This Digest provides guidance to engineers and builders on selecting and placing material for use as hardcore in building construction. It takes account of recent standards for specifying aggregate materials for use as hardcore, ensuring that the material is both physically stable and chemically inert.

In Part 1 candidate materials are reviewed, including recycled and secondary materials that are currently being promoted for use in construction as a sustainable option. Simplified recommendations for common situations are given in Section 6.

Part 2 deals with placing and compacting hardcore material. It also reviews some unsuitable materials that were used for hardcore before the mid-1970s, both as a cautionary note for current specifiers and as a guide for professionals dealing with a legacy of unstable hardcore problems in existing buildings.

This Digest replaces Digest 276, which is now withdrawn.

1 WHAT IS HARDCORE?

‘Hardcore’ is the construction term used to denote ‘engineered’ infill material that is placed within the confines of a building foundation (after removal of any unsuitable ground layers) in order to support a ground-bearing floor slab (Figure 1). Typical of older buildings, the term also refers to material used to support an ‘oversite’ concrete slab, which carries sleeper walls beneath a suspended timber floor. As such, the hardcore must provide a firm, dry, level base, at an appropriate height. Materials for hardcore should be granular and drain and compact readily, as well as being chemically inert and not affected by water. They should also be well compacted in layers of appropriate thickness.

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 occurrences have been chemical attack by hardcore materials on concrete, settlement due to poor compaction, and swelling or consolidation due to changes in water content and/or chemical instability. Because of these past failures, Approved Document C of The Building Regulations 2010 (England and Wales) includes, at Clause 4.7(a), the requirement for a ‘well-compacted hardcore bed, no greater than 600 mm deep, of clean, broken brick or similar inert material, free from materials including water-soluble sulfates in quantities that could damage the concrete’. The significance of these various characteristics is discussed in Section 3 (see the Appendix for alternative text for other UK countries).

In civil engineering terminology, material used for hardcore may be termed, according to context, an ‘unbound material’ or an ‘unbound mixture’ made up of aggregates. ‘Aggregate’ here is a general term for any granular material used in construction, while ‘unbound’ indicates that the material has no binding agent such as asphalt or cement.
This Digest describes materials for hardcore that conform to commonly used specifications and are examples of best practice. Their inclusion is not meant to exclude the use of materials specified by any alternative procedure that results in material that is demonstrably fit for purpose for use as hardcore in particular situations.

2 LIMITATIONS ON THE USE OF HARDCORE

The use of hardcore to support floors of buildings is appropriate only where the underlying ground is stable. The use of hardcore is not recommended where:

- the existing ground contains vegetative soil or organic matter including tree roots – this layer should be removed to leave an even bearing surface;
- the existing ground contains non-engineered fill;
- the existing ground comprises a clay soil that may shrink or swell significantly owing to changes in moisture content, such as that associated with the growth or removal of nearby trees;
- the existing ground comprises soft natural ground that may consolidate or compress significantly under superimposed load; or
- a hardcore thickness of greater than 600 mm would be required at any location for residential buildings.

Additionally, the advice of an appropriately qualified engineer should be sought where:

- for non-residential buildings the thickness of hardcore required to support a floor needs to be greater than 600 mm at any location within the foundations; or
- there is a potential for any upward groundwater flow into hardcore.

In the case of low-rise residential buildings, where any of the foregoing limiting ground conditions are encountered the use of suspended concrete floors is widely recommended.

3 SELECTION OF APPROPRIATE MATERIAL FOR HARDCORE

3.1 A framework for material selection

A good starting point for selecting materials for hardcore is the Approved Document to support Regulation 7 of The Building Regulations 2010 (England and Wales). This is a document that is often overlooked since it is not labelled with a letter, unlike the other Approved Documents. Building Regulation 7 states the ‘requirement’ that:

‘Building work shall be carried out:

a. with adequate and proper materials which:
   i. are appropriate for the circumstances in which they are used;
   ii. are adequately mixed or prepared; and
   iii. are applied, used or fixed so as adequately to perform the functions for which they are designed.’

The supporting Approved Document explains the ways in which the suitability of material for use for a particular purpose may be assessed. For hardcore these ways include:

- conformity with a British or European Standard;
- certification by an independent certification scheme, eg one accredited to the United Kingdom Accreditation Service (UKAS);
- tests and calculations; and
- past experience, eg satisfactory performance as in a building in use.

Material for use as hardcore in buildings needs to provide stable and adequately strong support for the ground floor slab and any superimposed loads during the working life of the building. Usually it will not be possible to rectify any post-construction problem originating in the hardcore without major disruption for building occupants and high remedial costs.

For this reason, the selection of material for hardcore must be undertaken with due care. In this context, it is relevant to note that material intended for the subbase of highways is often used as hardcore in buildings. While such subbase material generally does have all the properties needed for hardcore, the Highways Agency specifications for this material allow for it to be sometimes less dimensionally stable and more chemically active than is appropriate for use within the rigid confines of a building foundation and floor slab. Such marginal physical and chemical stability has been increasingly common in recent years, during which the specification for subbase has been extended to include greater use of recycled and secondary materials of marginal quality.

The essential characteristics of material to be used as hardcore are that it is:

- straightforward to handle, place and compact within the confines of a building foundation;
- capable of supporting the floor and superimposed loads without compression;
- dimensionally stable after placement, ie it must not be prone to expansion or compression;
- physically unaffected by change in water content;
- biologically inert, ie free from organic matter that might decay or sustain fungal growth;
- chemically inert, ie free of any substance that might react within the hardcore material causing volume change, or that might attack adjacent construction elements; and
- radioactively inert, eg not an emitter of radon gas.

One ideal material that will usually satisfy the above is clean, well-graded, granular aggregate comprising crushed hard rock (the rock should be crushed so that it passes through the holes of a 63 mm test sieve, and then sorted so that the product has a fairly even gradation of particle sizes such that smaller particles will readily fill voids that would otherwise be left between larger particles). The maximum particle size is chosen here to be compatible with compaction of the hardcore in placement layers of the order of 150–200 mm, which is the typical thickness possible with types of compaction plant appropriate for use within buildings.
The above term ‘clean’ requires the material to be free of any component or contaminating substance that renders it unfit for purpose. In respect of material made up entirely of naturally occurring rock, ‘clean’ may be taken to mean that the material:

- does not contain water-soluble sulfates in amounts that may result in sulfate attack to adjacent cementitious or metallic building components;
- does not contain potentially reactive pyrite or pyrrhotite in amounts that may result in material expansion or lead to formation of damaging levels of sulfates (see Section 3.2); and
- does not contain clay or silt-sized material (i.e., particles smaller than 0.063 mm) in amounts that make the material difficult to compact owing to the development of excess pore water; make it frost susceptible; or make it prone to volume change as water content varies. In an otherwise well-graded coarse material the fines content should ideally be no more than about 10%.

In practice, a range of source materials may be suitable for use as hardcore, either constituting the whole of the product or contributing to an appropriately proportioned mixture. Such source materials may include gravel and sand from natural sources, and crushed concrete and crushed bricks that are recycled following demolition of buildings and structures. In each case the material must be capable of being well compacted and, in its own terms, be ‘clean’, i.e., the quantities of any ‘contaminants’ are insignificant. In the case of recycled materials this means, in particular, that the material should be free of any organic material such as timber, should not contain deleterious amounts of sulfates (such as might be found in some types of brick and in adhering gypsum plaster) and should not contain any materials that could harm construction/repair workers (such as asbestos).

It is apparent from the foregoing discussion that the selection of material for use as hardcore should never be a casual process based on, say, just visual assessment and presumed knowledge of the material. Rather the material should be proved by appropriate testing to conform to a specification that has been found to be appropriate for end use as hardcore.

In the case of granular aggregates used in construction, such specifications are currently provided by a suite of UK-adopted European Standards for aggregates and by end-use specifications that conform directly with these. Figure 2 shows the key standards that have a bearing on the specification of material for use as hardcore and how these are interdependent.

The set of standards came into full force in 2004, when conflicting British Standards, such as BS 812, formerly used for aggregates, were withdrawn. The first and second tiers of standards are concerned with the testing of aggregate materials. These support, in order of dependence:

1. (Third tier) BS EN 13242:2002+A1:2007[5]. This standard specifies aggregates from individual sources for use as unbound materials in civil engineering work. As well as aggregates from primary sources such as rock, gravel and sand, also included are aggregates recycled from use in previous construction, and ‘secondary’ sources such as blast furnace slag and steel slag that are a by-product of metal production.

2. (Fourth tier) BS EN 13285:2010[6]. This standard specifies aggregates for use in unbound mixtures ‘used for construction of roads, airfields and other trafficked areas’ and within this general application is aimed primarily at the use of material for bases and subbases of pavements. It may therefore be regarded as an ‘end-use’ specification. The specified mixtures are composite materials characterised by having a controlled grading, which ranges from fine through to coarse. In the terminology of BS EN 13242:2002[5], such mixtures are ‘all-in’ aggregates having a lower limiting sieve size (‘d’) of zero (see Box 1). They may also be a combination of aggregates from different sources, say a mixture of crushed rock and sand/gravel or a mixture containing both primary and recycled aggregates.

3. (Fifth tier) Highways Agency Specification for Highway Works (SHW), Series 800: Road pavements – unbound mixtures for subbase, Clauses 801–805 (2004 onwards)[7]. SHW Series 800 is an end-use specification for subbase material. It dates back several decades but was radically amended in 2004 so that it conformed to the European Standards for aggregates. To a large extent it now aligns with the specification methodology and categories for aggregate mixtures set out in BS EN 13285:2010[6] (see Box 1). Where specific geometrical or physical properties of aggregates need to be included that are relevant to specification of subbase, they are required to comply with selected requirements of BS EN 13242:2002[5]. As an end-use specification, it has the right to override the requirements of the European Standards where deemed appropriate. It does this in respect of the requirements for limiting sulfur species in the subbase material, alternatively adopting the nomenclature and test procedures given in TRL Report TRL447[8] (see Box 2).
Figure 2: Relationship between key standards used for specification of aggregate for unbound mixtures
Box 1: Understanding the grading of aggregates in the new standards

Getting to grips with the extensive collection of new European-orientated standards in respect of specification of aggregate materials can be a daunting task due to the fact that new test procedures are used to determine some key characteristics such as grading, fines content and sulfate content, and most parameters are expressed in new ‘categories’ represented by new symbols. Mindful of this, two UK guidance documents have been issued by BSI, the first[7] in respect of European test method standards and the second[8] on the use of BS EN 13242, the principal standard for specifying aggregates from single sources.

Grading unbound aggregates

An example of the new complexity can be seen from consideration of the procedure for grading unbound aggregates. In BS EN 13242:2002+A1:2007[9], particle size grading is now described in terms of a lower limiting sieve size (‘d’) and an upper limiting sieve size (‘D’) and denoted as d/D. The sizes d and D are selected from a list of newly prescribed sieve sizes. For UK unbound materials, these sizes are (in mm): 1, 2, 2.8, 4, 6.3, 8, 10, 14, 16, 20, 31.5, 40, 63 and 80. Thus a particular aggregate may first be designated (d/D) as being, say, 4/40 or 6.3/14.

Aggregates may next be designated as either GC (coarse), GF (fine) or GA (all-in) where:

- coarse is for d ≥ 2 mm and D ≥ 6.3 mm;
- fine is for d = 0 mm and D ≤ 4 mm; and
- all-in is for d = 0 and D ≥ 6.3 mm.

Therefore 4/40 and 6.3/14 are both designated as grading category GC.

A ‘grading/tolerance’ category is now suffixed. For coarse aggregate, this is expressed as XY, where X is the required minimum percentage passing sieve size D, and Y is the maximum percentage allowed to pass sieve size d. For coarse aggregates, a likely material for use as hardcore, the recommended minimum percentage of material passing sieve D can be either 80% or 85% and the maximum percentage of material passing sieve d can be 15% or 20%. Thus for a coarse aggregate we may define a ‘category’ as Gc, 85/15 or Gc, 80/20. The combined designation will therefore be of the form d/D Gc, XY, eg 4/40 Gc, 85/15. Note that X pertains to D, and not to d, as might have been expected from their relative positions.

For all-in aggregate where the lower limiting sieve size, d, is always set to zero, the size and grading/tolerance category is simplified to the form d/D Gc, X, eg 0/40 Gc, 80, where the minimum percentage of material passing sieve D = 40 is 80%.

So far we have not considered maximum particle size. This is set at 2 x D, but for practical purposes may be taken as equal to 1.4 x D, since for any aggregate ‘category’ there is a requirement for 98–100% of material to pass a 1.4 D sieve size.

BS EN 13242 has an additional category, denoted GT, which can be suffixed to the foregoing to control the percentage of material passing the mid-size sieve D/2, but this appears to be much less used by material suppliers.

Proceeding up the standards chain to BS EN 13285:2010[8] (essentially an end-use standard for aggregate mixtures used in base and subbase construction), one encounters additional grading requirements with different nomenclature. As with BS EN 13242, the upper and lower size limits are controlled by the d and D sieves, but with d always equal to zero, as in the all-in aggregate category of BS EN 13242. However, unlike aggregate specified under BS EN 13242, no grading/tolerance category is suffixed to control the minimum percentage of material passing sieve D. Instead a different parameter is used, termed ‘oversize category’, and denoted as OCx7, OCx9, OCx12 or OCx15, where the affixed number is the minimum percentage of material passing sieve D.

Additionally under BS EN 13285, mid-range grading requirements are more tightly specified to ensure that the end product is well graded. For example, a grading category Gc is defined for a 0/31.5 mixture (d = 0, D = 31.5) that has 75–99% passing sieve D = 31.5 mm, 50–90% passing sieve D/2 = 16 mm, 30–75% passing sieve D/4 = 8 mm, 15–60% passing sieve D/8 = 4 mm and 0–35% passing a 1 mm sieve.

A fairly similar grading category, Gc, is also defined for a 0/31.5 mixture, but with a more tightly controlled grading.

At the top of the hierarchy of standards (Figure 2) sits SHW Series 800[10]. Clauses 801–805 of this series comprise an end-use specification for the use of unbound aggregate mixtures in subbase of road pavements. In respect of mixture and grading requirements, this conforms with BS EN 13285 by specifying:

- mixture designation (d/D), eg 0/31.5 for both Type 1 and Type 2 unbound mixtures;
- oversize category, eg OCx7 for both Type 1 and Type 2 unbound mixtures; and
- overall grading, eg Gc for Type 1 unbound mixture and Gc for Type 2 unbound mixture.

Limiting excess fines content in subbase materials

A high proportion of fines can be troublesome both in respect of compaction and long-term stability. The foregoing requirement of lower limiting sieve size d = 0 does not cater for this. Instead a ‘maximum value of fines’ category is introduced in BS EN 13242:2002+A1:2007[9], with the requirement that it be determined as the percentage passing a 0.063 mm sieve using the procedure given in test standard BS EN 933-1:1997[11]. For all-in material the maximum value of fines has six categories, denoted f0.063, f0.15, f0.26, f0.5, f1.0 and f1.4, where the numerical suffix is the percentage passing the 0.063 mm sieve.

The concept is carried forward to unbound mixtures standard BS EN 13285:2010[8] where identical numerical categories are specified for ‘maximum fines content’, but now denoted as UF0.063 UF0.15 UF0.26 UF0.5 UF1.0 and UF1.4. It is the latter set of categories that are adopted by SHW Series 800, Clauses 801–805, with UF0.063 (≤ 9% passing a 0.063 mm sieve) being specified for both Type 1 and Type 2 unbound mixtures for subbase.
The following tests and nomenclature used for sulfur species are those currently used in the UK for the assessment of unbound materials for use in highway pavements (eq as used in SHW Series 800\textsuperscript{[19]}), and also for the assessment of ground into which concrete will be placed (eg as used in BRE Special Digest SD 1\textsuperscript{[20]}). The quoted test procedures are taken from TRL447\textsuperscript{[6]}. Cross reference is made to European aggregate standards BS EN 1744-1:2009\textsuperscript{[11]} and BS EN 13242:2002+A1:2007\textsuperscript{[3]} where appropriate.

### Determination of water-soluble sulfate (WS)

In this test water-soluble sulfate is extracted from a 2:1 mixture of water and dry sample (by mass). This test is designed specifically as an index test for aggressiveness to concrete and intentionally does not measure all sulfates present. Rather, it preferentially extracts the more soluble sulfates (ie those with magnesium, potassium and sodium cations), these being the most harmful to concrete. The amount of calcium sulfate (gypsum, selenite, anhydrite) that is extracted from the material under test is capped at 1440 mg/l SO\textsubscript{4} owing to its low solubility. This is intended, since calcium sulfate is not as aggressive to concrete as the more soluble sulfates.

The procedure recommended for determination is that given as ‘Test No. 1 – Determination of water-soluble sulfur (WSS)’ in TRL447\textsuperscript{[6]}. Following sulfate extraction using a 2:1 mixture of water and crushed aggregate, the element sulfur is detected in the extract solution by inductively coupled plasma atomic emission spectroscopy (ICP-AES) analysis. This result is first expressed for calculation purposes as a percentage of sulfur (%S) in the extract solution. Then, using the known volume of the extract solution and the initial dried sample mass, the determined sulfur is calculated as % of the dry sample mass, this being termed ‘WSS’ (water-soluble sulfur). From this result the mass of water-soluble sulfate (WS) in one litre of extract water is calculated using the formula:

\[
WS \text{ mg/l } SO_4 = 15 \times 1000 \times WSS \%S
\]

WS mg/l SO\textsubscript{4} is the index parameter needed for reference to tables of aggressiveness to concrete, as given in BRE SD 1\textsuperscript{[20]} and BS EN 8500:2006\textsuperscript{[12]}.

### Notes

(a) Clause 10.1 of BS EN 1744-1:2009\textsuperscript{[11]} likewise specifies a 2:1 water:sample extract method for determination of water-soluble sulfate content of aggregates, but the result is expressed as a percentage of dry sample mass (in either %SO\textsubscript{3} or %SO\textsubscript{4}), so it is not easy to use it in the UK for consideration of aggressiveness to concrete.

(b) BS EN 13242:2002+A1:2007\textsuperscript{[3]} does not define any categories in respect of water-soluble sulfate content of natural aggregates. It does so for recycled aggregates (denoted SS0.2 etc.), but for this material testing is tied to Clause 10.2 of BS EN 1744-1:2009\textsuperscript{[11]}, which uses a radically different 40:1 hot water:sample extract method, thereby producing a result that is more akin to ‘total sulfate’.

### Determination of acid-soluble sulfate (AS), also termed ‘total sulfate’

This test is used to determine the total of all easily-soluble sulfates that may be present in the ground or as a construction material. The sulfate is extracted by boiling a sample of pulverised material in dilute hydrochloric acid. Pyrite is generally left untouched by the acid extraction.

The recommended procedure is that given as ‘Test No. 2 – Determination of acid-soluble sulfur (ASS)” in TRL447\textsuperscript{[6]}. Following extraction, sulfur is detected in the acidic sulfate solution by ICP-AES analysis. The result, termed ‘ASS’, is expressed as a percentage of sulfur in the initial dry sample mass. The final step of the procedure is to determine the required acid-soluble sulfate (AS) using the formula:

\[
AS \%SO_4 = 3 \times ASS \%S
\]

### Note

Clause 12 of BS EN 1744-1:2009\textsuperscript{[11]} specifies a similar method for determination of acid-soluble sulfate content of aggregates, with the result optionally being expressed as %SO\textsubscript{4}. Table 13 of BS EN 13242:2002+A1:2007\textsuperscript{[3]} defines categories that use these results, the principal ones being AS\textsubscript{0.2} for sulfate ≤ 0.8% and AS\textsubscript{0.8} for sulfate ≤ 0.8%. The ≤ 0.2% value equates to 2000 mg/kg SO\textsubscript{4}, which is the lower limit for the lowest sulfate exposure Class XA1 of Table 2 of European concrete standard BS EN 206-1:1-2000\textsuperscript{[13]}. However, the latter classification is passed over in BS 8500:2006\textsuperscript{[12]}, the UK Annex to BS EN 206-1:1-2000\textsuperscript{[13]}, in favour of sulfate aggressiveness based on water-soluble sulfate (WS).

### Determination of total sulfur (TS)

Total sulfur is defined as the total of all sulfur present as sulfate + any that is present as sulfide (including pyrite) + any that is present in any organic matter. The recommended procedure is that given as ‘Test No. 4B – Rapid high temperature combustion analysis’ in TRL447\textsuperscript{[6]}. The sample is subjected to combustion in an induction furnace through which pure oxygen is passed. The sulfur is evolved as sulfur dioxide, which is measured by an infrared detector. The test is rapid, taking only a few minutes to get computer-processed results. The result is expressed in %S as a percentage of the initial dry sample mass. But, for determination of pyrite content, the equivalent sulfate mass is first needed, where SO\textsubscript{2} = 3 x S.

### Notes

(a) Clause 11.2 of BS EN 1744-1:2009\textsuperscript{[11]} specifies a similar high temperature combustion method for determination of sulfur content of aggregates, with the result being expressed as %S.

(b) Table 14 of BS EN 13242:2002+A1:2007\textsuperscript{[3]} defines categories that use these results, the principal one being S1 for total sulfur ≤ 1%.
Box 2 (cont’d): Recommended test procedures and nomenclature for sulfur species

Determination of pyrite content
For most rocks used as aggregates, a representative value of pyrite content can be determined from the difference between the results of a total sulfur test and an acid-soluble sulfate test. The procedure is as follows:

(i) Determine the total sulfur content, TS %S
(ii) Determine the acid-soluble sulfate (also termed ‘total sulfate’) content, AS %SO₄
(iii) Calculate the oxidisable sulfides (OS) in the sample as %SO₄ using the formula:

\[ \text{OS} \% \text{SO}_4 = 3.0 \times \text{TS} \% \text{S} - \text{AS} \% \text{SO}_4 \]

(iv) Estimate the pyrite content by taking it as equivalent to the oxidisable sulfides using the formula:

\[ \text{Pyrite} \% \text{FeS}_2 = 0.623 \times \text{OS} \% \text{SO}_4 \]

Note
This procedure may overestimate pyrite content if barytes (barium sulfate) is present, since this is not soluble in the acid used in step ii. Barytes is a widely found vein mineral.

3.2 Key parameters for specification of material for use as hardcore
The principal parameters currently used to specify unbound material for use in construction and therefore of most relevance to hardcore are as follows.

Grading, including fines content
Grading is the distribution of particle size in an aggregate or aggregate mixture. The grading characteristics are determined by straightforward test sieving (the percentage passing through selected sieves), but they are unfortunately represented in current standards by some complex and far from intuitive definitions of category. For example, for a crushed rock aggregate intended for use as subbase or hardcore, the following categories may be specified in conformity with BS EN 13285:2010[14], the standard for use of aggregates in unbound mixtures:

- Mixture designation = 0/31.5
- Grading category = G₀ or Gₚ
- Oversize category = OC₇₅
- Maximum fines category = UF₉

An explanation of these terms is given in Box 1.

Resistance to fragmentation of coarse aggregates
While some degree of material fragmentation resulting from impact during compaction is desirable, this should not be excessive. The test adopted by European Standards to assess resistance to fragmentation of aggregate material is BS EN 1097-2:1998[14], also known as the ‘Los Angeles test method’. In this test, a dry sample of material is sieved to obtain the fraction sized from 10 mm to 14 mm. This is rolled with steel balls in a rotating drum for 500 revolutions. After rolling is complete the amount of material retained on a 1.6 mm sieve is determined. The Los Angeles coefficient (LA) is defined as the percentage of material lost (ie % < 1.6 mm). Therefore, the higher the coefficient, the weaker the material.

In respect of this test, the European Standards define ‘categories’ of LA in 5% steps, from LA₀ to LA₆₀. For a crushed rock aggregate for use as subbase and hardcore, categories of LA₀ and LA₅₀ are typically specified.

Durability of coarse aggregates, including resistance to freezing and thawing
Physical degradation of aggregates may occur owing to cyclical wetting and drying or due to freezing and thawing. Such degradation is generally unwelcome after placement of aggregates as unbound material in construction. The principal test adopted by European Standards to assess susceptibility to such degradation is the magnesium sulfate (MS) test as given in BS EN 1367-2:1998[15]. This test assesses how aggregate from the 10–14 mm size range degrades when subjected to five 48-hour cycles of immersion in a saturated solution of magnesium sulfate, followed by oven drying. At the end of the test, the mass of aggregate retained on the 10 mm sieve is determined. From this, the MS value is calculated as the percentage of the initial mass of the test specimen that has been lost. Note that the BS EN 1367-2 test method is identical to the magnesium sulfate soundness test of BS 812-121:1989[14], but the results are expressed in the opposite way. The MS value from the former is equivalent to (100 – MSSV), where MSSV is the magnesium sulfate soundness value from the latter.

In respect of this test, BS EN 13242:2002+A1:2007[11] defines categories of MS at MS₁₈, MS₂₅, and MS₃₅. For a crushed rock aggregate intended for use as subbase and hardcore, categories of MS₂₅ and MS₃₅ are typically specified.

Sulfate and sulfide contents
Sulfur mineral species found in aggregates include sulfates, the most common one being gypsum (CaSO₄.2H₂O), and sulfides, with pyrite (FeS₂) being widely found. Table 1 lists other such minerals, together with relevant characteristics.

There are three main reasons for determining the sulfate species in aggregates for unbound materials intended for use as subbase or hardcore:

- Sulfates in the aggregates may attack adjacent cementitious materials, particularly those that contain Portland cement. Highly expansive sulfate minerals ettringite and thaumasite are produced by such attack, which may initially crack cement-bound materials and can ultimately lead to complete disintegration. The mechanism of sulfate attack and types of susceptible cementitious materials are comprehensively described in BRE SD 1, Concrete in aggressive ground[10]. Not all
The rapid determination of sulfate content by using ICP-AES analysis to determine elemental sulfur in water and acid extracts (rather than using gravimetric analysis).

Test results expressed in a form that is directly comparable with UK concrete standards and allows pyrite content to be easily calculated. For example, for a crushed rock aggregate for use in subbase to be placed within 500 mm of concrete or other cementitious materials (the typical environment for hardcore), the following sulfate and sulfide parameters are specified in SHW Series 800 Clause 801 revises to TRL447[6]. For the most part, the latter are similar to test procedures included in the recently published BS EN 1744-1:2009[11]. Notable differences from the latter in TRL447 are:

- The rapid determination of sulfate content by using ICP-AES analysis to determine elemental sulfur in water and acid extracts (rather than using gravimetric analysis).
- Test results expressed in a form that is directly comparable with UK concrete standards and allows pyrite content to be easily calculated. For example, for a crushed rock aggregate for use in subbase to be placed within 500 mm of concrete or other cementitious materials (the typical environment for hardcore), the following sulfate and sulfide parameters are specified in SHW Series 800 Clause 801[11] in conformity with TRL447[6]:
  - Water-soluble sulfate, \( WS \leq 1500 \text{mg/l } \text{SO}_4 \)
  - Oxidisable sulfides content, \( OS \leq 0.5\% \text{ as } \text{SO}_4 \)

An explanation of these terms is given in Box 2.

### Table 1: Sulfur species found in some rocks used as aggregate

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Species</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gypsum</td>
<td>CaSO(_4).2H(_2)O</td>
<td>Very common sulfate species. Soluble to a concentration of only 1440 mg/l in water at neutral pH, therefore only moderately reactive in respect of sulfate attack on cementitious materials. Often seen (white or grey) in crystalline form in moist as well as dry material.</td>
</tr>
<tr>
<td>Epsomite</td>
<td>MgSO(_4).7H(_2)O</td>
<td>Highly soluble, seen in dry material. In moist material it will readily dissolve into pure water. Highly reactive in respect of sulfate attack on cementitious materials.</td>
</tr>
<tr>
<td>Mirabilite</td>
<td>NaSO(_4).10H(_2)O</td>
<td>As epsomite.</td>
</tr>
<tr>
<td>Barytes</td>
<td>BaSO(_4)</td>
<td>A common white-coloured vein mineral in rocks. Relatively insoluble.</td>
</tr>
<tr>
<td>Alunite</td>
<td>KAl(_7)(OH)(_6)(SO(_4))(_2)</td>
<td>Fairly common white-, grey- or yellow-coloured granular mineral. Often a weathering product produced by oxidation of pyrite.</td>
</tr>
<tr>
<td>Melanterite</td>
<td>FeSO(_4).7H(_2)O</td>
<td>Secondary mineral often formed by the oxidation of pyrite. Typically forms a white or pale green vitreous encrustation.</td>
</tr>
<tr>
<td>Pyrite</td>
<td>FeS(_2)</td>
<td>A common mineral in unweathered rocks. May be present as particles ranging from mm-sized irregular golden-coloured lumps and cubic crystals to myriad scattered micron-sized crystals. The latter (often missed during visual assessment) are prone to expansive oxidation in the presence of air, water and bacteria.</td>
</tr>
<tr>
<td>Pyrrhotite</td>
<td>FeS</td>
<td>Seldom found in UK rocks used for aggregate. When present, it is highly prone to oxidation.</td>
</tr>
<tr>
<td>Marcasite</td>
<td>FeS(_2)</td>
<td>Golden-coloured mineral with metallic appearance similar to pyrite but with more friable crystal structure. Common in sedimentary rocks. Highly prone to oxidation, with decay product similar to pyrite.</td>
</tr>
</tbody>
</table>

Sulfates are similarly reactive (Table 1). Part 2 of this Digest describes a legacy problem of sulfate attack to concrete floor slabs.

- Sulfates in the aggregates may cause corrosion of adjacent metallic elements of construction.
- In some vulnerable aggregates and particularly in those containing mudstone, sulfide minerals, particularly pyrite, may gradually oxidise in the presence of air and water, leading to the formation of hydrated sulfate minerals of greater volume, including gypsum, melanterite and jarosite (Table 1). This may cause expansion of compacted unbound material. In the UK this is largely a legacy problem, with the current employment of aggregates either having insignificant amounts of pyrite or containing it in a form that is non-reactive. The mechanism of expansion of aggregate mixtures due to pyrite oxidation is therefore described in more detail in Part 2 of this Digest. However, we should not be complacent in respect of this aspect of current aggregate selection: in recent years there have been reports of major problems in the Quebec province of Canada and the Dublin area of Ireland resulting from the expansion of pyrite-bearing aggregates used as hardcore in several hundred buildings.

Owing to a long history in the UK of sulfate attack to cementitious materials placed in ground containing sulfates or reactive pyrite, a collaborative methodology has been developed by ground engineers and concrete technologists, which first assesses the aggressiveness of the ground and then specifies a design mix of concrete that will withstand the determined conditions for the working life of the construction. This methodology is jointly explained in BRE SD 1[10] and in the UK Annex (BS EN 8500-1:2006[12]) to BS EN 206-1:2000[13].

For the parallel situation where structural fill material (including hardcore and subbase) is to be placed adjacent to existing concrete (or metallic elements), a compatible procedure for material assessment and specification was developed for the highways sector and published in 2001 as TRL Report TRL447, with a second edition being issued in 2005[6]. Because these procedures are embedded in UK Annexes and authoritative end-use specifications, they take precedence over procedures given in the chain of European Standards for aggregates (Figure 2) when the latter conflict.

Box 2 gives a summary of the key sulfate and sulfide parameters for aggregates in unbound materials that might be used as hardcore and the methods recommended for their determination. Comprehensive test procedures are given in TRL447[6]. For the most part, the latter are similar to test procedures included in the recently published BS EN 1744-1:2009[11]. Notable differences from the latter in TRL447 are:

- The rapid determination of sulfate content by using ICP-AES analysis to determine elemental sulfur in water and acid extracts (rather than using gravimetric analysis).
- Test results expressed in a form that is directly comparable with UK concrete standards and allows pyrite content to be easily calculated. For example, for a crushed rock aggregate for use in subbase to be placed within 500 mm of concrete or other cementitious materials (the typical environment for hardcore), the following sulfate and sulfide parameters are specified in SHW Series 800 Clause 801[11] in conformity with TRL447[6]:
  - Water-soluble sulfate, \( WS \leq 1500 \text{mg/l } \text{SO}_4 \)
  - Oxidisable sulfides content, \( OS \leq 0.5\% \text{ as } \text{SO}_4 \)
4 COMMONLY USED SPECIFICATIONS FOR MATERIAL INTENDED FOR HARDCORE

4.1 Type 1 and Type 2 unbound mixtures

By far the most common materials currently used for hardcore are Type 1 and Type 2 unbound mixtures, as specified respectively by Clauses 803 and 804 of SHW Series 800\(^5\). Since there are no national addenda for this series, the specifications are identical for England, Northern Ireland, Scotland and Wales. Attributes of these materials are:

- The materials (needed in the first instance for highway subbase construction) are widely available in the UK.
- They are well-graded granular aggregates that can be easily handled and readily compacted.
- Engineering performance after compaction is excellent provided care is taken with chemical composition.
- Comprehensive guidance on their use is given in Clauses 801–804 of SHW Series 800\(^5\) and Clauses NG 800–NG 804 of SHW Series NG 800\(^{17}\).
- Closely similar material has been in use for highway construction for several decades, so the behaviour of the material is generally well understood by practitioners. (The use of the anachronistic names ‘MOT Type 1’ and ‘MOT Type 2’, still commonly used for these materials by some suppliers and specifiers, indicates experience dating back to before 1981, when the former Ministry of Transport was renamed.)
- The materials can satisfy Building Regulation 7\(^{20}\), which requires use of materials that are demonstrably ‘adequate and proper’.

Type 1 and Type 2 unbound mixtures may both contain crushed rock, crushed slag, crushed concrete, recycled aggregates, well-burnt non-plastic shale, gravel and sand. They also both have a maximum particle size (2D sieve) of 63 mm, with 75–99% being smaller than 31.5 mm (D sieve) and with a maximum fines content (<0.063 mm fraction) of 9%. However, as explained later, not all the above listed constituents are necessarily welcome in material to be used as hardcore owing to some of them possibly containing potentially chemically reactive substances. While the two materials are similar in many respects, there are some important differences:

- Type 1 unbound mixture is designed for the subbase of heavily trafficked roads and as such is very strong and stable under dynamic loading. This performance stems from the composition and grading of Type 1 (denoted C\(_1\)): it dominantly comprises angular particles of well-distributed size that interlock when compacted. The percentage of well-rounded material (eg uncrushed water-rounded gravel) is limited to a maximum of about 10% (Figure 3). Also the fine fraction (particle size less than 0.425 mm) must be non-plastic. Such material has a tolerance to being compacted at a relatively wide range of water contents either side of the optimum.
- Type 2 unbound mixture is designed for the subbase of somewhat less heavily trafficked roads and as such is less strong and stable under dynamic loading. It is more flexible in respect of particle size grading (denoted C\(_2\)) and may contain an unlimited proportion of rounded gravel (Figure 4). A significant amount of fine material is permitted, provided that this has a plasticity index of less than 6. Owing to its grading and plastic fine fraction, it may have less tolerance to being compacted at water contents away from the optimum. Because of this, Clause 804 requires the material to be laid and compacted at a water content within the range of 1% above to 2% below the declared value of the optimum water content.

When free of potentially reactive substances and when appropriately placed and compacted, both materials perform well as hardcore, since the latter is normally subject only to static loading. In respect of choice between these materials, while for Type 1 unbound mixture the less demanding criteria for water content during compaction may be attractive, the typically lower cost of the less tightly graded Type 2 unbound mixture may be the key decider.

4.2 Cautionary notes concerning sulfate and pyrite in Type 1 and Type 2 unbound mixtures

It is essential when selecting Type 1 (Clause 803) and Type 2 (Clause 804) unbound mixtures for use as hardcore that the general requirements for unbound materials as set out in Clause 801 of SHW Series 800\(^5\) be given due consideration. In particular, Clause 801 advises against the use within 500 mm of concrete and other cementitious products of material that has either:

- a water-soluble sulfate (WS) content that exceeds 1500 mg/l as determined from a 2:1 water:aggregate extract test (Test 1 of TRL447\(^6\)); or

- a water:aggregate extract test (Test 1 of TRL447\(^6\)) of more than 1500 mg/l. The concentration of total sulfates (TS) determined from a 2:1 water:aggregate extract test (Test 1 of TRL447\(^6\)) and the presence of pyrite (<0.063 mm fraction) are limited by national and local addenda to ensure that the material is adequate and proper. (Courtesy of Kesgrave Aggregates)
• an oxidisable sulfides (OS) content that exceeds 0.5% SO₄ as determined from the difference of total sulfate and acid-soluble sulfate (Test 4 and Test 2, respectively, of TRL447).

OS is a measure of the pyrite content in a material. As noted previously, oxidation of pyrite may result in material expansion or lead to formation of additional sulfates. The WS and OS parameters are more fully explained in Box 2.

The set limits for WS and OS in Clause 801 are those considered generally necessary to prevent problems from sulfate attack to cementitious materials used in road construction. In some cases where pyrite is present but it can be shown to be in a form that does not readily oxidise (ie is non-reactive), the OS limit may be increased under the provisions for Appendix 7/1 of Highways Agency contract documents. An example would be where pyrite is present as large crystals in igneous or metamorphic rock, and there is a history of satisfactory use of the material. Further guidance on how to assess the likelihood of pyrite oxidising in highway construction materials is given in Clause NG 601 of SHW Series NG 600[18].

In respect of the use of Type 1 and Type 2 unbound mixtures for highway construction, similar considerations apply in respect of WS and OS (pyrite) content. In the large majority of cases, hardcore material will be in contact with cementitious materials in the form of foundation concrete, concrete block walls or the mortar in brick walls. Typically these will not have been specified to withstand a sulfate environment above DS-2, for which the upper limit of water-soluble sulfate (WS) content is 1500 mg/l SO₄.[19]

Particular consideration is needed in respect of reactive pyrite in material used as hardcore. If pyrite oxidises, it may not only lead to higher levels of sulfate, but also result in bulk expansion of the hardcore to an extent that is damaging to the building (see Part 2 of this Digest for details). The latter is not such a problem in respect of subbase for asphalt-paved roads, where there is tolerance for a small amount of volume change.

Taking a worldwide view, in cases where damage has been caused by expansion of pyritic material used as hardcore, the amount of pyrite reported as present ranges from about 0.5% FeS₂ to as high as 5% FeS₂. The deleterious threshold value for reactive pyrite is commonly regarded as 1% FeS₂. The latter amount of pyrite is mass equivalent to OS = 1.6% SO₄, so the Clause 801 limit of OS = 0.5% SO₄ is conservative in respect of problems from material expansion. It is also highly conservative in respect of many aggregate materials where pyrite occurs mostly or entirely in a non-reactive form.

4.3 Cautionary notes concerning use of recycled and secondary aggregates in material used as hardcore

Recycled aggregate is material resulting from the processing of inorganic material previously used in construction. Such aggregates include:

• crushed concrete (often termed ‘recycled concrete aggregate’ or RCA – Figure 5); and
• material principally consisting of crushed masonry, eg brickwork and blockwork (often termed ‘recycled aggregate’ or RA – Figure 6); and
• material principally consisting of crushed or milled asphalt (often termed ‘recycled asphalt pavement’ or RAP).

Secondary aggregates (SA) are generally by-products of industrial processes that have not been previously used in construction. They can be divided into:

• manufactured SA, such as air-cooled blastfurnace slag, steel slag, incinerator bottom ash aggregate (IBAA) and crushed glass; and
• natural SA, such as china clay stent and sand, slate mining discard and burnt colliery spoil.

While, since 2004, all the mentioned recycled and secondary aggregates are permitted for use in Type 1 and Type 2 unbound mixtures for highway construction[20], the amount allowed in a particular mixture is often limited owing to inferior physical or chemical properties compared with primary aggregates. For example, IBAA is generally limited to forming not more than 15% of subbase material[21]

When considering the use of Type 1 and Type 2 unbound mixtures for use as hardcore, the particular sensitivities of building construction and occupants of buildings must be brought to the fore. It is important not to include any material containing a significant amount of substances that may react with other construction elements, be inherently dimensionally unstable or be an emitter of substances that are toxic or irritating to occupants. For these reasons the following materials are best avoided as a routine component of hardcore. Some may be acceptable after comprehensive testing under expert supervision:
• crushed masonry that may contain gypsum plaster or crushed bricks with a high sulfate content;
• RAP;
• steel slag;
• blastfurnace slag;
• IBAA; and
• burnt colliery spoil.

Some of these materials contain reactive substances such as sulfates, while others, such as IBAA and steel slag, may have a residual tendency to hydrate and expand to an extent unacceptable for use in hardcore.

Crushed concrete (RCA) is perhaps the recycled material most widely used in hardcore, often constituting the whole of it (Figure 5). Provided that it is ‘clean’ and well graded, it is ideal for use in most situations. An exception is any site where there is a substantial amount of sulfate in soil or groundwater. There have been several cases in the UK and the USA where such sulfate has led to sulfate attack on compacted RCA, resulting in substantial expansion that has damaged construction. Section 3.2 explains the mechanism of such sulfate attack. It can be particularly virulent where concrete exposes a large surface area due to crushing.

BRE SD 1[10] gives guidance on assessing such aggressive conditions. RCA should not be used where it is subject to conditions equivalent to aggressive ground category ACEC Class 2 or above. For neutral pH conditions (ie no acidity) this equates to not using RCA when sulfate levels are Class DS-2 or above. The lower limit of Class DS-2 is 400 mg/l SO\textsubscript{4} for sulfate in groundwater, and 500 mg/l SO\textsubscript{4} for sulfate in a 2:1 water:soil extract test.

4.4 Provision for recycled and secondary materials in European Standards

When formally adopted by the UK in 2004, aggregates standard BS EN 13242:2002[3] and its supporting test standards (Figure 2) included dedicated requirements for the well-established secondary aggregates blastfurnace slag and steel slag. Other than that, the requirements of the standards were blind as to the sources of the material. However, the standard was revised in 2007 by the addition of Amendment A1:2007. The main purpose of this amendment was to introduce additional requirements for recycled aggregates.

A particular requirement is for material in coarse recycled aggregates to be sorted into constituent materials so that the respective proportions can be declared by producers. The constituents required to be so proportioned are:
• Rc – concrete and concrete products
• Ru – unbound aggregate, natural stone
• Rb – clay masonry units
• Ra – bituminous materials
• Rg – glass
• FL – floating material
• X – other, including cohesive soil, metals, plastic, rubber

Additionally the revised UK guidance document PD 6682-6:2009[8] explains the changes made in respect of recycled aggregate as follows:

BS EN 13242:2002+A1 now includes requirements for classification of the constituents of coarse recycled aggregates and indicates that their suitability be assessed in accordance with the regulatory requirements in the place of use. In the UK, this can include conformity with the WRAP Quality Protocol.

In respect of evaluation of conformity, BS EN 13242:2002+A1 requires that producers undertake and, on request, declare the results from initial type tests (ie tests carried out on an aggregate relevant to its intended end use) when new sources of aggregates are exploited, and when there is a major change in raw materials or processing which can affect the properties of the aggregate. For recycled aggregates in the UK, evaluation of conformity can also include conformity with quality protocols for the production of aggregates from inert waste (eg the WRAP Quality Protocol).

The WRAP quality protocol referred to is The quality protocol for the production of aggregates from inert waste[19]. It deals with the production of aggregates from ‘inert’ construction, demolition and excavation waste. It sets out the general procedures to be followed in respect of acceptance criteria for incoming waste, establishing an audit trail and testing the material in a manner appropriate to the end use. In respect of the latter, it suggests properties that it may be relevant to measure (quoting the relevant BS EN test standards), but does not set any limits for the use of material.

An additional regulatory benefit of producing recycled aggregates that conform with the quality protocol requirements is that the Environment Agency prerequisite for meeting the ‘end of waste criteria’[21] is accomplished and such aggregate need no longer be classed as a ‘waste’ or be required to comply with any national Waste Regulations.

The general outcome of these new procedures for dealing with recycled and secondary materials is a greater scrutiny and assurance of quality in respect of the contents of recycled aggregates and a route for the transfer of knowledge of such contents to an end user. Clearly this is reassuring if the aggregate is to be used for hardcore in building construction.

In respect of secondary materials, some care needs to be taken when selecting aggregate for use as hardcore. This is because, in addition to the explicitly included blastfurnace and steel slags, materials such as burnt shale, foundry sand and IBAA are acceptable as components of aggregates specified for general construction use under BS EN 13242:2002+A1:2007[16]. Note, however, that they are not specifically referred to in the standard since it is intentionally blind to the source of such materials; requiring only that resultant aggregate mixtures conform to specifications appropriate to the particular end use. Since, as noted in Section 4.3, some of these secondary materials are best avoided as a routine component of hardcore, it will be important to ask the supplier to declare the amounts (if any) of secondary materials that are included in any aggregates mixture. If these include steel slag, blastfurnace slag, IBAA or burnt colliery spoil, expert advice should be sought on material suitability for use.
5 AN ALTERNATIVE TO SHW SPECIFICATIONS FOR UNBOUND MIXTURES

This section considers how standards BS EN 13242:2002 + A1:2007(1) and BS EN 13285:2010(2) can be used to specify a material for dedicated end use as hardcore. The UK guidance document for the former (PD 6682-6:2009(3)) states that specifiers ‘need to define BS EN 13242:2002 categories that are relevant to a particular end use of an aggregate’. As an illustration of this process, the guidance document includes six examples of specifications with user-selected categories. None of these are considered directly applicable to the use of aggregate as hardcore. But an example of some relevance is Annex D, ‘Specification for unbound subbases for road pavements’. This largely follows the specifications given in SHW Series 800(4), but the categories chosen for sulfate species are different, and also incompatible with the usual UK procedures for assessing the likelihood of problems resulting from the presence of water-soluble sulfates and pyrite.

A suggested specification formulated here for use of aggregates as hardcore is given in Table 2. This specification, based for the most part on the requirements for SHW Type 1 unbound mixtures, is intentionally conservative. But it points the way to development of more economical or sustainable specifications whose performance can be proved by field trial.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixture designation d/D</td>
<td>0/31.5</td>
<td></td>
<td></td>
<td>Lower sieve size d = 0, upper sieve size D = 31.5 mm.</td>
</tr>
<tr>
<td>Oversize</td>
<td>OC75</td>
<td></td>
<td></td>
<td>Mass passing D sieve &gt; 75%.</td>
</tr>
<tr>
<td>Grading requirement</td>
<td>Cg</td>
<td>% passing intermediate sieves as given in Table 6 of BS EN 13285:2010.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum fines</td>
<td>UF0</td>
<td></td>
<td></td>
<td>Mass passing 0.063 mm sieve &lt; 9%.</td>
</tr>
<tr>
<td>Resistance to fragmentation</td>
<td>LA50</td>
<td></td>
<td></td>
<td>Mass lost in Los Angeles test &lt; 50%.</td>
</tr>
<tr>
<td>Water absorption</td>
<td>WA242</td>
<td></td>
<td></td>
<td>Water absorbed in 24-hour test &lt; 2%. A ‘declared value’ from the material supplier will satisfy.</td>
</tr>
<tr>
<td>Maximum magnesium sulfate soundness</td>
<td>MS15</td>
<td></td>
<td></td>
<td>Mass lost in test of 10–14 mm fraction &lt; 35%.</td>
</tr>
<tr>
<td>Maximum of water-soluble sulfate (WS)</td>
<td>1500 mg/l SO4</td>
<td></td>
<td></td>
<td>As measured in 2:1 aggregate:water extract test. This is equivalent to 0.3% SO4 as a % of dry mass. (This therefore allows for more SO4 than does the AS0.2 category of BS EN 13242.)</td>
</tr>
<tr>
<td>Maximum of oxidisable sulfides (OS)</td>
<td>0.8% SO4</td>
<td></td>
<td></td>
<td>Determined from difference between sulfate equivalent of total sulfur and acid-soluble sulfate. 0.8% as SO4 is equivalent to 0.5% by mass as pyrite (FeS2). This value is conservative in respect of many aggregate materials where pyrite occurs mostly or entirely in a non-reactive form. It can be disregarded if pyrite can be demonstrated to be non-reactive by an appropriate laboratory testing, optionally including petrographic description using thin sections and scanning electron microscopy.</td>
</tr>
</tbody>
</table>

In respect of sulfate species, it is presumed that some of the material specified for use as hardcore will be used in the close vicinity of concrete or other cementitious materials, eg brick mortar. For unbound mixtures put to such use, it therefore follows the recommendation of SHW Series 800, Clause 801 (General requirements for unbound mixtures) in having an upper limit for water-soluble sulfate (WS) = 1500 mg/l SO4. Reference to BRE SD 1(10) shows that this is the upper limit of Sulfate Class DS-2, which, if exceeded, may lead to substantial sulfate attack in typically specified construction materials. In respect of oxidisable sulfides (OS), the parameter that indicates the presence of pyrite, Table 2 sets a maximum of 0.8% SO4, as compared with a value of 0.5% SO4 set in SHW Series 800, Clause 801. This is because BRE knows of no significant sulfate attack and expansion problems for hardcore materials containing less than 0.5% mass of pyrite (FeS2) and this is mass equivalent to 0.8% SO4. In practice, this limit could be raised further for particular materials if it can be established (eg by petrographic study) that pyrite is predominantly present in a non-reactive form.
6  SIMPLIFIED RECOMMENDATIONS FOR COMMON SITUATIONS

• Check that site conditions are appropriate before choosing to use ground-bearing floor slabs supported by hardcore.

• Do not expect to find material on sale labelled ‘hardcore’. Hardcore is a construction term that describes the compacted material used for supporting ground-bearing floor slabs.

• Select material intended for use as hardcore with due care: it is required to be chemically inert and physically stable for the working life of a building, which may be at least 100 years.

• Select only material that can be proved to be inherently appropriate for use as hardcore, and is suitable for use on your particular site, eg will not react to sulfates or acid ground conditions if these are present.

• If you decide to use SHW Type 1 (Clause 803) or Type 2 (Clause 804) unbound mixtures as hardcore, inform potential suppliers of this intended end use.

• Check with the supplier that the material satisfies the chemical requirements set out in Clause 801 of SHW Series 800 in respect of unbound materials to be used within 500 mm of concrete and other cementitious products.

• Ask the supplier to declare the amounts (if any) of recycled or secondary materials that are included in the mixture; if these include crushed masonry, asphalt aggregate, steel slag, blast furnace slag, IBAA or burnt colliery spoil, seek expert advice on material suitability for use.

• If you decide to use SHW Type 2 (Clause 804) unbound mixtures as hardcore, ask the supplier to declare the typical value of laboratory dry density and optimum water content, as determined in the supplier’s mandatory system of production control.

• Keep the paper trail relating to procurement and delivery of your hardcore material. Remember, the objectives of quality assurance include not only delivery of a product having the required quality, but also having documentary proof.

7  GLOSSARY

Aggregate: The general term for any granular material used in construction. ‘Primary aggregate’ is material such as sand, gravel and crushed stone, taken from natural sources specifically for use as aggregate. ‘Recycled aggregate’ is material produced by the processing of selected inorganic material previously used in construction. ‘Secondary aggregates’ are generally by-products of mining, quarrying or industrial processes.

Compaction: The process of densifying soils by some mechanical means such as rolling, ramming or vibration to reduce the volume of voids.

Compression: A reduction in the volume of fill with time under constant imposed load. Fill that is initially loosely placed and dry may suffer ‘collapse compression’ if it later becomes wet.

Consolidation: A reduction in the volume of ground resulting from the expulsion of pore water due to imposed static loading or a reduction in ground water pressure (drainage).

Engineered fill: Fill that is selected, placed and compacted to an appropriate specification, so it will exhibit the required engineering behaviour.

Fill: Ground that has been formed by material deposited by human activity rather than geological processes. It is alternatively termed ‘made ground’ and ‘man-made ground’. When used to fill an excavation or placed behind a retaining wall, it is termed ‘backfill’. When placed within an enclosed space, it is termed ‘infill’.

Hardcore: Engineered infill material placed within the confines of a building foundation in order to support a ground floor slab or an oversite concrete slab.

Non-engineered fill: Fill material that has arisen as a by-product of human activity, often involving the disposal of waste materials; it has not been placed to facilitate a subsequent construction application.

Optimum water content: The water content at which a maximum dry density of fill is achieved using some specified compaction procedure.

Unbound mixtures: This is the term used by current standards for materials made up of graded and blended aggregates that are used in construction without the addition of a binding agent such as asphalt or cement. Hardcore is generally such an unbound mixture.

Well-graded material: Material (dominantly granular) that has a wide and even distribution of particle sizes.
REFERENCES


Acknowledgements

The preparation and publication of this Digest was funded by NHBC.

* These documents are available free of charge from the websites of the respective organisations.
APPENDIX: CORRELATION WITH THE BUILDING REGULATIONS OF SCOTLAND AND NORTHERN IRELAND

The foregoing text of this part of the Digest is aligned primarily with the requirements of The Building Regulations 2010 (England and Wales). The following table points to the equivalent requirements in The Building (Scotland) Regulations 2004 and The Building Regulations (Northern Ireland) 2000.

<table>
<thead>
<tr>
<th>The Building Regulations 2010 (England and Wales)</th>
<th>The Building (Scotland) Regulations 2004 + Building (Scotland) Amendment Regulations 2010</th>
<th>The Building Regulations (Northern Ireland) 2000 + The Building (Amendment No. 2) Regulations (NI) 2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regulation 7: Materials and workmanship Building work shall be carried out: a. with adequate and proper materials which: i. are appropriate for the circumstances in which they are used; ii. are adequately mixed or prepared; and iii. are applied, used or fixed so as adequately to perform the functions for which they are designed.</td>
<td><strong>Requirement:</strong> 1. Work to every building designed, constructed and provided with services, fittings and equipment to meet a requirement of Regulation 9 to 12, must be carried out in a technically proper and workmanlike manner, and the materials used must be durable, and fit for their intended purpose.</td>
<td><strong>Regulation B2: Fitness of materials and workmanship</strong> In any relevant work: a. the materials used shall: i. be of a suitable nature and quality in relation to the purposes for which they are used; ii. be adequately mixed and prepared; iii. be applied, used or fixed so as adequately to perform the functions for which they are designed; and iv. not continue to emit any harmful substance longer than is reasonable in the circumstances.</td>
</tr>
<tr>
<td>Practical guidance Approved Document to support Regulation 7: Materials and workmanship lists ‘ways of establishing fitness of materials’.</td>
<td><strong>Practical guidance</strong> Approved Document to support Section 3 of Schedule 5: Environment. <strong>Text relevant to hardcore</strong> Clause 3.4.2 Ground-supported concrete floors. ‘The solum is brought to a level surface. Hardcore bed 100 mm thick of clean broken brick or similar inert material, free from materials including water-soluble sulphates in quantities which would damage the concrete’.</td>
<td>Table B of The Building Regulations refers only to ‘A relevant British Standard or British Standard Code of Practice’.</td>
</tr>
<tr>
<td>Part C of Schedule 1: Site preparation and resistance to contaminants and moisture <strong>Requirement:</strong> C2 Resistance to moisture. The floors, walls and roof of the building shall adequately protect the building and people who use the building from the harmful effects caused by: a. Ground moisture</td>
<td><strong>Section 3 of Schedule 5: Environment</strong> <strong>Requirement:</strong> 3.4 Moisture from the ground. Every building must be designed and constructed in such a way that there will not be a threat to the building or the health of the occupants as a result of moisture penetration from the ground.</td>
<td><strong>Part C of The Building Regulations:</strong> <strong>Preparation of site and resistance to moisture</strong> <strong>Regulation C4 Resistance to ground moisture and weather.</strong> Every wall, floor and roof shall be constructed so as to prevent any harmful effect on the building or the health of the occupants caused by the passage of moisture to any part of the building from: a. the ground; and b. the weather. <strong>Practical guidance</strong> Methods and standards of building as given in Technical Booklet C: Site preparation and resistance to moisture (2004). <strong>Text relevant to hardcore</strong> Section 1.4 Ground preparation for floors next to the ground. ‘Prepare the ground to an even surface. Lay a hardcore bed 100 mm thick of stone, clean broken brick or similar inert material free from fine material and water soluble sulphates in quantities which would damage the concrete; consolidated and blinded to form an even surface.’</td>
</tr>
</tbody>
</table>
BRE Connect Online

What is BRE Connect Online?

BRE Connect Online gives you access to the unrivalled expertise and insight of BRE – the UK's leading centre of excellence on the built environment. BRE Connect Online is an annual subscription service from IHS BRE Press giving online access to over 1600 BRE titles.

What do I get?

ALL new and published BRE titles
650 books, reports and guides – research, innovation, best practice and case studies, including:
- The Green Guide to Specification
- Designing Quality Buildings
- Complying with the Code for Sustainable Homes
- Roofs and Roofing
- Site Layout Planning for Daylight and Sunlight
250 Digests – authoritative state-of-the-art reviews
550 Information Papers – BRE research and how to apply it in practice
150 Good Building and Repair Guides – illustrated practical guides to good building and repair work and much more...

What’s new in 2011?

More than 50 new titles, including:
- Airtightness in commercial and public buildings
- BREEAM In-Use
- Design of durable concrete structures
- Environmental impact of floor finishes
- Low-water-use fittings
- Performance of photovoltaics in non-domestic buildings
- Ventilation for healthy buildings

Call now on +44 (0) 1344 328038 to find out more
This Digest provides guidance to engineers and builders on selecting and placing material for use as hardcore in building construction. It takes account of recent standards for specifying aggregate materials for use as hardcore, ensuring that the material is both physically stable and chemically inert.

In Part 1 candidate materials are reviewed, including recycled and secondary materials that are currently being promoted for use in construction as a sustainable option.

Part 2 deals with placing and compacting hardcore material. It also reviews some unsuitable materials that were used for hardcore before the mid-1970s, both as a cautionary note for current specifiers and as a guide for professionals dealing with a legacy of unstable hardcore problems in existing buildings. A summary of key recommendations is given in Section 4.

This Digest replaces Digest 276, which is now withdrawn.

1 PLACING AND COMPACTING HARDCORE MATERIAL

Material for hardcore should be placed in thin horizontal layers and each layer should be well compacted.

A ‘method’ specification is normally adopted for compaction of hardcore, rather than an ‘end-product’ specification. For the selected material, a method specification prescribes a particular type of plant and compaction capability, together with comprehensive instructions for material placement and compaction. Use of such a method specification avoids the requirement for any in-situ testing of hardcore after compaction (eg dry density determination).

In the absence of method specifications dedicated to hardcore, those given in the Highways Agency Specification for highway works (SHW), Series 800: Road pavements – unbound mixtures for subbase(1) are commonly used. Table 8/4 of SHW Series 800 (‘Compaction requirements for unbound mixtures’) lists a range of types of compaction plant available for compacting hardcore. For each type – such as a vibrating-plate compactor (Figure 1) – categories are set according to the compaction pressure applied to the ground. Then for each of these categories the table gives the number of passes of the plant required to compact layers of different thickness.

When a small floor slab is constructed, as in a residential building, only light compaction equipment (such as a vibrating-plate compactor, vibro-tamper or power rammer) is likely to be available, and consequently the maximum permissible layer thickness after compaction is unlikely to be larger than 200 mm. In
practice the adoption of a 150 mm compacted thickness is typical. Such a thickness is readily compatible with a maximum lump size of 63 mm as specified for SHW Type 1 and Type 2 unbound mixtures for subbase[1] (materials also commonly used for hardcore; see Part 1 of this Digest).

In respect of overall thickness, a maximum of 600 mm is typically specified for routine construction (eg as in Clause 4.7 of Approved Document C of The Building Regulations 2010 (England and Wales)[2]) in order to avoid problems from cumulative volume change after compaction (see ‘Cautionary note’ below).

Where floor slabs are required to be more than 600 mm above the excavated level of ground, the use of suspended ground floors is accepted practice for dwellings and is recommended for most other buildings. Such suspended floors (typically comprising concrete beam and block construction) are in any case a widely used alternative to hardcore, particularly so where construction is on shrinkable clay.

For buildings where such suspended construction is structurally inappropriate, a hardcore thickness in excess of 600 mm may be employed below a ground-bearing slab providing it is designed and supervised by an appropriately qualified engineer.

For practical reasons, it is also common for general guidance documents on hardcore to specify a minimum workable thickness of hardcore such as 150 mm or 100 mm (eg as in Section 1.4 of Technical Booklet C of The Building Regulations (Northern Ireland) 2000[3]). However, for particular building works, design drawings may indicate a greater minimum thickness that takes account of particular site conditions.

For larger floor areas, heavier compaction plant may be available and a compacted layer thickness of up to 225 mm may be appropriate. The latter is the limiting layer thickness for compaction of unbound mixture for subbase in SHW (for all types of compaction plant) and is the upper limit stipulated in NHBC Standards[4]. Approved Document C of The Building Regulations 2010 (England and Wales) gives no such limit.

The hardcore material should be placed in a moist (damp) condition, ie not too wet and not too dry, the aim being to compact it at a water content near to the optimum, particularly so for SHW Type 2 unbound mixtures (see Boxes 1 and 2). A moist condition is indicated by a damp feel and a darker appearance of the hardcore. There should not be a significant amount of free water visible in the material.

---

Box 1: Determining the water content of hardcore

The water content of hardcore material is defined as the mass of water that can be removed from the material by heating at 110˚C, expressed as a percentage of the dry mass. The relevant standard for such an unbound material made of aggregates is BS EN 1097-5:1999[5]. This standard supersedes BS 812-109:1990, which was withdrawn in 2004, a significant difference being a 5˚C increase in the recommended temperature of the oven used to dry the test specimen. In older standards ‘water content’ is referred to as ‘moisture content’.

---

Box 2: Optimum water content for hardcore

The degree of compaction of hardcore material is indicated by its dry density; the higher this is, the better the engineering performance of the hardcore. For a given amount of compaction effort, the achieved dry density of the material depends mainly on its water (moisture) content – the so-called ‘optimum water content’ giving the maximum dry density.

When the water content is significantly lower than the optimum, the hardcore material is stiff and difficult to compact, thus low dry densities and high air contents are obtained. Near to the optimum water content, the water acts as a lubricant, causing the material to soften and become more workable. This results in higher dry densities and lower air contents. At water contents significantly above the optimum, the additional water in the voids tends to keep the particles of material apart and the dry densities achieved are again less. This is why for Type 2 unbound mixtures, SHW Clause 804[1] states that the material should be laid and compacted at a water content within the range 1% above to 2% below the declared value of the optimum water content.

To adopt such a precise procedure for routine use of hardcore in buildings would necessitate employing materials tests that are generally unfamiliar to the building community. Not surprisingly, therefore, site construction practice in the placing and compaction of hardcore material has typically relied on the judgement of operatives; the instruction to place in a ‘damp’ or ‘moist’ condition generally being considered sufficient for compacting material that is predominantly granular.

Some improvement over such site practice may be readily achievable in respect of using Type 2 unbound mixtures as hardcore. For materials conforming to BS EN 13285:2010[6] (the standard relied on by Type 2 unbound mixtures), a typical value of optimum water content is generally determined as part of the system of production control and should be available from the material producers. In conjunction with easily carried out testing of delivered material for water content (Box 1), this declared value of optimum water content can be used to guide any adjustments to water content needed prior to placement of the material as hardcore.

---

* The main text of this Digest primarily references The Building Regulations 2010 (England and Wales). Correlation with parallel documentation for Scotland and Northern Ireland is included in the Appendix.
1.1 Cautionary note

Hardcore material may compress with time after building operations are complete if it has been inadequately compacted. One reason for this may be so-called ‘collapse compression’ resulting from the wetting of hitherto dry material owing to infiltration of groundwater or floodwater. The water results in both a weakening of particles in coarse-grained materials and a weakening of inter-particle bonds; both potentially leading to denser packing of hardcore.

If such compression occurs, the ground floor slab loses its support over part or all of its area and settlement may occur. Typically, gaps appear between the floor and skirting board, the slab can crack and any partitions or features built off it can be disrupted (Figure 2). There have been many cases where this has occurred to some extent. Sites where a considerable depth of hardcore is needed are particularly vulnerable. This is why for routine construction, Approved Document C[2] gives a limiting depth of 600 mm and recommends, as an alternative, the use of a suspended floor slab.

Note that even on sites where the average depth of hardcore over the site is relatively small, difficulties can still be experienced at the edges if battered-back deep trenches have been formed to facilitate the construction of the foundations. The now popular use of trench fill concrete foundations reduces the need for hardcore infill of such a foundation trench. While a light partition wall may be built on a hardcore-supported floor slab, in no case should such walls themselves be load-bearing. Load-bearing walls always require adequate foundations.

2 OVERLAY OF HARDCORE BY THERMAL INSULATION AND DAMP-PROOF MEMBRANE OR GAS BARRIER

Current building regulations may call for hardcore to be overlaid with thermal insulation, a damp-proof membrane (DPM) and a gas barrier to resist radon or methane. To prevent damage to these elements, the top of the hardcore must be given a level and smooth finish by ‘blinding’ with a thin layer of fine aggregate (sand). A typical arrangement is shown in Figure 3.

References to practical measures that satisfy The Building Regulations 2010 (England and Wales) in respect of thermal insulation, DPM and gas barrier are included in the associated Approved Documents as follows:

- Approved Document L1A[7] and Approved Document C[2] deal with the requirement to limit heat transmission through floors of buildings. Typically this requires the U-values of floors to be of the order of 0.25 W/m²·K. To achieve this with a concrete slab supported by hardcore, the floor will normally require the incorporation of an insulating layer (eg made up of proprietary floor insulation boards).
- Approved Document C[2] deals with the requirement to resist the passage of ground moisture to the upper surface of the floor. For a concrete slab supported by hardcore, this is typically achieved by the incorporation of a DPM consisting of a 300 micron (0.3 mm) thick sheet of polyethylene placed between the hardcore and the concrete. This position for the DPM is mandatory if there is any sulfate present in the hardcore in order to prevent sulfate attack to the concrete slab.

Figure 2: Typical damage to floor and partition wall of an older building resulting from compression of inadequately profiled and compacted hardcore
Selection of such permeable material for hardcore requires some consideration. Since SHW Series 800 Type 1 and Type 2 unbound mixtures may contain a substantial proportion of fines, they may fail to offer sufficient permeability when well compacted. SHW Series 800, Type 3 unbound mixture (Clause 805[1]) (designed for use as a free-draining subbase layer) is more open graded with a substantial reduced fines content. However, it is coarser overall than SHW Type 1 and Type 2 mixtures, with a maximum particle size (at 2D) of 80 mm, so it is not so readily compacted in 100–150 mm placement layers.

A practical solution may be to use SHW Type 1 and Type 2 unbound mixtures for all hardcore material except the topmost layer, and then to form the top layer with crushed rock coarse aggregate, graded 4/20 Gc 85/15 to aggregate standard BS EN 13242:2002+A1:2007[10] (see Part 1 of this Digest for explanation of symbols). This has less than 15% of material passing a 4 mm sieve and less than 5% passing a 2 mm sieve. (Such an aggregate is currently a recommended option for use as permeable subbase when paving over gardens to form driveways[11].)

The permeable hardcore material will need to be blinded before laying a DPM. A material likely to be appropriate for this is a 50 mm thick layer comprising Type 0/4 (CP) Gc 85 concreting sand to BS EN 12620:2002+A1:2008[12] as interpreted by Annex D of PD 6682-1:2009[13]. This is a relatively coarse sharp sand containing little or no material of silt or clay particle size. It should be levelled and lightly compacted in a slightly moist condition.

Figure 3: Floor slab construction on hardcore with a typical configuration for blinding, DPM and floor insulation
3 LEGACY MATERIALS AND PROBLEMS

The use of hardcore to support ground floor slabs of low-rise buildings became common after the end of World War II, owing to a shortage of the timber that was previously used for suspended timber floors. A wide range of materials was employed as hardcore in early post-war years, with little or no consideration being given to long-term performance. Typically the material used was any predominantly granular material that was locally available at low cost or zero cost other than for transportation. Several such materials were subsequently found to be unsuitable, especially when the post-construction conditions were damp, with their use in the long term often leading to costly damage to buildings. Former editions of this BRE Digest on hardcore[14, 15, 16, 17] document the gradual recognition of problems arising from the inclusion of unsuitable material, leading to a progressive restriction of materials recommended for use. Table 1 lists materials, some used extensively as hardcore, which subsequently proved to have latent problems.

A particularly widespread problem that has affected many thousands of residential buildings built between 1945 and 1970 is sulfate attack to concrete floor slabs and oversite concrete constructed on sulfate-bearing hardcore without an intervening DPM (Figure 4). The material most often at fault is burnt colliery spoil taken from coal tips that had suffered from internal fire due to spontaneous combustion. While this burning turns initially weak Coal Measures mudstone into a hard material with good load-bearing properties, it also causes oxidation of contained pyrite (iron disulfide), resulting in the formation of substantial amounts of soluble sulfates.

The still-emerging legacy from this problem material is extensive damage to houses as the sulfate-attacked concrete expands, resulting in heave and cracking of floor slabs and displacement and cracking of adjoining walls. Additionally, in some areas large numbers of undamaged houses have suffered market blight owing to the suspected presence of deleterious sulfate-bearing hardcore. The continuing problems are comprehensively discussed in a 2008 guidance document written by BRE for the Department for Communities and Local Government (DCLG)[19].

<table>
<thead>
<tr>
<th>Material</th>
<th>Where used in the UK</th>
<th>Problems arising from use</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unburnt colliery spoil</td>
<td>In and around former coalfield areas in England, Wales and Scotland.</td>
<td>Unburnt colliery spoil typically contains pyrite (iron sulfide). In the presence of air, water and calcium carbonates (limestone), this may oxidise leading to the formation of gypsum and other soluble sulfates. The chemical reactions may lead to bulk expansion of hardcore that has the potential to cause floor uplift. However, reference to BRE files indicates that only rarely in the case of unburnt colliery spoil has this mechanism led to building damage. Unburnt colliery spoil may also contain significant amounts of clay material. This can result in swelling of hardcore if it is placed in a dry condition but subsequently becomes wet. Again, BRE files indicate that only rarely, if ever, has such swelling of colliery spoil led to building damage.</td>
<td>[17]</td>
</tr>
<tr>
<td>Burnt colliery spoil (red shale)</td>
<td>In and around former coalfield areas in England, Wales and Scotland.</td>
<td>Sulfate attack to concrete floor slabs and oversite concrete when used as hardcore material in conditions that are moist due to groundwater or leaking services. Burnt colliery spoil typically contains water-soluble sulfates. Where there is no DPM below the floor slab, dissolved sulfates may be drawn through the slab by capillary action. Such sulfates can attack the matrix of concrete made with Portland cement. The result is expansion of the concrete, typically producing doming and cracking of floors and displacement of adjacent walls.</td>
<td>[18]</td>
</tr>
<tr>
<td>Quarried mudstone and shale containing pyrite</td>
<td>Pyramic mudstones are found in most parts of the UK (other than south-east England), but the only location where damage to houses is known is the Cleveland area south of the River Tees in north-east England. The Cleveland problems arose in the 1970s from the use of mudstone quarried from beds in the Alum Shale and Jet Rock members of the Whitby Mudstone Formation (of Whitbrian, Upper Liassic, Jurassic age). Pyrites in the mudstone oxidised leading to the formation of gypsum crystals on the bedding plane laminae, which in turn prised lumps apart, causing bulk expansion of hardcore and consequent damage to many houses. A similar mechanism was found by BRE in 1989 to be the cause of 25 mm floor heave in a Midlands warehouse where up to 2 m of pyritic shale had been used as hardcore.</td>
<td>[17, 20, 21]</td>
<td></td>
</tr>
<tr>
<td>Furnace bottom ash (black ash)</td>
<td>In and around former heavy industrial areas in England, Wales and Scotland.</td>
<td>Ash and cinders from coal-burning boilers and furnaces typically contain water-soluble sulfates. When used as hardcore material, problems have arisen similar to those associated with use of burnt colliery spoil.</td>
<td>[19]</td>
</tr>
</tbody>
</table>
Incinerator bottom ash aggregate (IBAA)  In any area of the UK.  IBAA results from the combustion of domestic refuse. It may contain a significant concentration of sulfates, though no related cases of damage to buildings from sulfate attack are known to BRE. One case is known of uplift of a floor slab resulting from expansion of IBAA used as hardcore. [17]

Oil shale residue  In the Lothians area of the Midlands Valley of Scotland. An oil extraction industry was based here from the 1850s through to 1963 that left a legacy of some 200 million tonnes of spent shale in waste tips. Some problems of sulfate attack to concrete floor slabs have reputedly arisen from the use of ‘spent’ oil shale (blaes) taken from the waste tips (bings) left after extraction of oil by retorting at high temperature. Much of the sulfur compounds in the raw oil shale (including pyrite) evolved during oil distillation as the gas hydrogen sulfide (subsequently captured by ammonium to produce the by-product ammonium sulfate, used as fertiliser). However, a variable and sometimes substantial amount of soluble sulfate often remains in the spent shale. [17]

Blastfurnace slag  In areas of England, Wales and Scotland where iron and steel were produced. Often these coincided with coalfield areas. Some blastfurnace slags from old slag banks have undergone expansive reactions when used as fill and hardcore. They may contain excessive amounts of sulfate and dicalcium silicate. Under wet conditions the latter can hydrate and subsequently carbonate; the carbonated slag then reacts under cool conditions with sulfates to form the sulfate-bearing reaction product, thaumasite. The formation of thaumasite is expansive and has led to severe heave of numerous concrete floor slabs. Modern air-cooled blastfurnace slags are not susceptible to attack from sulfates by this mechanism. [17, 20, 23]

Steel slag  In areas of England, Wales and Scotland where iron and steel were produced. Often these coincided with coalfield areas. Steel slag, both fresh and from old slag heaps, can contain free lime (calcium oxide) and periclase (magnesium oxide), which, in the presence of water, can hydrate to hydroxides. The reaction produces a volume expansion that may continue for many years. A substantial number of houses in the Midlands and north England have suffered floor uplift and outward displacement of walls below the damp-proof course (DPC) owing to long-term expansion of hardcore material made up of steel slag (Figure 5). [17, 20, 23]

Demolition rubble containing gypsum plaster or bricks with a high soluble sulfate content  In all areas of the UK, but particularly in cities such as Bristol and Hull where rubble from bombed buildings was used after World War II. Rubble from building demolition may contain gypsum plaster or bricks with a high soluble sulfate content, which, when conditions are moist, can cause sulfate attack to oversite concrete or floor slabs. In a 1970s bungalow in the West Midlands, such sulfate attack caused some 50 mm domed uplift and cracking of oversite concrete, which in turn damaged overlying sleeper walls and suspended wooden floors (Figure 4). [17, 18, 19, 20]

Crushed concrete placed in a sulfate environment  In areas of the UK where sulfate is found in geological strata (see Figure C2 of BRE SD 1[18].) Crushed concrete may expand due to sulfate attack if placed in a location where there is sulfate in soil or groundwater. In one case, recycled concrete used below floor slabs in a coalfield area reacted with sulfates in groundwater resulting in the formation of the highly expansive sulfate minerals ettringite and thaumasite. [17, 18, 20]

Materials that are frost susceptible such as chalk  Frost-susceptible chalk is found in south-east England. Chalk and other materials made up of silt-sized particles may cause problems of frost heave in floors when a prolonged frost occurs during construction. Movements result from capillary migration of water and formation of ice layers within the hardcore. Such ice formation can exert considerable expansive pressure, with consequent disruption to the prior compacted state. This may result in a potential for deleterious compression over the longer term. [17]

Table 1 (cont’d): Some materials used as hardcore that have resulted in damage to buildings in the UK

<table>
<thead>
<tr>
<th>Material</th>
<th>Where used in the UK</th>
<th>Problems arising from use</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incinerator bottom ash aggregate (IBAA)</td>
<td>In any area of the UK.</td>
<td>IBAA results from the combustion of domestic refuse. It may contain a significant concentration of sulfates, though no related cases of damage to buildings from sulfate attack are known to BRE. One case is known of uplift of a floor slab resulting from expansion of IBAA used as hardcore.</td>
<td>[17]</td>
</tr>
<tr>
<td>Oil shale residue</td>
<td>In the Lothians area of the Midlands Valley of Scotland. An oil extraction industry was based here from the 1850s through to 1963 that left a legacy of some 200 million tonnes of spent shale in waste tips.</td>
<td>Some problems of sulfate attack to concrete floor slabs have reputedly arisen from the use of ‘spent’ oil shale (blaes) taken from the waste tips (bings) left after extraction of oil by retorting at high temperature. Much of the sulfur compounds in the raw oil shale (including pyrite) evolved during oil distillation as the gas hydrogen sulfide (subsequently captured by ammonium to produce the by-product ammonium sulfate, used as fertiliser). However, a variable and sometimes substantial amount of soluble sulfate often remains in the spent shale.</td>
<td>[17]</td>
</tr>
<tr>
<td>Blastfurnace slag</td>
<td>In areas of England, Wales and Scotland where iron and steel were produced. Often these coincided with coalfield areas.</td>
<td>Some blastfurnace slags from old slag banks have undergone expansive reactions when used as fill and hardcore. They may contain excessive amounts of sulfate and dicalcium silicate. Under wet conditions the latter can hydrate and subsequently carbonate; the carbonated slag then reacts under cool conditions with sulfates to form the sulfate-bearing reaction product, thaumasite. The formation of thaumasite is expansive and has led to severe heave of numerous concrete floor slabs. Modern air-cooled blastfurnace slags are not susceptible to attack from sulfates by this mechanism.</td>
<td>[17, 20, 23]</td>
</tr>
<tr>
<td>Steel slag</td>
<td>In areas of England, Wales and Scotland where iron and steel were produced. Often these coincided with coalfield areas.</td>
<td>Steel slag, both fresh and from old slag heaps, can contain free lime (calcium oxide) and periclase (magnesium oxide), which, in the presence of water, can hydrate to hydroxides. The reaction produces a volume expansion that may continue for many years. A substantial number of houses in the Midlands and north England have suffered floor uplift and outward displacement of walls below the damp-proof course (DPC) owing to long-term expansion of hardcore material made up of steel slag (Figure 5).</td>
<td>[17, 20, 23]</td>
</tr>
<tr>
<td>Demolition rubble containing gypsum plaster or bricks with a high soluble sulfate content</td>
<td>In all areas of the UK, but particularly in cities such as Bristol and Hull where rubble from bombed buildings was used after World War II.</td>
<td>Rubble from building demolition may contain gypsum plaster or bricks with a high soluble sulfate content, which, when conditions are moist, can cause sulfate attack to oversite concrete or floor slabs. In a 1970s bungalow in the West Midlands, such sulfate attack caused some 50 mm domed uplift and cracking of oversite concrete, which in turn damaged overlying sleeper walls and suspended wooden floors (Figure 4).</td>
<td>[17, 18, 19, 20]</td>
</tr>
<tr>
<td>Crushed concrete placed in a sulfate environment</td>
<td>In areas of the UK where sulfate is found in geological strata (see Figure C2 of BRE SD 1[18].)</td>
<td>Crushed concrete may expand due to sulfate attack if placed in a location where there is sulfate in soil or groundwater. In one case, recycled concrete used below floor slabs in a coalfield area reacted with sulfates in groundwater resulting in the formation of the highly expansive sulfate minerals ettringite and thaumasite.</td>
<td>[17, 18, 20]</td>
</tr>
<tr>
<td>Materials that are frost susceptible such as chalk</td>
<td>Frost-susceptible chalk is found in south-east England.</td>
<td>Chalk and other materials made up of silt-sized particles may cause problems of frost heave in floors when a prolonged frost occurs during construction. Movements result from capillary migration of water and formation of ice layers within the hardcore. Such ice formation can exert considerable expansive pressure, with consequent disruption to the prior compacted state. This may result in a potential for deleterious compression over the longer term.</td>
<td>[17]</td>
</tr>
</tbody>
</table>
A less frequent occurrence has been expansion (swelling) of chemically unstable hardcore, which has lifted ground floor slabs and pushed outwards enclosing walls below the damp-proof course (DPC) (Figure 5). Several materials used in the past have been the cause of substantial damage to buildings in the UK. The most commonly encountered ones have included:

- blastfurnace slags from old slag banks;
- steel slag, both fresh and from old slag heaps; and
- weak laminated rock (mudstone and shale) containing pyrite.

A common factor in the more severe cases of damage has been the availability of water to permeate through the hardcore, feeding an expansive chemical reaction that typically results in hydrated minerals that have greater volume than the source material. Such water may come from groundwater or from leaking fresh or foul water service pipes.

In the case of mudstone and shale containing pyrite, the presence of oxygen is also needed to oxidise the pyrite. In the presence of water and air, often aided by bacterial action, pyrite (FeS₂) may oxidise to form red-brown ferric oxide (Fe₂O₃) or yellow-brown hydrated ferric oxide (Fe(OH)₃) together with sulfuric acid (H₂SO₄). If calcium carbonate (CaCO₃) is present, the sulfuric acid (H₂SO₄) will further react with it to produce calcium sulfate in the form of gypsum (CaSO₄·2H₂O). This hydrated mineral has a substantially greater volume than the source pyrite. Additionally, the gypsum crystals tend to form on planes of weakness (laminations) within the mudstone and shale, prising lumps apart. Other reactions may produce similarly expansive jarosite (KFe₃(OH)₆(SO₄)₂), melanterite (FeSO₄·7H₂O) and other hydrated sulfate minerals.

While numerous types of rock may contain pyrite, not all are similarly prone to oxidation of pyrite. Pyrite in dark-coloured mudstone and shale rocks (Figure 6) is particularly susceptible since the pyrite tends to be distributed in myriad small particles that collectively have a large surface area. Additionally, because such rock is weak it fractures easily, allowing greater access to air and water. Because the particles are generally too small to be seen by the naked eye, the pyrite content may easily be overlooked even though pyrite content may approach 5% of mass.

In the UK there is a continuing legacy of problems in the Cleveland area of north-east England arising from the use in the 1970s of mudstone quarried from beds of Upper Lias of Jurassic age. There have also been some cases where the pyrite content of unburnt colliery spoil (of Carboniferous age) has reputedly caused expansive problems. Similar problems have been reported elsewhere in the world, notably in recent years in the Quebec province of Canada and the Dublin area of Ireland. In the latter, many residential and other buildings have been reported as damaged owing to expansion of pyritic Carboniferous mudstone used as hardcore.
4 SUMMARY OF RECOMMENDATIONS

1. Ensure adequate compaction of hardcore material by use of an appropriate method specification. For a given type of hardcore material this should specify the compacted thickness of placement layers, the type and mass of compaction plant and the number of passes required. Guidance can be found in Table 8/4 of SHW Series 800 ("Compaction requirements for unbound mixtures")..

2. Total compacted hardcore thickness should generally be in the range of 100–600 mm. For greater thickness seek expert advice.

3. If you decide to use SHW Type 2 (Clause 804) unbound mixtures as hardcore material, ask the supplier to declare the typical value of laboratory dry density and optimum water content, as determined in his mandatory system of production control. Ensure that the water content of the hardcore material at the time of compaction is close to this value, ideally within the range 1% above to 2% below.

4. If you decide to use SHW Type 1 (Clause 803) unbound mixtures as hardcore, you can compact the material adequately for use as hardcore without reference to its optimum water content as long as the material is visibly damp but not wet.

5. Give consideration to local requirements of building regulations and consequent architectural detailing as these may put constraints on the topping out of the hardcore. An upper layer of permeable hardcore may be needed to vent radon or other gas. If a water- or gas-proof membrane is to be laid over the hardcore, the hardcore must first be blinded with fine material so that the membrane is not subsequently punctured.

6. Be aware of the numerous incidences of building damage that have resulted in the past from use of inappropriate materials and work procedures. Remedy of post-construction problems originating in the hardcore material causes major disruption for building occupants and incurs high remedial costs.

Figure 5: House in Staffordshire damaged by expansion of ferrous slag used as hardcore
(a) Foundation wall (yellow bricks) thrust outwards by expansion of hardcore causing horizontal cracking and 7 mm stepping of wall at DPC level and vertical crack at corner (arrowed)
(b) Block of hardcore removed from below the ground floor slab. The originally granular grey ferrous slag has become welded into a hard solid mass and is encrusted with soft white and orange reaction products.

Figure 6: Pyrite-bearing mudstone and limestone of Carboniferous age that had been used as hardcore in Ireland, now heaped up for disposal following removal from a damaged house
REFERENCES


19 Longworth T I. Sulfate damage to concrete floors on sulfate-bearing hardcore: identification and remediation. London, RIBA Publishing (for Department for Communities and Local Government), 2008.†


24 Association des Consommateurs pour la Qualité dans la Construction (ACQC). Pyrite and your house: What homeowners should know about swelling backfills. Quebec, ACQC, 2000.†

25 Evening Herald (Dublin). Pyrite is putting 60,000 houses at risk of crumbling. 3 December 2008.

26 Irish Times. Youth centre ‘ruined’ because infill used not fit for purpose. 26 May 2011.

† These documents are available free of charge from the websites of the respective organisations.
### APPENDIX: CORRELATION WITH THE BUILDING REGULATIONS OF SCOTLAND AND NORTHERN IRELAND

The foregoing text of this Part of the Digest is aligned primarily with the requirements of The Building Regulations 2010 (England and Wales). The following table points to the equivalent requirements in The Building (Scotland) Regulations 2004 and The Building Regulations (Northern Ireland) 2000. For references to thickness and compaction of hardcore see the Appendix of Part 1 of this Digest.

<table>
<thead>
<tr>
<th>Requirement</th>
<th>The Building Regulations 2010 (England and Wales)</th>
<th>The Building (Scotland) Regulations 2004 + Building (Scotland) Amendment Regulations 2010</th>
<th>The Building Regulations (Northern Ireland) 2000 + The Building (Amendment No. 2) Regulations (NI) 2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>Part C of Schedule 1: Site preparation and resistance to contaminants and moisture</td>
<td>Requirement: C2 Resistance to moisture. The floors, walls and roof of the building shall adequately protect the building and people who use the building from the harmful effects caused by: a. Ground moisture. <strong>Practical guidance:</strong> Technical solutions as given in Approved Document C: Site preparation and resistance to contaminants and moisture (2004).</td>
<td><strong>Section 3 of Schedule 5: Environment</strong> Requirement: 3.4 Moisture from the ground. Every building must be designed and constructed in such a way that there will not be a threat to the building or the health of the occupants as a result of moisture penetration from the ground. <strong>Practical guidance:</strong> Technical Handbook, Domestic, 2011. <strong>Section 3: Environment.</strong></td>
<td><strong>Part C of Building Regulations:</strong> Preparation of site and resistance to moisture. Regulation C4 Resistance to ground moisture and weather. Every wall, floor and roof shall be constructed so as to prevent any harmful effect on the building or the health of the occupants caused by the passage of moisture to any part of the building from: a. the ground; and b. the weather. <strong>Practical guidance:</strong> Methods and standards of building as given in Technical Booklet C: Site preparation and resistance to moisture (2004).</td>
</tr>
<tr>
<td><strong>Text relevant to damp-proof membrane above hardcore</strong></td>
<td>C4.7(c) Ground-supported floors. ‘Damp-proof membrane above or below the concrete, and continuous with the damp-proof courses in walls, piers and the like. If the ground could contain water soluble sulphates, or there is any risk that sulphate or other deleterious matter could contaminate the hardcore, the membrane should be placed at the base of the concrete slab.’</td>
<td>Clause 3.4.2 Ground-supported concrete floors. ‘Damp-proof membrane above or below the slab or as a sandwich; jointed and sealed to the damp-proof course or damp-proof structure in walls, columns and other adjacent elements in accordance with the relevant clauses in Section 3 of CP 102:1973 ...’</td>
<td><strong>Section 3: Environmental.</strong> <strong>Text relevant to damp-proof membrane above hardcore</strong></td>
</tr>
</tbody>
</table>
WHAT IS BRE CONNECT ONLINE?
BRE Connect Online gives you access to the unrivalled expertise and insight of BRE – the UK’s leading centre of excellence on the built environment. BRE Connect Online is an annual subscription service from IHS BRE Press giving online access to over 1600 BRE titles.

WHAT DO I GET?
ALL NEW AND PUBLISHED BRE TITLES
650 books, reports and guides – research, innovation, best practice and case studies, including:
- The Green Guide to Specification
- Designing quality buildings
- Complying with the Code for Sustainable Homes
- Roofs and roofing
- Site layout planning for daylight and sunlight

250 Digests – authoritative state-of-the-art reviews

550 Information Papers – BRE research and how to apply it in practice

150 Good Building and Repair Guides – illustrated practical guides to good building and repair work

and much more ...

WHAT’S NEW IN 2011?
More than 50 new titles, including:
- Airtightness in commercial and public buildings
- BREEAM In-Use
- Design of durable concrete structures
- Environmental impact of floor finishes
- Low-water-use fittings
- Sustainable shopfitting equipment
- Ventilation for healthy buildings

All this for an annual subscription of only £349 + VAT
Call now on +44 (0) 1344 328038 to find out more
This CD-ROM compilation from IHS BRE Press gives you access to a huge training resource of practical guidance and expertise from BRE, the UK’s leading centre of excellence on the built environment. Containing over 150 Good Building and Repair Guides, the CD-ROM covers a range of topics, including:

- Water services
- Basement construction
- Installing thermal insulation
- Fixing and finishing plasterboard
- Roofing
- Achieving airtightness
- Loft conversion
- Radon protection
- Plastering

A vast reference library of concise and practical advice for only £150 + VAT

Order now @ www.brebookshop.com
or phone +44 (0) 1344 328038

BRE is the UK’s leading centre of expertise on the built environment, construction, energy use in buildings, fire prevention and control, and risk management. BRE is a part of the BRE Group, a world leading research, consultancy, training, testing and certification organisation, delivering sustainability and innovation across the built environment and beyond. The BRE Group is wholly owned by the BRE Trust, a registered charity aiming to advance knowledge, innovation and communication in all matters concerning the built environment for the benefit of all. All BRE Group profits are passed to the BRE Trust to promote its charitable objectives.

BRE is committed to providing impartial and authoritative information on all aspects of the built environment. We make every effort to ensure the accuracy and quality of information and guidance when it is published. However, we can take no responsibility for the subsequent use of this information, nor for any errors or omissions it may contain.

BRE is the UK’s leading centre of expertise on the built environment, construction, energy use in buildings, fire prevention and control, and risk management. BRE is a part of the BRE Group, a world leading research, consultancy, training, testing and certification organisation, delivering sustainability and innovation across the built environment and beyond. The BRE Group is wholly owned by the BRE Trust, a registered charity aiming to advance knowledge, innovation and communication in all matters concerning the built environment for the benefit of all. All BRE Group profits are passed to the BRE Trust to promote its charitable objectives.

BRE is committed to providing impartial and authoritative information on all aspects of the built environment. We make every effort to ensure the accuracy and quality of information and guidance when it is published. However, we can take no responsibility for the subsequent use of this information, nor for any errors or omissions it may contain.

BRE, Garston, Watford WD25 9XX
Tel: 01923 664000, Email: enquiries@bre.co.uk, www.bre.co.uk

BRE Digests are authoritative summaries of the state-of-the-art on specific topics in construction design and technology. They draw on BRE’s expertise in these areas and provide essential support for all involved in design, specification, construction and maintenance. Digests, Information Papers, Good Building Guides and Good Repair Guides are available on subscription in hard copy and online through BRE Connect. For more details call 01344 328038.

BRE publications are available from www.brebookshop.com, or IHS BRE Press, Willoughby Road, Bracknell RG12 8BF
Tel: 01344 328038, Fax: 01344 328005, Email: brepress@ihs.com

Requests to copy any part of this publication should be made to:
IHS BRE Press,
Garston,
Watford WD25 9XX
Tel: 01923 664761
Email: brepress@ihs.com
www.brebookshop.com

Acknowledgements

The preparation and publication of this Digest was funded by NHBC.