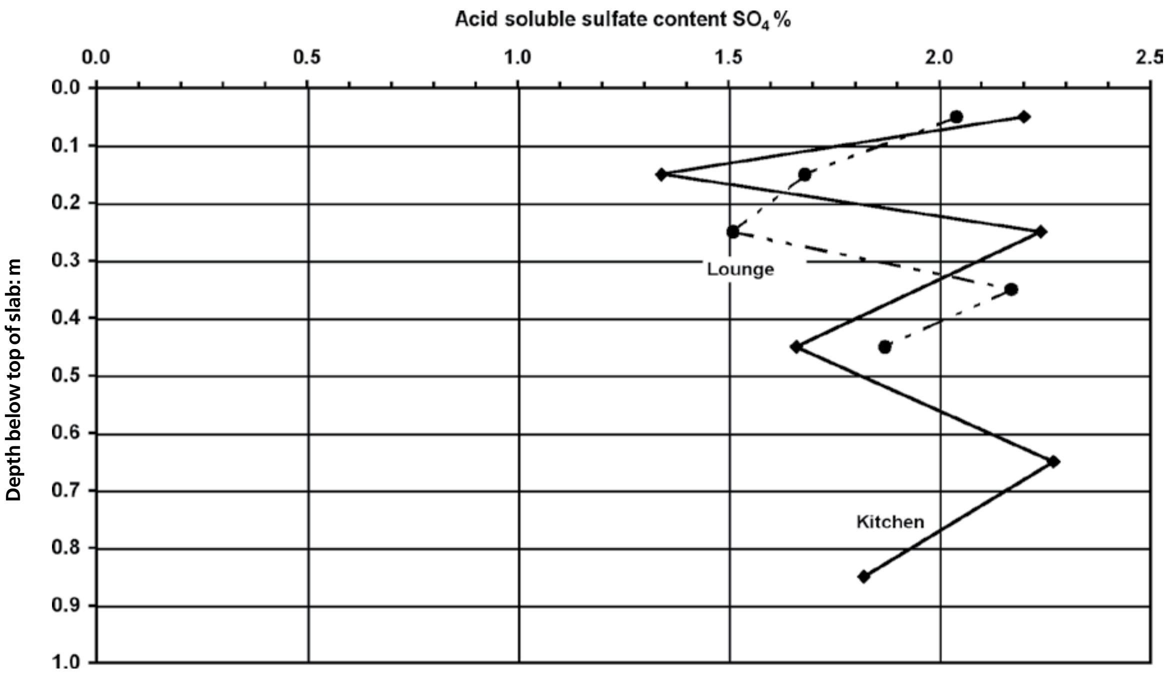


Figure 2: Acid-soluble sulfate contents in burnt colliery spoil (red shale) sampled at depths below a concrete floor slab in a 40 year old house. The values, which represent the total amount of sulfates present in the hardcore, vary erratically with depth from 1.3 to 2.25 per cent SO_4, reflecting the original variability of the hardcore.

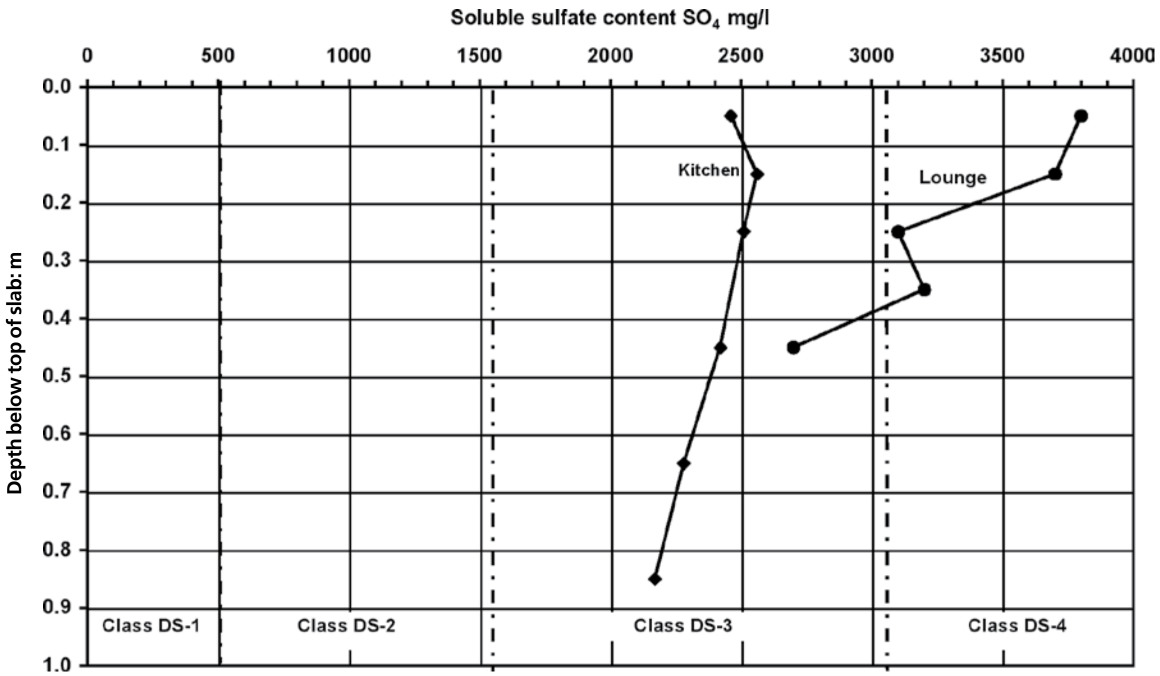


Figure 3: Water-soluble sulfate contents in burnt colliery spoil (red shale) sampled at depths below a concrete floor slab in a 40 year old house. Also shown are the Sulfate Class Limits from BRE SD1:2005. The profiles show values of sulfate which increase upwards. This is likely to be due to these soluble sulfates being drawn upwards by water passing through the slab to the warm rooms above.

Factors inherent in concrete

- Whilst several chemically different types of concrete have been used in construction over the years, the type used for floor slabs has invariably been one based on the use of Portland cement, and of these the majority have employed the commonly available ordinary Portland cement (OPC). This type of cement is the most vulnerable to sulfate attack as it imparts to concrete abundant amounts of both calcium aluminate hydrates and calcium silicate hydrates that are readily attacked by sulfates. Some past use may, however, be expected of a variety of Portland cement that has a restricted amount of tricalcium aluminate (C_3A in cement notation) known as sulfate-resisting Portland cement (SRPC). Use of this was recommended for concretes exposed to sulfate environments in BRE Digests from 1951 onwards, and explicitly recommended for concrete floor slabs from 1968 onwards.
- In addition to the cement type, the vulnerability of concrete to sulfate attack depends on how easily sulfates can migrate into it. What controls this is the permeability of the concrete to water, a property which depends on the size and interconnectivity of pores in concrete. Concrete that is well-mixed and well-compacted and has a moderate to high cement content and a low ratio of mix water to cement is the least permeable and therefore has the greatest resistance to sulfate attack. Unfortunately, such concrete is not typical of many floor slabs and oversite concrete constructed in the early decades after World War 2, where concrete was often mixed on site with minimal amounts of cement and liberal amounts of water and only lightly compacted.

- Concrete which has become partly or wholly 'carbonated' is more resistant to sulfate attack. Carbonation of concrete results from a reaction with carbon dioxide (CO_2) from the air. The principal reaction is with the calcium hydroxide $Ca(OH)_2$ in the matrix of concrete, the end products being calcite ($CaCO_3$) and water. The reaction results in a loss of alkalinity that is associated with the presence of calcium hydroxide (pH may drop from greater than 12 to less than 9) and as a result the formation of the expansive minerals ettringite and thaumasite, which needs a high pH, is impeded.

  Carbonation of concrete proceeds most readily in permeable concrete that is exposed at warm temperatures to air with a relative humidity of 50-70 per cent and is progressive with time, starting at the concrete surface. Wet conditions impede carbonation. Since, however, the former conditions will be encountered by many floor slabs during some of their life, a significant amount of carbonation and consequent resistance to sulfate attack may be expected.

- A few cases of sulfate attack have been reported where the concrete has been contaminated with excess sulfates as a result of faulty cement production, or where there has been on-site contamination with gypsum plaster.

Migration of sulfates

- Sulfates in hardcore will not be harmful to concrete if the hardcore remains dry. Water is needed to dissolve the sulfates and transport the sulfate anions to the concrete. Water is also needed for deleterious sulfate reactions in the concrete. The amount of water needed is not large, the hardcore need only be moist rather than saturated, for example in the case illustrated in Figures 2 and 3 the moisture content of the hardcore was a modest 12-14 per cent. A common source is groundwater that is drawn up through the finer fraction of the hardcore by capillary action. Occasionally the source may be surface water floods, or leaking drains and water pipes. Once in contact with the concrete floor slab, the water is typically drawn through a concrete floor slab or oversite concrete by capillary action owing to evaporation from its upper surface.
- Sulfate migration from hardcore into concrete may be prevented by the use of a separating membrane. Polythene sheets, installed primarily as a damp-proof membranes (DPM), began to serve this purpose from the mid 1960s, and became almost universal for concrete slab construction on sulfate-bearing hardcore by the early 1970s. DPMs installed in the 1960s were typically only 500 gauge (125 micron) thick, and doubts have been cast by some practitioners on their effectiveness as a barrier to sulfate migration. However, no case of deleterious sulfate attack where such a membrane was installed has been brought to the attention of BRE. Thicker membranes that are more resistant to perforation during installation were installed in later decades (eg Figure 4), the current standard being 300 micron.

- A damp-proof membrane (DPM) has sometimes alternatively been installed at the top of the concrete slab and underlying the screed. Such a membrane will form a barrier to movement of water right through the slab driven by capillary action, and impede, but not prevent, sulfate migration into the concrete.
- Similarly, using an impermeable floor finish such as a layer of asphalt (common in the 1950s) or tiles of asphalt or plastic will impede, but not prevent, sulfate migration into the concrete. There have been cases where the stripping off of such a floor finish has been followed by rapid deterioration of the floor owing to sulfate attack.[5]

Figure 4: Laying of concrete in the mid 1970s on a 300 micron damp-proof membrane that has been placed over hardcore in the foundations of a house.

Construction factors

- **The form of construction of interior walls**. If any wall is founded on a floor slab or oversite concrete, then if the concrete element lifts and cracks, then so will the wall.
- **The form of construction of exterior walls below DPC**. Exterior walls are more likely to be displaced outwards by an the expanding floor slab if, as is common, the cavity below DPC has been infilled with cementitious material, or, if the exterior walls below DPC stand well above ground and therefore lack external support, eg due to the sloping away of the ground.
- **Time since construction**. The process of sulfate attack is typically slow. A period of several years is generally needed before chemical and physical changes to the concrete are sufficient to cause building damage.

4. Historical perspective

Use of hardcore in house construction first became common in mid-1940s. In the immediate post-war period, when construction materials were in short supply, solid floors, comprising a concrete floor slab over hardcore, largely superseded suspended timber floors that were typically used in the 1930s. Also, waste materials, such as burnt colliery shale and blastfurnace slag were promoted by government as being appropriate materials for use. Unfortunately, little or no guidance on the selection and use of suitable materials was available in the early post-war years and there was some use of deleterious materials, and particularly of materials containing sulfate. Whilst it was always standard practice for such solid floor construction to incorporate a damp-proof membrane (DPM), it was not until the 1960s that it became common to use a polythene sheet below the concrete floor slab as a DPM.

A history of national recommendations given for new construction in respect of sulfate-bearing hardcore is itemised in Box 2 and a parallel history concerning damp-proof membranes is summarised in Box 3. Together, these histories indicate the age of properties that might have hardcore with significant levels of sulfate and what measures (if any) may have been taken to minimise risk of sulfate attack. The following conclusions may be drawn:

- Domestic buildings constructed from the 1940s through to the mid-1970s may have solid floors that include hardcore which has relatively high levels of sulfates, but have no protective measures that will prevent sulfate attack on concrete floor slabs or oversite concrete.
- There is no limit to the thickness of hardcore that may be encountered in pre-1970 houses. Thicknesses of up to 1.5 m are not uncommon, particularly on sloping sites.
- Domestic buildings constructed from the late 1950s onwards have an increasing likelihood of incorporating precautionary measures that will minimise or prevent sulfate attack on concrete floor slabs or oversite concrete. These include more careful selection of hardcore, the use of a waterproof membrane to separate hardcore from concrete, and the use of sulfate-resisting concrete.
- Domestic buildings constructed from the early-1970s onwards are unlikely to have concrete floor slabs that will be affected by sulfate attack.
- Domestic buildings constructed from the mid-1970s onwards are unlikely to have oversite concrete that will be affected by sulfate attack.
- No particular type of low-rise building stock is potentially more affected by sulfate-bearing hardcore than any other type. Affected properties may include traditional brick-built houses and also most of the post-war innovative forms of construction, such as the Wimpey No-fines concrete and Cornish Units types.

Box 2: History of recommendations for new construction concerning sulfate-bearing hardcore

1951 Ministry of Works Housing Manual[6] stated 'During the present shortage of timber, the construction of ground floors of wood joists and boards is not allowed except on steeply sloping sites where the cost of a solid concrete floor would be prohibitive. Solid ground floors, which are being laid generally today are, proving highly satisfactory when properly constructed, and seem likely to be used even if timber becomes freely available again'. No guidance was given in this manual on the selection of appropriate materials for hardcore.

1956 BRS Digest 84[7] warned of problems arising from use of sulfate-bearing colliery shale and issued the advice that 'on wet sites, a covering of waterproof building paper be laid over the shale before the concrete is placed'.

1964 A paper published in the Municipal Journal[8], advised that 'since there is no sure way of obtaining [colliery] shale of low sulfate content, it is necessary to prevent transfer of sulfates from the shale to the concrete. The simplest way of doing this is to lay a sheet of polythene or waterproof building paper on the hardcore before placing the concrete'.

1965 Building Regulations[9] published February 1966 included Regulation C3 (3) which stated 'No hardcore laid under such floor shall contain water-soluble sulfates or other deleterious matter in such quantities as to be liable to cause damage to any part of the floor'. Note that, neither in these, nor in subsequent Building Regulations, was there any directive that a membrane should be included between hardcore and floor specifically to stop floor damage from sulfate attack.

1965 Shaws' Commentary on the 1965 Building Regulations[10] recommended that, due to problems with the control of quality of hardcore, 'it is advisable in any case of doubt to insert a suitable membrane to separate the hardcore from the floor or to construct the slab using sulfate resisting cement'.

1968 BRE Digest 90[11] informed of the potential damage to properties arising from attack on floor slabs due to the presence of sulfate-bearing hardcore. However, no precautions specific to floor slabs were included. It is presumed that many persons responsible for domestic building design and construction would have acted on the Digest information either by avoiding use of hardcore containing substantial levels of sulfate, and/or use of Table 1 of the Digest to specify an appropriate mix of sulfate-resistant concrete.

1972 BRE Digest 142[12] gave the first comprehensive guidance on the selection of materials for use as hardcore. This advised that 'the soluble sulfate content in representative samples of hardcore for use on a wet site and which will be in contact with normal Portland cement concrete should not exceed 0.5%'. It further advised that 'concrete can be protected against excess sulfates by a layer of bitumen felt or plastic sheeting placed on the hardcore; alternatively, or in addition, more resistant types of cement can be used'.

1973 National House Building Council (NHBC) Practice Note 6[13] issued as guidance for private sector development, effectively banned use of solid floors which had hardcore greater than 600 mm deep, specifying instead the use of suspended floors. While this measure was introduced primarily to avoid problems with compaction of fill, it also further reduced the likelihood of attack from sulfate-bearing hardcore.

Box 2: History of recommendations for new construction concerning sulfate-bearing hardcore *(continued)*

1979 Digest 222[14] superseded Digest 142 and gave recommendations for assessment of hardcore in terms of Sulfate Class based on determination of water-soluble sulfate. For Class 2 sulfate conditions and above the digest states 'it is recommended that a water barrier such as a polythene sheet is placed beneath any concrete floor slab as an additional precaution'. The digest no longer explicitly offers sulfate-resisting concrete as an alternative to use of a membrane, though reference is made to Digest 174[15] which deals with the design of concretes to resist sulfate attack.

1983 Digest 276[16] superseded Digest 222 and gave the following multi-layered recommendations:

"In general, hardcore materials containing sulfates should be avoided

Alternatively, a concrete quality should be chosen that will resist the effects of sulfates … in accordance with the recommendations of Digest 250.[17]

If any sulfate is found or suspected in hardcore, a moisture barrier (such as a polythene sheet at least 0.2 mm thick should be placed between the hardcore and the concrete floor slab."

1991 Digest 363[18] stated that hardcore of sulfate Classes 3, 4 & 5 were not recommended for use, even with a membrane used between the fill and the hardcore.

1992 Digest 276[3] was re-issued with the clarification that 'in general, hardcore materials containing water soluble sulfates above Class 2 in Digest 363 should not be used beneath concrete ground floor slabs'.

2004 Approved Document C of Building Regulations 2000[19] instructed, with reference to the mandatory damp-proof membrane for floors that 'If the ground could contain soluble sulfates, or there is any risk that sulfate or other deleterious matter could contaminate the hardcore, the membrane should be placed at the base of the concrete slab'. The included approved method is to install polythene sheeting at least 300 microns thick.

2005 Third edition of Special Digest 1[4] (which first superseded Digest 363 in 2001) omits specific reference to concrete floor slabs supported by hardcore owing to the comprehensive recommendations now included in UK Building Regulations.

Box 3: History of recommendations for new construction concerning damp-proof membranes

Damp-proof membranes (DPM) have been advocated for solid floors in most guidance issued for floors since at least 1950. Whilst such membranes have had a role in mitigating the risk of sulfate attack on floor slabs this was not their primary purpose. The essential role of DPM in respect of solid floors is to prevent passage of water through to the inside of a dwelling. As such, a DPM may be either laid below a concrete floor slab, embedded within it (sandwich DPM), or laid on the surface of the slabs. A DPM placed directly below the concrete slab will additionally isolate concrete from any underlying hardcore and thereby prevent sulfate attack. A DPM within or on the upper surface of the slab will not prevent sulfate attack, but will significantly impede it. This is because it will resist the drawing of water through a concrete floor slab by a combination of evaporation from its upper surface and capillary action. Key guidance documents concerning DPM are as follows:

1949-1951 The Ministry of Works Housing Manual 1949 [6] stated that for solid ground floors 'If the floor is to be finished with material which is not in itself impervious to moisture, the floor should consist of two layers of concrete separated by one of a material impervious to water and water vapour. The lower layer of concrete should be at least 3 inches thick'. Recommended materials for this 'sandwich' DPM were coal-tar pitch and asphaltic bitumen laid at least 1/8 inch thick.

1966 In the1965 Building Regulations[9], Regulation C3 (1) gave a general requirement that 'such a part of a building as is next to the ground shall have a floor which is so constructed as to prevent passage of moisture from the ground to the upper surface of the floor'. In practice this requirement was often met by insertion of DPM between the main concrete slab and an overlying floor screed, rather than between hardcore and concrete. Such an arrangement was in fact specifically detailed in Regulation C5 (b) (i) for solid floors incorporating timber, viz ' the concrete incorporates a damp-proof sandwich membrane consisting of a continuous layer of hot applied soft bitumen or coal tar pitch not less than 1/8 inch thick, or consisting of not less than three coats of bitumen solution, bitumen/rubber emulsion or tar/rubber emulsion'. Further typical details of sandwich (within floor) and surface damp-proof membranes of this era were given in BS Code of Practice 102:1963[20] and BRE Digest 54 (1965)[21].

1965-1999 Subsequent editions of the Building Regulations prior to 2000 and guidelines such as the NHBC Standards have continued to require installation of a DPM and to permit this to be placed anywhere in relation to the floor, as long as it prevented passage of water through to the inside of the dwelling. Nevertheless, it remained an option for this DPM to be installed between hardcore and concrete thereby simultaneously preventing sulfate attack.

2004 Approved Document C of Building Regulations 2000[19] instructed, with reference to the mandatory damp-proof membrane for floors that 'If the ground could contain soluble sulfates, or there is any risk that sulfate or other deleterious matter could contaminate the hardcore, the membrane should be placed at the base of the concrete slab'.

5. Regions where sulfate-bearing hardcore was utilised

Whilst scattered cases of sulfate attack to floor slabs have been reported to the Building Research Establishment (BRE) from across the UK, the large majority have been located in and adjacent to the coal fields and related industrial centres that ultilised the coal for iron and steel production (Figure 5). Prominent amongst the affected areas are the English Midlands from Coventry and Birmingham northwards to Stoke-on-Trent and east Cheshire, the North-east of England from Doncaster northwards to Newcastle upon Tyne, and the Midland Valley of Scotland between Glasgow and Edinburgh. In these areas the sulfate-bearing material typically comprises burnt colliery spoil (called locally red shale or red ash) taken from coal mine tips, coal combustion ashes from furnaces (often called black ash) and blastfurnace slags from the smelting of iron.

Elsewhere, clusters of sulfate attack have been associated with the use of certain geological strata as hardcore, for example the use in the Whitby – Middlesbrough region of sulfide and sulfate-bearing shaley mudstones of the Whitby Mudstone Formation and Cleveland Ironstone Formation (known locally as Cleveland shale), though with this material internal expansion is often the key problem.

The individually scattered cases of sulfate attack known to BRE have generally been associated with the local use of coal combustion ashes or of brick rubble that has been contaminated with gypsum (calcium sulfate) plaster. Hull is one area reported as formerly having many properties with such plaster-contaminated rubble, the source of which were buildings destroyed by World War 2 bombing.

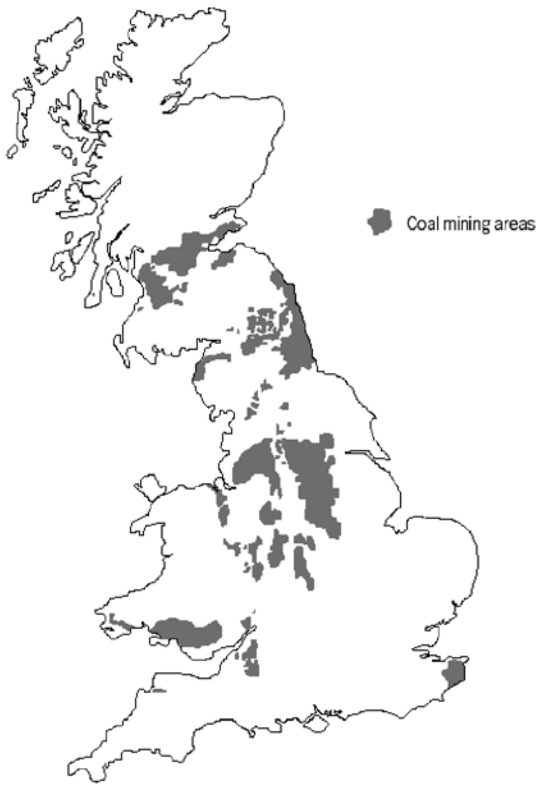


Figure 5: Map showing Coalfield areas of the UK. In and adjacent to these areas there has been widespread use of sulfate-bearing hardcore derived from burnt colliery spoil, furnace bottom ash and mineral processing slags.

6. How to recognise typical damage from sulfate attack

The mechanism of damage

An excellent account of damage caused to buildings by sulfate attack is included in Chapter 3 of the BRE Building Elements book: *Floors and flooring, performance, diagnosis, maintenance, repair and the avoidance of defects*, (BR 460)[22], and from which Figure 6 (below) is taken.

Expansive sulfate reaction within the concrete floor slabs will tend to produce horizontal expansion of the floor slab or oversite concrete. However, these are generally constrained at the perimeter, where the concrete abuts external and internal walls. As a result the slab or oversite concrete is typically uplifted into a dome shape which, with time, may achieve a deflection of several centimetres. The doming will put the upper part of the concrete element into tension, leading to a map pattern of cracking (Figure 1). This cracking may penetrate through floor slabs, or be confined to the topmost 'screed' layer, which often comprises a much weaker mix of sand and cement, 25–35 mm thick.

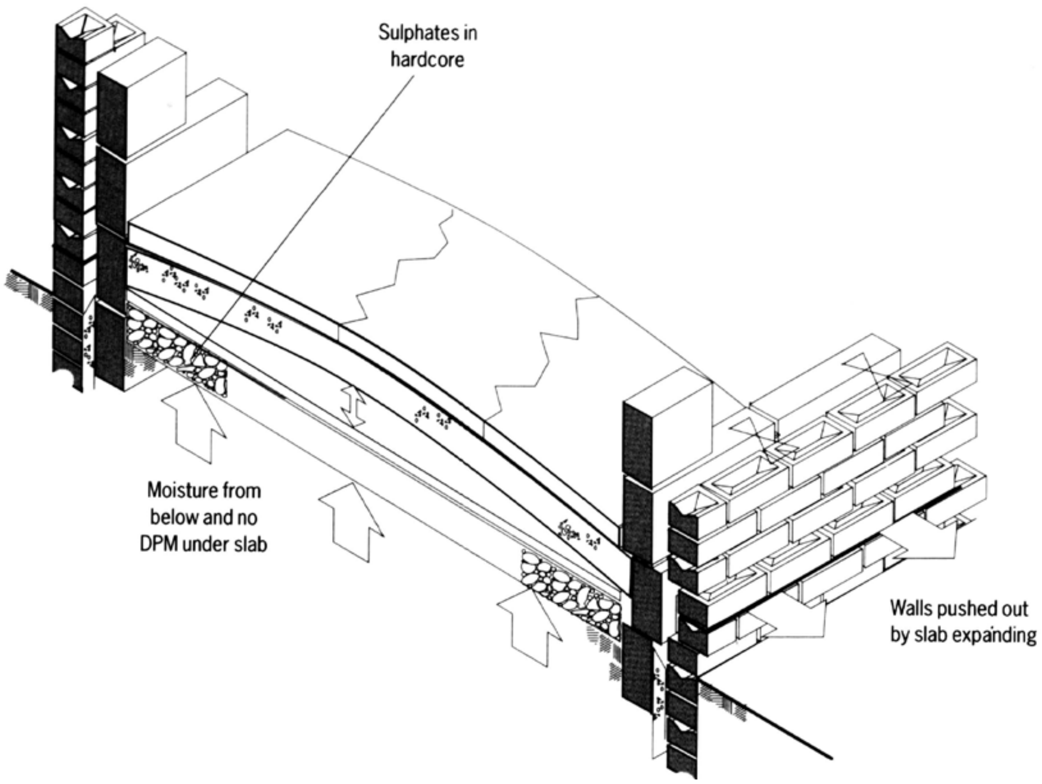


Figure 6: Doming and cracking of floor slab and outward displacement of walls resulting from expansion of concrete due to sulfate attack.

Figures 7(a) to 7(c) show sulfate attacked oversite concrete that was laid over plaster contaminated brick rubble beneath a suspended wooden floor of a bungalow in the West Midlands. The concrete, much softened as result of TSA, domed upwards in several rooms lifting the sleeper walls that supported the floor. The doming was accompanied by radiating and map pattern cracks.

Figures 7(a, b & c): Sulfate-attacked oversite concrete that was laid over plaster contaminated brick rubble beneath a suspended wooden floor (here removed together with the sleeper walls).

(a) An improvised straight edge shows some 50 mm doming of the oversite concrete that lifted brick sleeper walls and wooden floors.

(b) Map pattern cracks in sulfate-attacked oversite concrete beneath a suspended wooden floor of an adjacent room.

c

(c) 70 mm thick sample of oversite concrete affected by TSA. The concrete has been softened and discoloured white and yellow-brown. Much white thaumasite can be seen in the upper part of the section. Concrete missing from the bottom of the section was so friable it fell away during sampling.

In the worst cases the external walls bounding the floor slab can be pushed outwards, causing undersailing or over-sailing at the damp-proof course (DPC) and/or disruption of the masonry (eg Figures 8(a) and 8(b)). Where, however, the wall cavity is not filled with concrete or mortar beneath DPC, the outward movement of the concrete slab can push the inner leaf towards the outer leaf without necessarily moving the latter.

Visible appearance

The first visible sign of sulfate attack to a concrete floor slab is usually some unevenness in the floor. This may be accompanied by appearance of cracks in the concrete screed and floor finish that are at first narrow, but which widen with time (eg Figure 9). The unevenness of the floor will typically progress into an obvious heave and there may be increasing difficulty in using internal doors as a result of the lower edge

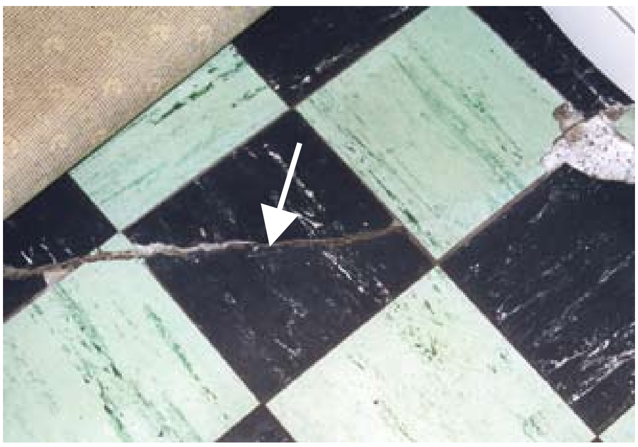


Figure 9: Stepped crack in floor of 1950s house that may indicate sulfate attack. The uneveness could be felt through the (rolled back) carpet.

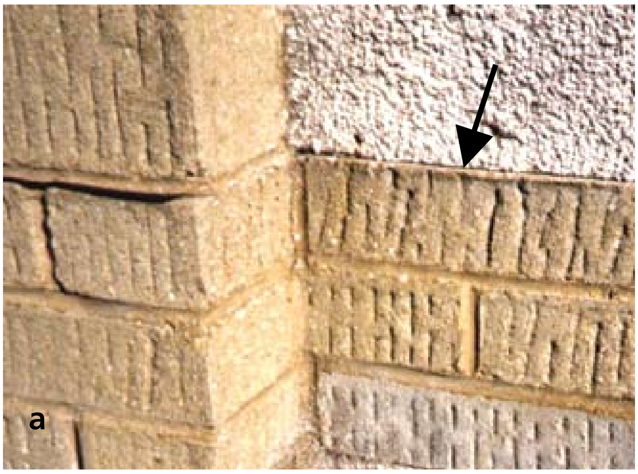
fouling the floor. However, lifting is generally highest in the centre of the room resulting in a doming in the floor that is detectable with an adequately long straight edge. The doming is commonly accompanied by a radiating or map pattern of cracking, with some cracks making vertical steps in the floor of the order of several millimetres.

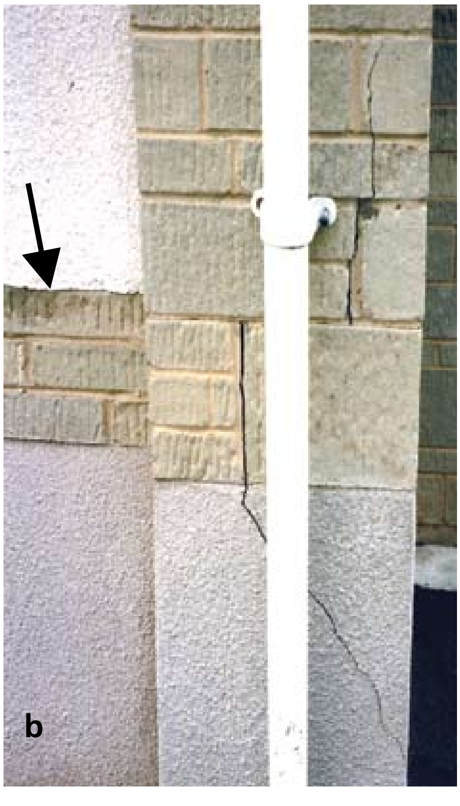
Externally, the pushing out of walls by the sideways expansion initially causes horizontal cracks to appear in mortar courses at or near to DPC level. With time these typically show a horizontal step in the masonry with the courses above being thrust out (oversailing) relative to the courses below. There may also be irregular displacement of blocks of the wall adjacent to the DPC particularly near to corners, as in Figures 8(a) and 8(b).

A further indication of sulfate attack may be efflorescence on the outer face of a wall which has mortar filled cavities below DPC level.

Most interior walls will be carried down to their own foundations and behave similarly to external walls. In some cases, however, partition walls will have been constructed using a floor slab as bottom support. Such walls may be uplifted by doming of the slab, causing deformation and diagonal cracking particularly near to door openings. Door openings and frames may distort from square, making doors difficult to open or close.

A hole excavated through the floor slab may reveal that the concrete has arched out of contact with the hardcore. The lower part of the slab thickness may show white crystalline deposits which are the products of the chemical reaction. If sulfate attack is advanced there may be sufficient loss of strength for concrete at the base of the slab to be broken by a hand. In the worst cases it may have deteriorated to a flaky consistency, or even (as in the case of severe TSA) a soft white mush.





Figures 8(a & b): Exterior of a bungalow affected by sulfate attack in South Wales. The worst damage is on the downslope side where there is about 1 m of exposed masonry below internal floor level.

(a) Wall below DPC level (arrowed) has been thrust outward by 5 mm by sideways expansion of the floor slab.

(b) Masonry at a corner, above and below DPC level, has been disrupted by outward thrusting of floor slab.

7. Confirming the cause of damage as sulfate attack

Where there is visual evidence of damage to floors or adjacent walls that may be the result of sulfate attack the following procedure may be followed to confirm or discount the suspected occurrence and assess the level of damage:

(1) Fully expose the ground floor slab or oversite concrete suspected as having sulfate attack. Record the character and extent of any cracks and the amount and extent of any doming of the concrete. Record any cracking or distortion of walls. Compare with the types of damage known to be characteristic of sulfate attack to floor slabs (see Section 6).

(2) Carry out a penetrative examination of the floor slab or oversite concrete at locations where damage is apparent. (It may be informative also to make a comparative examination at a location where there is no obvious damage.) Record the type of floor slab construction, thickness and appearance. Note the type, thickness, position and condition of any waterproof membrane. Take samples of the concrete as required for sulfate testing and petrographic examination. Compare the types of construction and DPM characteristics with the factors known to be relevant to the occurrence of sulfate attack (see Section 3). Compare the appearance of the concrete with that described in Section 5.

(3) Sulfate tests on the concrete can be made as given in BS 1881: Part 124: 1988[23]. The sulfate content should be expressed as % SO_4 by mass of cement (assuming cement comprises 15 per cent of the concrete mass). Sulfate attack on the concrete floor slab is indicated by a value of SO_4 that is significantly greater than 5 per cent by mass of cement. (As a guide, values of the order of 10–15 per cent have reported in some cases of severe sulfate attack). If conclusive proof of sulfate attack is necessary, samples can be taken for petrographic and/or X-Ray Diffraction (XRD) examination in a specialist laboratory to look for the presence of ettringite or thaumasite.

Sulfate testing and petrographic examination of the concrete may not be necessary if general appearance of concrete and sulfate tests on hardcore provide sure evidence that damage is due to sulfate attack.

(4) Examine the underlying blinding (if any) and hardcore, accessible through the holes made in the concrete floor slab. Note the composition and moisture condition of the hardcore, and if possible determine its depth. Take representative samples as required for petrographic examination, moisture content determination and sulfate analysis.

Representative samples should be taken of any separately identifiable materials and also from a range of depths. As a guide, for coarse-grained material (having more than 10 per cent of particle sizes larger than 20 mm), a sample mass of at least 3 kg is recommended. For fine and medium-grained material (having more than 90 per cent of particle sizes less than 20 mm), 0.5 kg should be sufficient. The key samples to be analysed first are the ones taken from the upper 300 mm of the hardcore.

Sulfate tests on hardcore samples from below 300mm may aid understanding of the source of the sulfates (if for example the hardcore adjacent to the concrete has become depleted of sulfates over time). They may also assist decisions on whether to remove all or part of the hardcore.

An appropriate test procedure is for the samples to be dried at a temperature not exceeding 70°C and the moisture contents determined. For chemical analysis, the dry sample can then be jaw crushed down to less than 10 mm size, then quartered down or riffled to obtain a 1 kg sample. This should be ground down to a maximum size of 2 mm. Divide the material passing a 2 mm sieve by successive riffling through a 15 mm divider to produce a sample weighing approximately 100 g. Then further grind to pass a 425 µm sieve.

A 2:1 water-soil extract test (see options in Table C10 of BRE SD1:2005 1[4]) may be used to determine water-soluble sulfate content and, if appropriate, the water-soluble magnesium content.

Table 1: Classification of sulfate-bearing hardcore
– based on Table C2 of Special Digest 1[4].

Sulfate content in 2:1 water/solids extract	Magnesium content in 2:1 water/soil extract	Sulfate Class
SO_4 mg/l(a)	**Mg mg/l**	
<500		DS-1
500-1500		DS-2
1600-3000		DS-3
3100-6000	≤1200	DS-4
3100-6000	>1200	DS-4m
>6000	≤1200	DS-5
>6000	>1200	DS-5m

Note (a): The use of mg/l (instead of g/l) as the unit of sulfate indicates that these Sulfate Classes have new limiting values as defined in SD1:2005.

The hardcore can be classified for sulfates using Table 1. An indication of the durability of existing Portland cement (PC) concretes can then be obtained by looking at the (fairly conservative) recommendations for new concrete in Table D2 of SD1:2005. From this, all old concretes should have good durability under wet conditions with Sulfate Class DS-1 providing there are no aggravating factors such as significant acidity. Additionally, PC concrete slabs may be expected to adequately resist sulfate attack under wet Sulfate Class DS-2 conditions providing the concrete is of good quality with a thickness of more than 140 mm. With wet Sulfate Class DS-3 conditions and above, SD1:2005 gives no assurance of durability for PC concretes.

Where conditions are nominally dry, SD1:2005 rates the durability of concretes for one Sulfate Class higher. For example, PC concretes that are of good quality with a thickness of more than 140 mm are indicated as adequately resisting sulfate attack under Sulfate Class DS-3 dry conditions.

In general, for Sulfate Class DS-3 and above, the higher the water-soluble sulfate content and corresponding sulfate class the more likely it is that any degradation of concrete in the slab has been caused by sulfate attack and the more likely it is that there is potential for further sulfate attack.

On the other hand, a low presently determined Sulfate Class, eg Class DS-2 and even Class DS-1, does not eliminate sulfate-bearing hardcore as the root cause of past floor slab damage as the majority of originally-contained sulfates may have already migrated into the concrete.

It is timely to remember that assessments based just on a one or two determinations of water-soluble sulfate may be misleading owing to the variability of the hardcore.

If the origin of the hardcore is a dark grey or black coloured sedimentary rock, eg unburnt colliery minestone or a quarried mudstone or shale, it is possible that it contains **pyrite**. Since pyrite is a latent source of additional sulfates (see Section 3.1), the amount present is relevant to assessment of the potential for future sulfate attack.

In the geological materials likely to be encountered as hardcore, an effective procedure for determining pyrite content is to determine both the total sulfur content (TS %S) and the acid-soluble sulfate (AS $\%SO_4$) content. Then the sulfate equivalent of pyrite content can be taken as equivalent to:

$$(3 \times TS - AS)\ \%SO_4$$

and the actual pyrite content as:

$$0.623 \times (3 \times TS - AS)\ \%\ FeS_2.$$

Further details on determination of pyrite are given in SD1:2005.[4] However, for evaluation of existing buildings, it will not be appropriate to follow the very conservative procedure given in that publication for determining a sulfate class for concrete design from the sulfate equivalent of pyrite content (known as Total Potential Sulfate).

For buildings that are several decades old, it may reasonably be assumed that any pyrite that was initially in a form readily susceptible to oxidation would already have been converted to sulfate, and that the remainder would disassociate only very slowly – enough perhaps to raise the sulfate class by one, but not more.

8. Assessing the potential for further damage

Any assessment of whether a building will be subjected to sulfate attack in the future should be based on its history to date and on the continued presence or absence of the various risk factors and mitigating factors that are discussed in Section 3. Knowledge of the floor construction and behaviour of other buildings in the neighbourhood can be valuable aid.

Such assessment calls for judgement from a practitioner who is experienced in this field and who carries appropriate professional indemnity insurance. What is clearly inappropriate is a simplistic judgement based solely on one or two spot determinations of soluble sulfate in hardcore: such a conclusion may be too optimistic or too pessimistic, owing to samples not being representative. And sole focus on the sulfate content of hardcore neglects relevant consideration of the character of the concrete and of the availability of a mechanism of sulfate transport.

With the exception of cases where a membrane has been found between the hardcore and the concrete, it is often difficult to be completely sure that a building, or parts of a building, which have sulfate-bearing hardcore will not be affected by sulfate attack in the future, particularly if there is a change in water regime. For example, hardcore, which has been hitherto too dry for sulfate attack to occur, could become wet owing to exceptional flooding of the area or leakage from a service pipe.

It may therefore be appropriate to make an assessment in terms of **probability** (the likelihood of an occurrence) or **risk** (likelihood of an occurrence compounded by the seriousness of the consequences), using qualifiers such as low, moderate and high.