Improving specifications for use of recycled and secondary aggregates in construction

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Executive Summary

National targets have been set for the use of recycled and secondary aggregates (RSA), rising from 40 million tonnes in 2001 to 55 million tonnes by 2006 (or 60 million tonnes by 2011 in draft guidance). The increase in the use of these materials required to achieve the 2006 target needs to be 2-3 million tonnes a year.

A key issue, in relation to client perceptions and their willingness and ability to allow or even encourage the use of RSA, is the role of fit for purpose specifications. Fit for purpose specifications are difficult to define precisely. However, recent BRE industry workshops indicate that they are best interpreted as specifications that are easy to use and designed to encourage the use of RSA.

The current work by BRE will seek to achieve these aims through:

- Preparation of user-friendly guidance and/or specification systems;
- Production and dissemination of technical documentation;
- A campaign (prepared in consultation with specifiers) to speed up the removal of specification barriers;
- Development of design and specification guidelines for new applications such as hydraulically bound materials and roller-compacted concrete.

The aim is to encourage, through appropriate guidance, the development and use of performance-based specifications in order to improve confidence in secondary and recycled materials as aggregates.

This report presents the final specifications documents produced by BRE.
1 Introduction to the project

National targets have been set for the use of recycled and secondary aggregates (RSA), rising from 40 million tonnes in 2001 to 55 million tonnes by 2006 (or 60 million tonnes by 2011 in draft guidance). The increase in the use of these materials required to achieve the 2006 target needs to be 2-3 million tonnes a year.

Recent research funded by WRAP and DTI has examined a number of barriers to the increased use of these materials in construction. A key issue, in relation to client perceptions and their willingness and ability to allow or even encourage the use of RSA is the role of fit for purpose specifications. There are a number of examples where fit for purpose specifications have been used to advantage in road construction. In building construction the perception remains that insurers and other stakeholders are not likely to accept any risks from the use of fit for purpose specifications unless clearly taken on board by product manufacturers.

The project seeks to provide:

- User-friendly guidance and specification systems, facilitating the use of RSA (where not already explicitly covered in existing guidance notes).
- Development of design and specification guidelines for new applications of RSA such as in hydraulically bound materials and roller-compacted concrete including hydraulically bound uses as being introduced shortly for roads by the EN 14227 series of standards. This will take into account North American experience in the use of roller compacted concrete and hydraulically bound materials in dams and water retaining structures, erosion control and sea defences.

The current BRE project is funded by DTI/WRAP. The aim is to encourage, through appropriate guidance, the development and use of performance-based specifications in order to improve confidence in the long-term durability of secondary and recycled materials. Client reference numbers are STBF/013/00006C and CC 2487. The BRE proposal number for the work is 110870. The project is managed on behalf of DTI/WRAP by Davis Langdon Consultancy.
2 Background in relation to the new European aggregates standards

The new European Standards for aggregates will potentially have a positive effect on the use of recycled and secondary (RSA) aggregates because they are included in the scope of the new Standards on an equal basis with natural aggregates. However, this potential is undermined by the fact that the relevant clauses for RSA are not yet in place. Therefore, for the next few years, the maintenance and encouragement of the use of these materials depends heavily on the adequacy of existing UK guidance. It was further identified that existing guidance for use in road construction was better provided than for use in building construction.

Guidance in standards for RSA is currently in a state of transition from that based solely on British Standards to that focussed around the new European Standards. By the beginning of 2004 it is the intention of the producers to produce to the new European standards so this report will concentrate on these.

There is now extensive guidance published by BSI in the PD 6682: 2003 series of documents on the application in the UK of the new ENs for aggregates. Specific guidance is given for each aggregate end use. However, reflecting the situation in the ENs themselves, there is very little on RSAs except for the use of blastfurnace and steel slags, which are well covered.
3 Introduction to the proposed for new/revised guidance to improve the specification of RSA in building construction

3.1 Materials covered in the guidance

The term RSA could potentially cover a wide range of materials. Amounts available and suitability for use as aggregates vary widely. The guidance covers a range of materials in outline form as well as the following materials in greater detail on the basis of their availability and suitability:

- Recycled concrete aggregate (RCA): specifications follow those in BS 8500: 2002, but will be easier to use.
- Incinerator bottom ash from domestic refuse incinerators (IBA).
- Recycled glass.

Other materials are covered in outline.

3.2 Form of guidance

Two forms are presented:

1) Outline guidance on a wide range of materials. This takes the form of a matrix of potential applications in building construction (e.g. foundations) against candidate RSAs with comments on major issues to be taken into account.

2) More detailed guidance on the use of the key materials identified above. This covers:

- Applications:
  - Concrete (pavement quality (PQ), floor slabs, foundations etc.);
  - Unbound (under floor slabs, pipe bedding etc)
  - Cross referenced to RCC and HBM documents (see below) where appropriate;
- Mix designs for particular conditions.
- Key specification limits (e.g.: chlorides, sulfates etc.).
- Special considerations for the particular material (e.g. ASR for glass aggregate).
4 Introduction to the new guidance on hydraulic bound materials in road applications

The UK is about to enter a two-year period of significant changes in the specification of hydraulic bound materials which has the potential to lead to considerable savings in the use of primary aggregates both through an increase of the use of RSA and through more innovative use of indigenous materials on construction sites.

The new guidance produced under this project comprises the following:

- Guidance on the use of HBM for road pavements. This gives an overview of the relevant standards, properties, mix proportions. The guidance also gives suggested testing schedules for mechanical performance of material combinations.

- Case studies illustrating successful use of HBM in road construction, including mix design information.
5 Introduction to the new guidance on the use of CBM, RCC and HBM for non-road applications

The use of roller compacted cementitious mixtures (CBM, RCC and HBM) for road and airfield pavement construction is relatively well known in the UK, but outside of the UK, such mixtures have been used for many other construction purposes.

Overall there is very little UK advice for the non-road use of such mixtures, particularly in what can be termed ‘water related applications’ i.e. linings, erosion protection, rip-rap, lagoons, dikes etc. The UK potential for the expansion of CBM, RCC and HBM into these “water related” and other applications, can be considered large. Such uses are very appropriate for RSA as many of these are suitable for use in these mixtures.

Recognizing this potential and the lack of UK design and specification literature, the project has produced documentation that fills this gap. This documentation draws on the UK experience in the roads field as well as drawing on US (PCA and ACI) and European (ICOLD, Germany) experience and data in the non-road market. The documentation covers amongst other subjects: material selection with particular reference to RSA, binder selection (including pfa and slag), design parameters for the various applications covered, mixture design, construction methods and control, end-product/performance requirements.

The documents on CBM, RCC and HBM are provided in appendices to this report in the following format:

Guidance on roller compacted concrete, CBM and HBM in marine and fluvial construction works. The guidance includes the principles by which soil and aggregates including RSA, that are well established in road construction, can be used in non-roads applications such as shore/slope stabilisation and erosion control.

The images provided in Appendix F are from PCA (Portland Cement Association) sources. WRAP will need to seek their permission prior to publication on AggRegain.
6  Brief overview of the new guidance

The new detailed guidance (one document per material), has been based on the following materials on the basis of their availability and suitability:

- Recycled concrete aggregate (RCA). Specifications follow those in BS 8500: 2002 but will be easier to use;
- Recycled aggregate (RA). Specifications extend those in BS 8500: 2002;
- Incinerator bottom ash from domestic refuse incinerators (IBA);
- Recycled glass.

The guidance covers the following applications/information as appropriate:

- Applications
  - Concrete (pavement quality (PQ), floor slabs, foundations etc.)
  - Unbound (under floor slabs, pipe bedding etc)
  - Cross referenced to RCC and HBM documents (see below) where appropriate
- Mix designs for particular conditions
- Key specification limits (e.g. chlorides, sulfates etc.)
- Special considerations for the particular material (e.g. ASR for glass)

Other materials are covered in outline in a further document giving tables of potential use against material (Appendix A).

Further documents are also included: one on opportunities for the use of RSA in HBM for road construction, and the other on opportunities for the use of RSA in RCC for non-road applications.
7 References

BRE client report 211-140: 2003 - Implications of the Harmonisation of Construction Product Standards for the Use of Secondary and Recycled Aggregates; Final report”.

BRE client report 211-274: 2003 - The role of fit for purpose specifications in secondary and recycled aggregate market.


EN 14227: Unbound and hydraulically bound mixtures. Specifications

BS 8500: 2002 Concrete - Complementary British Standard to BS EN 206-1 (Incorporating Amendment No.1 of 20 October 2003):
  Part 1: Method of specifying and guidance for the specifier
  Part 2: Specification for constituent materials and concrete
Appendix A - Outline guidance document to improve the specification of RSA in building construction and introduction to candidate RSAs

This document provides outline guidance on a wide range of materials. The guidance takes the form of a matrix of potential applications in building construction (e.g. foundations) against candidate RSAs with comments on major issues to be taken into account.

### Table A1: Outline guidance on use of RSAs in (building) construction
(Potential: High••• Some•• Low• None○)

<table>
<thead>
<tr>
<th>Material</th>
<th>Unbound aggregate</th>
<th>Concrete aggregate</th>
<th>Manufacture of Light-weight aggregate</th>
<th>Aggregate in Building Components</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crushed Concrete (RCA)</td>
<td>○○○</td>
<td>○○○</td>
<td>0</td>
<td>•</td>
</tr>
<tr>
<td>Crushed Masonry (RA)</td>
<td>○○○</td>
<td>○○○</td>
<td>○○○</td>
<td>•</td>
</tr>
<tr>
<td>Recycled Glass</td>
<td>○○○</td>
<td>○○○</td>
<td>○○○</td>
<td>•○○○</td>
</tr>
<tr>
<td>Blastfurnace Slag †</td>
<td>○○○</td>
<td>○○○</td>
<td>○○○</td>
<td>•○○○</td>
</tr>
<tr>
<td>Steel Slags</td>
<td>○○○</td>
<td>○○○</td>
<td>○○○</td>
<td>○○○</td>
</tr>
<tr>
<td>Burnt Colliery Spoil</td>
<td>○○○</td>
<td>○○○</td>
<td>○○○</td>
<td>•○○○</td>
</tr>
<tr>
<td>Unburnt Colliery Spoil</td>
<td>○○○</td>
<td>○○○</td>
<td>○○○</td>
<td>•○○○</td>
</tr>
<tr>
<td>Fly Ash (pfa)</td>
<td>○○○</td>
<td>○○○</td>
<td>○○○</td>
<td>•○○○</td>
</tr>
<tr>
<td>Furnace Bottom Ash</td>
<td>○○○</td>
<td>○○○</td>
<td>○○○</td>
<td>•○○○</td>
</tr>
<tr>
<td>China Clay Sand</td>
<td>○○○</td>
<td>○○○</td>
<td>○○○</td>
<td>•○○○</td>
</tr>
<tr>
<td>Slate Waste</td>
<td>○○○</td>
<td>○○○</td>
<td>○○○</td>
<td>•○○○</td>
</tr>
<tr>
<td>Incinerator Bottom Ash (IBA)</td>
<td>○○○</td>
<td>○○○</td>
<td>○○○</td>
<td>•○○○</td>
</tr>
<tr>
<td>Sewage sludge synthetic aggregate</td>
<td>○○○</td>
<td>○○○</td>
<td>○○○</td>
<td>○○○</td>
</tr>
<tr>
<td>Used Foundry waste</td>
<td>○○○</td>
<td>○○○</td>
<td>○○○</td>
<td>•○○○</td>
</tr>
<tr>
<td>Ceramic wastes</td>
<td>○○○</td>
<td>○○○</td>
<td>○○○</td>
<td>•○○○</td>
</tr>
<tr>
<td>Scrap tyres</td>
<td>○○○</td>
<td>○○○</td>
<td>○○○</td>
<td>•○○○</td>
</tr>
<tr>
<td>Plastics (mixed)</td>
<td>○○○</td>
<td>○○○</td>
<td>○○○</td>
<td>•○○○</td>
</tr>
<tr>
<td>Clay waste</td>
<td>○○○</td>
<td>○○○</td>
<td>○○○</td>
<td>•○○○</td>
</tr>
<tr>
<td>Non-ferrous slags</td>
<td>○○○</td>
<td>○○○</td>
<td>○○○</td>
<td>•○○○</td>
</tr>
<tr>
<td>Railway ballast</td>
<td>○○○</td>
<td>○○○</td>
<td>○○○</td>
<td>•○○○</td>
</tr>
</tbody>
</table>

† - Potential for material from old tips is low
¶ - Ensure unbound uses comply with BRE Digest SD1: 2001

More detailed guidance on the major issues for RA, RCA, glass and incinerator bottom ash (IBA) are given in Tables A2 to A4. Table A2 focuses on the major issues for each of the candidate RSAs in concrete and concrete products.
### Table A2: Potential durability/service life issues for key RSAs in concrete and concrete products (in comparison with natural materials)

<table>
<thead>
<tr>
<th>Material</th>
<th>Alkali silica reaction (ASR)</th>
<th>Weathering and frost resistance</th>
<th>Other expansive reactions or dimensional stability</th>
<th>Sulfates</th>
<th>Chloride levels</th>
<th>Carbonation</th>
<th>Leaching</th>
<th>Organics</th>
</tr>
</thead>
<tbody>
<tr>
<td>RCA</td>
<td>Y</td>
<td>Y</td>
<td>-</td>
<td>Y (in fines)</td>
<td>?</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>RA</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y (in fines)</td>
<td>?</td>
<td>Y</td>
<td>-</td>
<td>?</td>
</tr>
<tr>
<td>IBA</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>?</td>
<td>Y</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>Waste glass</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Natural Aggregates (for comparison)</td>
<td>Y for most</td>
<td>Test or service record required</td>
<td>Test for excessive shrinkage</td>
<td>-</td>
<td>Test marine aggs.</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Y = highly relevant issue to this material  
? = may be relevant issue to this material  
- = unlikely to be an issue for this material  
Y = relevant issue to this material

This Table can be restructured to give the following which highlights major issues, first in general terms and then by application (Table A3).
### Table A3: Potential durability/service life issues for key candidate RSAs in concrete and concrete products

<table>
<thead>
<tr>
<th>Material</th>
<th>Unbound use</th>
<th>Concrete and concrete products generally</th>
<th>Non-structural precast products</th>
<th>Structural pre-cast products</th>
<th>General applications (eg kerb bedding)*</th>
<th>Floors (house, garage or wearing surfaces)*</th>
<th>Paving (house and domestic or heavy duty)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>RCA</td>
<td>Sulfates in fines</td>
<td>ASR Weathering and frost resistance Carbonation</td>
<td>Weathering and frost resistance</td>
<td>ASR Weathering and frost resistance Carbonation</td>
<td>ASR Weathering and frost resistance</td>
<td>ASR Weathering and frost resistance</td>
<td>Weathering and frost resistance</td>
</tr>
<tr>
<td>RA</td>
<td>Sulfates in fines</td>
<td>ASR Weathering and frost resistance Carbonation</td>
<td>Weathering and frost resistance</td>
<td>ASR Weathering and frost resistance Carbonation</td>
<td>ASR Weathering and frost resistance</td>
<td>ASR Weathering and frost resistance</td>
<td>Weathering and frost resistance</td>
</tr>
<tr>
<td>IBA</td>
<td>Leaching</td>
<td>Possible ASR, weathering and frost resistance Dimensional stability Carbonation Leaching if recycled</td>
<td>Possible ASR, weathering and frost resistance Dimensional stability Carbonation Leaching if recycled</td>
<td>Possible ASR, weathering and frost resistance Dimensional stability Carbonation Leaching if recycled</td>
<td>Possible ASR, weathering and frost resistance Dimensional stability Carbonation Leaching</td>
<td>Possible ASR, weathering and frost resistance Dimensional stability Carbonation Leaching</td>
<td>Dimensions stability Leaching</td>
</tr>
<tr>
<td>Waste glass</td>
<td>Possible lead from cathode ray tubes if present</td>
<td>ASR Weathering and frost resistance</td>
<td>Weathering and frost resistance</td>
<td>ASR Weathering and frost resistance</td>
<td>ASR Weathering and frost resistance</td>
<td>ASR Weathering and frost resistance</td>
<td>Weathering and frost resistance</td>
</tr>
</tbody>
</table>
References:

BRE IP 18/01: 2001 – Blastfurnace slag and steel slag: their use as aggregates.

BRE Special Digest SD1: 2001 – Concrete in aggressive ground. Replacement of Digest 363.


BS EN 490: 1994 -Concrete roofing tiles and fittings - product specifications.

BS 7263: 1981 - Precast concrete masonry units.
   Part 1: Specification for precast concrete masonry units
   Part 2: Method for specifying precast concrete masonry units

BS EN 6073: 1981 - Precast concrete masonry units.
   Part 2: Method for specifying precast concrete masonry units.

BS 8500: 2002 Concrete - Complementary British Standard to BS EN 206-1 (Incorporating Amendment No.1 of 20 October 2003):
   Part 1: Method of specifying and guidance for the specifier
Appendix B - Guidance document for RCA and RA

Recycled concrete aggregate (RCA) and Recycled aggregate (RA)

Definitions:
recycled concrete aggregate (RCA): *recycled aggregate principally comprising crushed concrete*
recycled aggregate (RA): *aggregate resulting from the reprocessing of inorganic material previously used in construction*

Use in concrete

Coarse RCA and coarse RA and composites of RCA or RA and natural aggregates to be used in concrete should conform to the general requirements of BS EN 12620: 2002 and the guidance on the use of BS EN 12620: 2002 in BS PD 6682-1: 2003 Additionally the aggregates should meet the requirements below which are based on those in BS 8500: 2002, the new complementary British Standard to BS EN 206-1: 2000.

Fine RCA and fine RA are not generally suitable in normal concretes due to the increases in water demand which these materials normally cause; however

- quality-controlled fine RCA in a pre-cast works can be used to replace up to 10% of the sand
- fine RCA may be used to replace up to 100% of the sand in foamed concrete.

Compositional/chemical requirements:

RCA and RA to be used in concrete should meet the compositional and chemical requirements of Table B1.
<table>
<thead>
<tr>
<th>Properties</th>
<th>Category to BS EN 12620: 2002 or other limit&lt;sup&gt;b&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Grading</strong></td>
<td></td>
</tr>
<tr>
<td>Coarse aggregate</td>
<td>See Annex C in BS PD6682-1: 2003</td>
</tr>
<tr>
<td><strong>Flakiness index</strong></td>
<td></td>
</tr>
<tr>
<td>FI</td>
<td></td>
</tr>
<tr>
<td>35</td>
<td></td>
</tr>
<tr>
<td>35 (There should be no difficulty in consistently producing RCA or RA to this limit)</td>
<td></td>
</tr>
<tr>
<td><strong>Shell content of coarse aggregate</strong></td>
<td></td>
</tr>
<tr>
<td>Not required unless blended with marine aggregate or deliberately contaminated with shell</td>
<td></td>
</tr>
<tr>
<td><strong>Fines</strong></td>
<td></td>
</tr>
<tr>
<td>RCA</td>
<td></td>
</tr>
<tr>
<td>$f_0$</td>
<td></td>
</tr>
<tr>
<td>0.06</td>
<td></td>
</tr>
<tr>
<td>RA</td>
<td></td>
</tr>
<tr>
<td>$f_0$</td>
<td></td>
</tr>
<tr>
<td>0.06</td>
<td></td>
</tr>
<tr>
<td><strong>Resistance to fragmentation</strong></td>
<td></td>
</tr>
<tr>
<td>No requirement. RCA will normally comply with LA&lt;sub&gt;40&lt;/sub&gt; and RA with LA&lt;sub&gt;40&lt;/sub&gt; or LA&lt;sub&gt;50&lt;/sub&gt;</td>
<td></td>
</tr>
<tr>
<td><strong>Acid soluble sulfate content</strong></td>
<td></td>
</tr>
<tr>
<td>$AS_{r_0}$</td>
<td></td>
</tr>
<tr>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td><strong>Total sulphur</strong></td>
<td></td>
</tr>
<tr>
<td>≤ 1 % by mass</td>
<td></td>
</tr>
<tr>
<td><strong>Masonry</strong>&lt;sup&gt;b&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>RCA</td>
<td></td>
</tr>
<tr>
<td>≤ 5% by mass</td>
<td></td>
</tr>
<tr>
<td>≤ 100% by mass</td>
<td></td>
</tr>
<tr>
<td>RA</td>
<td></td>
</tr>
<tr>
<td>≤ 0.5% by mass</td>
<td></td>
</tr>
<tr>
<td>≤ 1.0% by mass</td>
<td></td>
</tr>
<tr>
<td><strong>Lightweight material</strong>&lt;sup&gt;a,b&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>RCA</td>
<td></td>
</tr>
<tr>
<td>≤ 0.5% by mass</td>
<td></td>
</tr>
<tr>
<td>RA</td>
<td></td>
</tr>
<tr>
<td>≤ 1.0% by mass</td>
<td></td>
</tr>
<tr>
<td><strong>Asphalt</strong>&lt;sup&gt;b&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>RCA</td>
<td></td>
</tr>
<tr>
<td>≤ 5% by mass</td>
<td></td>
</tr>
<tr>
<td>≤ 10% by mass</td>
<td></td>
</tr>
<tr>
<td>RA</td>
<td></td>
</tr>
<tr>
<td>≤ 10% by mass</td>
<td></td>
</tr>
<tr>
<td><strong>Other foreign material eg glass, plastics, metals</strong>&lt;sup&gt;b&lt;/sup&gt;</td>
<td>≤ 1.0% by mass</td>
</tr>
<tr>
<td><strong>Constituents in RCA or RA fine aggregate which alter the rate of setting and hardening of concrete</strong>&lt;sup&gt;c&lt;/sup&gt;</td>
<td>≤ 120 minutes</td>
</tr>
<tr>
<td>-increase in mortar setting time</td>
<td>≤ 20% at 28days</td>
</tr>
<tr>
<td>-decrease in compressive strength of mortar</td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup> Material with a density less than 1,000 kg/m³.

<sup>b</sup> Property where currently no BS EN 12620: 2002 limit – test and limits taken from BS 8500-2: 2002

<sup>c</sup> Comparison should be with mortar made with standard clean sand; heating one sample according to the method in BS EN 1744-1: 1998 is not appropriate for RCA/RA. Alternatively, if concrete is made on a regular basis from these materials, consistent strength development in the concrete should be checked for each day’s production or batch of materials.
Table B2: Additional recommended BS EN 12620: 2002 designations for RCA and RA for particular end uses (derived from Annex B in BS PD 6682-1: 2003, Table B.1).

<table>
<thead>
<tr>
<th>End use</th>
<th>Property</th>
<th>Category to BS EN 12620: 2002</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exposed aggregate wearing surfaces</td>
<td>Polishing resistance</td>
<td>$PSV_{xx}$</td>
</tr>
<tr>
<td></td>
<td>Resistance to wear</td>
<td>$M_{oE,XX}$</td>
</tr>
<tr>
<td></td>
<td>Resistance to abrasion</td>
<td>$AAV_{XX}$</td>
</tr>
<tr>
<td>Note: the Highways Specification does not recommend RCA or RA for this purpose</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Concrete subject to freeze-thaw environment:</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Frost free or continuously dry or moderate water saturation (BS EN 206-1: 2000 exposure classes XF1 and XF2)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>High water saturation without de-icing agent (BS EN 206-1: 2000 exposure classes XF3)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>and/or High water saturation with deicing agent (BS EN 206-1: 2000 exposure class XF4)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>The Magnesium Sulfate Soundness test is not appropriate for RCA or RA. If an assessment of the freeze/thaw resistance is needed, Testing should be carried out on the concrete to be used.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>No requirement applicable Tests on concrete to be used to show adequate durability for service life</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Structural concrete</td>
<td>Drying shrinkage $^a$ $\leq 0.075$</td>
</tr>
<tr>
<td></td>
<td>Pavement wearing surfaces and heavy duty concrete floor finishes</td>
<td>Los Angeles co-efficient $^b$</td>
</tr>
</tbody>
</table>

$^a$Test method not appropriate for RCA or RA. Where information is required durability/shrinkage testing should be carried out on the concrete to be used. See also BRE Digest 357: 1991.

$^b$Values for these properties, appropriate for the end use, should be inserted from available categories in BS EN 12620: 2002 according to need. Further guidance is available in the Highways Agency design manual for roads and bridges, Highways Agency: 2001.

$^c$The degree of water saturation should be taken as reflecting the relative frequency of the likely occurrence of freezing whilst wet, i.e. moderate = occasional freezing when wet and high = frequent freezing when wet.

When determining that the maximum chloride content of concrete has not been exceeded as specified in clause 5.27 of BS EN 206-1: 2000, the chloride content of RCA and RA and its variability shall be established and taken into account. The method detailed in BS 1881-124: 1998 should be used.

**Limitations on the use of coarse RCA and RA**

**Strength Class of concrete**

RCA obtained by crushing hardened concrete of known composition that has not been contaminated by use may be used in new concrete of any strength class.

Other RCA and RA should not be used in concrete with a strength class greater than C40/50.

BS 8500-2: 2002 requires individual project specifications to define the extent to which RA may be used other than in standardized prescribed mixes ST1, ST2, ST3 and similarly for RCA of unknown composition in designated concretes RC25 to RC50 unless the RCA is limited to 20% as a mass fraction of the coarse aggregate, but these conditions may reasonably be extended if a quality control scheme based on BRE (2000) is used for RCA and RA.
Resistance to alkali-silica reactions

The risk of a damaging alkali-silica reaction in concrete containing RCA or RA can be minimised by adopting the preventive measures detailed in the guidance in BRE Digest 330: 1998 depending on the aggregate reactivity classification.

These measures include:

- limiting the total alkali content of the concrete mix (including a contribution from the RCA or RA; see below);
- use of additions such as pfa, fly ash, ggbs, microsilica or metakaolin;
- use of lithium salts.

Aggregate Classification and concrete mix limitations:

RCA can be classified as normally reactive (according to BRE Digest 330: 1998) if:

- The aggregate other than the RCA is not classed as highly or extremely reactive (see BRE Digest 330: 1998).
- The RCA is not from a source of concrete which originally contained a highly reactive or extremely reactive aggregate combination or a concrete which has itself been damaged by alkali-silica reaction.

NOTE 1. Only a very small proportion of source concrete will be unsuitable for classification as normally reactive. Input control in a quality control scheme based on BRE (2000) is recommended to ensure either (a) that concrete is derived from appropriate identified structures or (b) in the case of mixed source material that no source of concrete not classed as normally reactive can constitute more than 5% of the product. Decorative concretes containing highly or extremely reactive aggregates are seen as the main source of risk, and thus visual rather than petrographic examination of the input material should be sufficient.

- The alkali contribution from the RCA is included in the calculation of the alkali content of the concrete as 0.20 kg Na\textsubscript{2}O eq per 100 kg of RCA; or the composition of the RCA is known (eg surplus precast units; fresh concrete returned to a plant, allowed to harden and then crushed) and its alkali content is calculated from that of the original concrete and is included in the calculation of the alkali content of the concrete.

NOTE 2. The 0.20 kg Na\textsubscript{2}O eq per 100 kg of RCA is based on:

\[(4.8 \text{ kg Na}_2\text{O eq/m}^3) \times (1 \text{ m}^3/2400 \text{ kg}) \times 100 \text{ kg RCA} = 0.20 \text{ kg Na}_2\text{O eq per 100 kg RCA}\]

This limit is sufficiently conservative to cover most concretes in the UK which have suffered from ASR.

In this case the risk of damaging alkali-silica reaction is minimal if the calculated total alkali content of the concrete (including the calculated contribution from the RCA) does not exceed:

- 3.5 kg/m\textsuperscript{3} Na\textsubscript{2}O eq where the declared mean alkali content of a cement or the CEM I component of a combination is not greater than 0.75%;
- 3.0 kg/m\textsuperscript{3} Na\textsubscript{2}O eq where the declared mean alkali content of a cement or the CEM I component of a combination is 0.76% or greater.

The proportions and limiting compositions of any ggbs, pfa or flyash, microsilica, metakaolin or lithium salts used should be according to BRE Digest 330.

If the above calculations of alkali contributed by the RCA are not made, the RCA should classified as highly reactive and appropriate precautions taken in accordance with BRE Digest 330: 1998.
RA, because of the potential variability of its composition and a lack of information on the reactivity of UK masonry materials, should be classified as *highly reactive* (according to BRE Digest 330: 1998).

Additionally, the alkali contribution from the RA should be included in the calculation of the total alkali content of the concrete as 0.20 kg Na₂O eq per 100 kg of RA.

**NOTE 3.** The 0.20 kg Na₂O eq per 100 kg of RCA is based on a survey of UK bricks (248 samples) - (BRS (1950))

The risk of damaging alkali-silica reaction is then minimal if the calculated total alkali content of the concrete (including the calculated contribution from the RCA) does not exceed 2.5 kg/m³ Na₂O eq.

The proportions and limiting compositions of any ggbs, pfa or flyash, microsilica, metakaolin or lithium salts used should be according to BRE Digest 330: 1998.

**Alternative, Simpler Approach for Use of RCA in Standardized Prescribed Concrete**

In standardized prescribed concrete, the risk of a damaging alkali-silica reaction can be minimised by restricting the maximum values for the declared mean alkali content of the bagged cement to the values given in the Table B3 (derived from table 11 in BS 8500-2: 2002).

<table>
<thead>
<tr>
<th>Standardized prescribed concrete</th>
<th>Declared mean alkali content of bagged cement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Strength class of cement 42.5</td>
</tr>
<tr>
<td></td>
<td>500kg/m³ RCA*</td>
</tr>
<tr>
<td>ST1</td>
<td>0.84</td>
</tr>
<tr>
<td>ST2</td>
<td>0.75</td>
</tr>
<tr>
<td>ST3</td>
<td>0.75</td>
</tr>
<tr>
<td>ST4</td>
<td>0.73</td>
</tr>
<tr>
<td>ST5</td>
<td>0.67</td>
</tr>
</tbody>
</table>

* Assuming no highly or extremely reactive aggregates or aggregates recycled from concrete already damaged by ASR

**Exposure Class**

**Weathering and frost resistance**
RCA and RA can be used in exposure environments which are not liable to cause severe freezing and thawing damage or sulfate attack on the concrete i.e. those designated X0, XC1, XC2, XC3, XC4, XF1, XF2, DC-1, DC-2, XD1, XS1 in BS 8500: 2002.

BS8500-2 specifically permits the use of RCA in exposure classes X0, XC1, XC2, XC3, XC4, XF1, DC-1 but this may reasonably be extended as above if a quality control scheme based on BRE (2000) is used for RCA and RA.

RCA and RA aggregate may also be used in other exposure classes provided it has been demonstrated that the resulting concrete is suitable for the intended environment, e.g. freeze/thaw resisting, sulfate-resisting, etc.

The freezing and thawing resistance of concrete is only an issue if the concrete is used in severe freezing environments where the concrete may also be saturated with water. Moreover, the mix design of the concrete and whether or not it is air entrained will influence the durability of the concrete in such environments more than the choice of aggregate.

**Carbonation**

Adequate resistance for the intended service life of the structure will be provided by the limiting compositional requirements in BS 8500: 2002 for the exposure classes for concrete to resist corrosion induced by carbonation (XC classes).

**Quality Control**

A quality control scheme based on BRE (2000) recommended for RCA and RA, with the minimum frequencies of test given in Table B4:

<table>
<thead>
<tr>
<th>Property description</th>
<th>Test method</th>
<th>Minimum test frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aggregate composition</td>
<td>BS 8500-2: 2002 Annex B</td>
<td>1 per week</td>
</tr>
<tr>
<td>Bulk density</td>
<td>BS EN 1097-3: 1998</td>
<td>1 per week</td>
</tr>
<tr>
<td>Grading</td>
<td>BS EN 933-1: 1997</td>
<td>1 per week</td>
</tr>
<tr>
<td>Fines Content</td>
<td>BS EN 933-1: 1997</td>
<td>1 per week</td>
</tr>
<tr>
<td>Particle Shape</td>
<td>BS EN 933-3: 1997</td>
<td>2 per year</td>
</tr>
<tr>
<td>Sulfate content (acid soluble)</td>
<td>BS EN 1744-1: 1998</td>
<td>4 per year</td>
</tr>
<tr>
<td>Chloride content (acid soluble) (where required)</td>
<td>BS 1881-124: 1998</td>
<td>4 per year</td>
</tr>
<tr>
<td>Drying shrinkage (if required)</td>
<td>eg BRE Digest 357: 1991</td>
<td>2 per year</td>
</tr>
<tr>
<td>Strength development in concrete containing RCA/RA</td>
<td>BS EN 12390: 2000</td>
<td>1 per day of casting</td>
</tr>
</tbody>
</table>

**Unbound use**

Both RCA and RA are highly suitable for use under floor slabs and for pipe bedding as well, as for general fill materials in building construction. Contaminants such as metals, plastic and wood should normally be kept below 2% by weight (by volume for low density contaminants) and the grading should be suitable for full compaction where this is required.
The only other consideration when using them is that the fine fractions of both RCA and RA could be contaminated with sulfate salts (e.g. from gypsum plaster) to a degree sufficient to cause sulfate attack on concrete in contact with it. Therefore the soluble sulfate content of material, containing fine RCA or RA and intended for use as fill or hardcore in contact with concrete, should be tested using the 2:1 water extract method (see Appendix1; BRE Special Digest SD1) and appropriate precautions taken in the design of the concrete according to SD1.

References


BS 8500:2002 Concrete - Complementary British Standard to BS EN 206-1 (Incorporating Amendment No.1 of 20 October 2003):
Part 1: Method of specifying and guidance for the specifier
Part 2: Specification for constituent materials and concrete

BS EN 206 – 1: 2000 – Concrete. Specifications, performances, production and conformity.


BRE Special Digest SD1: 2001 – Concrete in aggressive ground. Replacement of Digest 363.


Appendix C - Guidance document for IBA

Specifications for RSA in building construction: Incinerator bottom ash from domestic refuse incinerators (IBA)

Incinerator bottom ash (IBA) is the solid ash residue left at the bottom of municipal waste incinerators. These specifications cover technical specification issues relating to the use of these materials as aggregates. Issues of leaching of contaminants into groundwater and/or contact with people will need to be addressed. Reports by the Environment Agency: 2002 and BREWEB: 2003 give further details.

IBA needs to be processed to remove both ferrous and non-ferrous metals before it is suitable for use as a construction material. All references below to IBA are for the processed material.

Use of IBA in Concrete and Concrete Products

IBA and composites of IBA and natural aggregates to be used in concrete should conform to the general requirements of BS EN 12620: 2002 and the guidance on the use of BS EN12620: 2002 in BS PD 6682-1: 2003. These and additional compositional and chemical requirements specific to IBA are include in Table C1.

Table C1: Recommended BS EN 12620: 2002 designations for IBA concreting aggregates for general uses

<table>
<thead>
<tr>
<th>Properties</th>
<th>Category to BS EN 12620: 2002 or other limit&lt;sup&gt;b&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grading</td>
<td></td>
</tr>
<tr>
<td>Coarse aggregate</td>
<td>See Annex C</td>
</tr>
<tr>
<td>Flakiness index</td>
<td>$F_{15}$</td>
</tr>
<tr>
<td>Shell content</td>
<td>≤ 10 % by mass</td>
</tr>
<tr>
<td>Fines</td>
<td>$f_f$</td>
</tr>
<tr>
<td>Resistance to fragmentation</td>
<td>$L_A_{40}$ or $L_A_{60}$ or no requirement.</td>
</tr>
<tr>
<td>Acid soluble sulfate content</td>
<td>$A_S_{1.0}$</td>
</tr>
<tr>
<td>Total sulfur</td>
<td>≤ 1 % by mass&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Constituents which alter the rate of setting and hardening of concrete</td>
<td></td>
</tr>
<tr>
<td>- increase in mortar setting time</td>
<td>≤ 120 minutes</td>
</tr>
<tr>
<td>- decrease in compressive strength of mortar</td>
<td>≤ 20% at 28days</td>
</tr>
<tr>
<td>Organic matter:</td>
<td>Free of organic matter</td>
</tr>
<tr>
<td>- Humus content</td>
<td></td>
</tr>
<tr>
<td>- Fulvo acid (when indicated humus content is high)</td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup>Material with a density less than 1,000 kg/m³.

<sup>b</sup>Property where currently no BS EN 12620: 2002 limit/test
Table C2: Additional recommended BS EN 12620: 2002 designations for IBA for particular end uses in concrete

<table>
<thead>
<tr>
<th>End use</th>
<th>Property</th>
<th>Category to BS EN 12620: 2002</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exposed aggregate wearing surfaces (not recommended for IBA)</td>
<td>Polishing resistance</td>
<td>$PSV_{xx}$ $^a$</td>
</tr>
<tr>
<td></td>
<td>Resistance to wear</td>
<td>$M_{DE}XX$ $^a$</td>
</tr>
<tr>
<td></td>
<td>Resistance to abrasion</td>
<td>$AAV_{xx}$ $^a$</td>
</tr>
<tr>
<td>Concrete subject to freeze-thaw environment:</td>
<td>Magnesium sulfate soundness</td>
<td>No requirement ($MS_{NR}$)</td>
</tr>
<tr>
<td>Frost free or continuously dry or moderate water saturation $^b$ (BS EN 206-1: 2000 exposure classes XF1 and XF2)</td>
<td></td>
<td>$MS_{2S}$</td>
</tr>
<tr>
<td>High water saturation $^b$ without deicing agent (BS EN 206-1: 2000 exposure classes XF3)</td>
<td></td>
<td>$MS_{1S}$</td>
</tr>
<tr>
<td>High water saturation $^b$ with deicing agent (BS EN 206-1: 2000 exposure class XF4)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Structural concrete</td>
<td>Drying shrinkage</td>
<td>$\leq 0.075$</td>
</tr>
<tr>
<td>Pavement wearing surfaces and heavy duty concrete floor finishes</td>
<td>Los Angeles co-efficient</td>
<td>$LA_{xx}$ $^a$</td>
</tr>
</tbody>
</table>

$^a$ Values for these properties, appropriate for the end use, should be inserted from available categories in BS EN 12620: 2002 according to need. Further guidance is available in the Highways Agency design manual for roads and bridges, Highways Agency: 2001.

$^b$ The degree of water saturation should be taken as reflecting the relative frequency of the likely occurrence of freezing whilst wet, i.e. moderate = occasional freezing when wet and high = frequent freezing when wet.

When determining that the maximum chloride content of concrete specified in BS EN 206-1: 2000, 5.27 has not been exceeded, the chloride content of the IBA and its variability shall be established and taken into account.

**Limitations on the use of IBA**

**Strength Class of concrete**

IBA should not be used in concrete with a strength class greater than C40/50.
Resistance to alkali-silica reactions

The risk of a damaging alkali-silica reaction in concrete containing IBA can be minimised by adopting the preventive measures detailed in the guidance in BRE Digest 330: 1998 depending on the aggregate reactivity classification.

These measures include:

- limiting the total alkali content of the concrete mix (including a contribution from the RCA or RA; see below);
- use of cement additions such as pfa, flyash, ggbs, microsilica or metakaolin;
- use of lithium salts.

Aggregate Classification and concrete mix limitations:

Because of the potential variability of its composition and the possibility, in particular of the inclusion of glass particles, should be classified as highly reactive (according to BRE Digest 330: 1998).

Additionally, the alkali contribution from the IBA should be included in the calculation of the total alkali content of the concrete as 0.40 kg Na₂O eq per 100 kg of IBA.

The risk of damaging alkali-silica reaction is then minimal if the calculated total alkali content of the concrete (including the calculated contribution from the IBA) does not exceed 2.5 kg/m³ Na₂O eq.

The proportions and limiting compositions of any ggbs, pfa or flyash, microsilica, metakaolin or lithium salts used should be according to BRE Digest 330: 1998.
Exposure Class

Weathering and frost resistance

IBA can be used in exposure environments which are not liable to cause severe freezing and thawing damage or sulfate attack on the concrete i.e. those designated X0, XC1, XC2, XC3, XC4, XF1, XF2, DC-1, DC-2 in BS 8500: 2002.

IBA may also be used in other exposure classes provided it has been demonstrated that the resulting concrete is suitable for the intended environment, eg freeze/thaw resisting, sulfate-resisting, etc.

The freezing and thawing resistance of concrete is only an issue if the concrete is used in severe freezing environments where the concrete may also be saturated with water. Moreover, the mix design of the concrete and whether or not it is air entrained will influence the durability of the concrete in such environments more than the choice of aggregate.

However, if the concrete containing IBA is to be used in a severe freeze/thaw environment where it will also be saturated with water (XF3 in BS 8500: 2002), or, especially if it is also subject to de-icing salts (XF4), the aggregate should comply with the Magnesium sulfate categories recommended in BS EN PD 6682-1: 2003.

Carbonation

Adequate resistance for the intended service life of the structure will be provided by the limiting compositional requirements in BS 8500: 2002 for the exposure classes for concrete to resist corrosion induced by carbonation (XC classes).

Quality Control

The quality control scheme for production of aggregates from IBA is under discussion, based on the quality control: 2000.

Unbound uses

IBA is technically suitable for most types of unbound use in building construction. The potential for leaching will need to be considered although the health risk is slight.

The principal technical consideration is that the IBA could contain soluble sulfate salts to a degree sufficient to cause sulfate attack on concrete in contact with it. Therefore the soluble sulfate content of IBA intended for use as fill or hardcore in contact with concrete, should be tested using the 2:1 water extract method (see Appendix1; BRE Special Digest SD1: 2001) and appropriate precautions taken in the design of the concrete according to BRE Special Digest SD1: 2001.

References


BS EN 206 – 1: 2000 – Concrete. Specifications, performances, production and conformity.

BS 8500: 2002 Concrete - Complementary British Standard to BS EN 206-1 (Incorporating Amendment No.1 of 20 October 2003):
  Part 1: Method of specifying and guidance for the specifier
  Part 2: Specification for constituent materials and concrete


BRE Special Digest SD1: 2001 – Concrete in aggressive ground. Replacement of Digest 363.


Appendix D - Guidance document for glass

Specifications for RSA in building construction: Recycled glass aggregate

Definition of recycled glass

Glass covers a range of materials, each with different properties and applications. The principal types are:

- Container glass for bottles and jars
- Flat glass for glazing (buildings and motor vehicles)
- Fibre glass for insulation and reinforcement.

To date, all aggregate applications have concentrated on container glass. Recycled glass has almost zero water absorption, it can lead to improved concrete flow properties, has a hardness superior to most natural aggregates and has aesthetic properties, making it appealing for use in decorative applications.

Use in concrete

At present, glass is not specifically mentioned in BS EN 12620: 2002. Glass aggregate and combinations of glass and natural aggregates to be used as a coarse or fine aggregate in concrete should conform to the general requirements of BS EN 12620: 2002 and the guidance on the use of BS EN 12620: 2002 in BS PD 6682-1: 2003.

These and additional compositional and chemical requirements specific to glass are included in Table D1:
### Table D1: Recommended BS EN 12620: 2002 designations for glass concreting aggregate for general uses

<table>
<thead>
<tr>
<th>Properties</th>
<th>Category to BS EN 12620: 2002 or other limit&lt;sup&gt;b&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Grading</strong></td>
<td></td>
</tr>
<tr>
<td>Coarse aggregate</td>
<td>See Annex C</td>
</tr>
<tr>
<td>Fine aggregate</td>
<td>See Annex C</td>
</tr>
<tr>
<td><strong>Flakiness index</strong>&lt;sup&gt;a&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Fines</td>
<td></td>
</tr>
<tr>
<td>Resistance to fragmentation</td>
<td></td>
</tr>
<tr>
<td>Acid soluble sulfate content</td>
<td></td>
</tr>
<tr>
<td>Total sulphur</td>
<td>≤ 1% by mass&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Total silica&lt;sup&gt;b&lt;/sup&gt;</td>
<td>&gt;68%</td>
</tr>
<tr>
<td>Total lead&lt;sup&gt;b&lt;/sup&gt;</td>
<td>≤ 0.10% by mass (no test is required for sources derived entirely from bottle glass or window glass)</td>
</tr>
<tr>
<td>Light weight material&lt;sup&gt;a&lt;/sup&gt;</td>
<td>≤ 0.5% by mass</td>
</tr>
<tr>
<td>Other foreign material eg plastics, metals&lt;sup&gt;b&lt;/sup&gt;</td>
<td>≤ 1.0% by mass</td>
</tr>
<tr>
<td>Constituents which alter the rate of setting and hardening of concrete</td>
<td></td>
</tr>
<tr>
<td>Increase in mortar setting time</td>
<td>≤ 120 minutes</td>
</tr>
<tr>
<td>Decrease in compressive strength of mortar</td>
<td>≤ 20% at 28days</td>
</tr>
<tr>
<td>Organic matter:</td>
<td></td>
</tr>
<tr>
<td>-Humus content</td>
<td></td>
</tr>
<tr>
<td>-Fulvo acid (when indicted humus content is high)</td>
<td>Free of organic matter</td>
</tr>
</tbody>
</table>

<sup>a</sup> Material with a density less than 1,000 kg/m³.

<sup>b</sup> Property where currently no BS EN 12620: 2002 limit/test

**Grading:** there should be no difficulty in matching many of the finer aggregate grades using glass particles.

**Flakiness:** Larger glass fractions are likely to be more flaky than smaller sizes. No published data has been found concerning the flakiness index of glass.
Table D2: Additional recommended BS EN 12620: 2002 designations for glass aggregate for particular end uses in concrete

<table>
<thead>
<tr>
<th>End use</th>
<th>Property</th>
<th>Category to BS EN 12620: 2002</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exposed aggregate wearing surfaces</td>
<td>Polishing resistance</td>
<td>( PSV_{xx} )^a</td>
</tr>
<tr>
<td></td>
<td>Resistance to wear</td>
<td>( M_{DDE} )^a</td>
</tr>
<tr>
<td></td>
<td>Resistance to abrasion</td>
<td>( AAV_{xx} )^a</td>
</tr>
<tr>
<td>Concrete subject to freeze-thaw environment:</td>
<td>Resistance to abrasion</td>
<td>( M_{DDE} )^a</td>
</tr>
<tr>
<td>Frost free or continuously dry or moderate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>water saturation (^b) (BS EN 206-1: 2000</td>
<td>Magnesium sulfate soundness</td>
<td>No requirement (( MS_{NR} ))</td>
</tr>
<tr>
<td>exposure classes XF1 and XF2)</td>
<td></td>
<td>( MS_{25} )</td>
</tr>
<tr>
<td>High water saturation (^b) without deicing</td>
<td></td>
<td>( MS_{18} )</td>
</tr>
<tr>
<td>agent (BS EN 206-1: 2000 exposure classes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>XF3)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>High water saturation (^b) with deicing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>agent (BS EN 206-1: 2000 exposure class</td>
<td></td>
<td></td>
</tr>
<tr>
<td>XF4)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Structural concrete</td>
<td>Drying shrinkage</td>
<td>( \leq 0.075 )</td>
</tr>
<tr>
<td>Pavement wearing surfaces and heavy duty</td>
<td>Los Angeles co-efficient</td>
<td>( LA_{xx} )^a</td>
</tr>
<tr>
<td>concrete floor finishes</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^a\) Values for these properties, appropriate for the end use, should be inserted from available categories in BS EN 12620: 2002 according to need. Further guidance is available in the Highways Agency design manual for roads and bridges, Highways Agency: 2000.

\(^b\) The degree of water saturation should be taken as reflecting the relative frequency of the likely occurrence of freezing whilst wet, i.e. moderate = occasional freezing when wet and high = frequent freezing when wet.

### Compositional and chemical requirements

Upon visual inspection, the source material shall contain any combination of clear, brown or green glass. Limits are defined in PAS 101: 2003. Limits will need to be defined for the following (which are not covered in BS EN 12620: 2002):

- Acceptable levels of contamination by sugars and organic matter that may influence setting
- Acceptable levels of contamination by aluminium or other non-ferrous metals which may lead to localised "pop-outs".

When determining that the maximum chloride content of concrete specified in BS EN 206-1: 2000, 5.27 has not been exceeded, the chloride content of glass aggregate and its variability shall be established and taken into account.

Although limits for sulphur and acid soluble sulfate are provided in Table D1, these substances are unlikely in glass sources unless contaminated by other wastes.

### Quality control

Quality control schemes, based on PAS 101: 2003 are recommended for sources of glass, with the minimum frequencies of test given in the table below.
Limitations on the use of glass aggregate

Strength class of concrete

Glass aggregate should not be used in concrete with a strength class greater than C40/50.

Resistance to alkali-silica reactions

Clearly the risk of a damaging alkali-silica reaction in concrete containing glass aggregate must be guarded against. This risk can be minimised by adopting the preventive measures detailed in the guidance in BRE Digest 330: 1998 depending on the aggregate reactivity classification.

These measures include:

- Using the concrete in situations where it will not be exposed to external moisture;
- Limiting the total alkali content of the concrete mix;
- Use of cement additions such as pfa, fly ash, ggbs, microsilica or metakaolin;
- Use of lithium salts.

Research has shown that the risk of ASR can be minimised through use of fine glass aggregate of diameter less than 1 mm.

Aggregate Classification and concrete mix limitations

Glass (along with other exceptionally reactive forms of silica) is presently outside the scope of Digest 330: 1998. However, preliminary laboratory work indicates that the reactivity and alkali threshold for recycled glass aggregates may not be very different to flint. The advice given here is therefore thought to be conservative and will be revised when more data is available.

It is recommended that recycled glass aggregate should be classified as highly reactive (according to BRE Digest 330: 1998). Additionally, if the concrete using the glass aggregate is to be exposed to an external source of moisture, the concrete should be made with a low alkali (less than 0.6 kg Na$_2$O equiv) CEM1 cement.

The risk of damaging alkali-silica reaction is then minimal if the calculated total alkali content of the concrete does not exceed 2.5 kg/m$^3$ Na$_2$O equiv.

The proportions and limiting compositions of any ggbs, pfa or fly ash, microsilica, metakaolin or lithium salts used should be in accordance with BRE Digest 330: 1998 for use with a high reactivity aggregate.

Exposure Class

Weathering and frost resistance

Adequate weathering and frost resistance for the intended service life of the structure will be provided by the limiting compositional requirements in BS 8500: 2002 for the exposure classes for concrete to resist freezing and thawing damage(XF classes).
Carbonation

Adequate resistance for the intended service life of the structure will be provided by the limiting compositional requirements in BS 8500: 2002 for the exposure classes for concrete to resist corrosion induced by carbonation (XC classes).

Unbound Use

Glass is technically suitable for unbound use in building construction however the most widespread use is a bedding sand for concrete block paving. Glass sand of the appropriate grading is technically equivalent to the natural sands specified in BS 7533-3: 1997 for all types of laying course.

Although crushed recycled glass is rounded and does not offer an injury threat to people if undisturbed, its brittleness means that it would need to be protected by an overlying layer.

Use in concrete products

Glass can be used in non-structural pre-cast products such as architectural cast stone to BS 1217: 1997, Kerbs (BS 7263: 1990), tiles (BS EN 490: 1994), blocks and bricks (BS 6073: 1981) and pavers (BS 7263: 1990), and according to draft ENs.

Quality Control

Publicly available specification PAS 101: 2003 gives guidance on good practice in the recovery and specification of quality for recovered container glass. Minimum frequencies of test (based on those for RA and RCA), are proposed below.

<table>
<thead>
<tr>
<th>Property description</th>
<th>Test method</th>
<th>Minimum test frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aggregate composition</td>
<td>BS 8500-2 Annex B: 2002</td>
<td>1 per week</td>
</tr>
<tr>
<td>Bulk density</td>
<td>BS EN 1097-3: 1998</td>
<td>1 per week</td>
</tr>
<tr>
<td>Grading</td>
<td>BS EN 933-1: 1997</td>
<td>1 per week</td>
</tr>
<tr>
<td>Fines Content</td>
<td>BS EN 933-1: 1997</td>
<td>1 per week</td>
</tr>
<tr>
<td>Particle Shape</td>
<td>BS EN 933-3: 1997</td>
<td>2 per year</td>
</tr>
<tr>
<td>Sulfate content (acid soluble)</td>
<td>BS EN 1744-1: 1998</td>
<td>4 per year</td>
</tr>
<tr>
<td>Chloride content (acid soluble) (where required)</td>
<td>BS 1881-124: 1998</td>
<td>4 per year</td>
</tr>
<tr>
<td>Drying shrinkage (if required)</td>
<td>eg BRE Digest 357: 1991</td>
<td>1 per year</td>
</tr>
<tr>
<td>Strength development in concrete containing glass</td>
<td>BS EN 12390: 2000</td>
<td>1 per day of casting</td>
</tr>
</tbody>
</table>
References


BS EN 206 – 1: 2000 – Concrete. Specifications, performances, production and conformity.


BS 8500: 2002 – Concrete - Complementary British Standard to BS EN 206-1 (Incorporating Amendment No.1 of 20 October 2003):
  Part 1: Method of specifying and guidance for the specifier
  Part 2: Specification for constituent materials and concrete

BS 7533 – 3: 1997 - Pavements constructed with clay, natural stone or concrete pavers. Code of practice for laying precast concrete paving blocks and clay pavers for flexible pavements


BS 7263: 1990 – Precast concrete flags, kerbs, channels, edgings and quadrants.
  Part 1: specifications.

BS EN 490: 1994 – Concrete roofing tiles and fittings - Product specifications.

BS EN 6073: 1981 – Precast concrete masonry units.
  Part 2: Method for specifying precast concrete masonry units.

BS 7263: 1990 – Precast concrete flags, kerbs, channels, edgings and quadrants.
  Part 1: specifications.
  Part 2: Code of practice for laying


Appendix E - Hydraulically bound mixtures for road pavements

New opportunities for resource conservation and the use of recycled and secondary aggregates

1 By definition, cement bound materials (CBM) are hydraulically bound mixtures (HBM). In other words, they set and harden in the presence of water. It is well known that CBM set and harden relatively quickly in the presence of water. However there are other HBM which are slow setting and slow hardening; these are based on the hydraulic combinations of lime/PFA and lime/blast-furnace slag and do not contain any cement. Although used widely in France, Holland and Germany, they have also been used in the UK but to a lesser extent. However they will be included in the Highways Agency’s Specification for Highway Works (SHW) when the European standards for such mixtures become available. As will be seen later in this guidance document, such HBM provide an opportunity for recycled and secondary aggregates (RSA). Indeed already in actual jobs in the UK, slow setting and hardening HBM have utilized air-cooled slag, asphalt planings and incinerator bottom ash (IBA) as aggregate. As well as illustrating the potential for the use of RSA, the purpose of this document is to also provide a history of slow setting and hardening HBM in the UK (Annex A) and a general understanding of their behaviour including illustrative data and advice on their properties for pavement design and utilization purposes. The data is drawn from existing UK data including:
- TRL report 408 (1999),
- the Leeds (1999) and Nottingham (2002) University symposia papers on bituminous and hydraulic materials in pavements,
- UKQA data sheets (www.ukqa.org) on fly ash bound mixtures,
- Euromin data sheet on Flushing slag bound mixture,

2 Slow setting slow hardening HBM are specified in the following draft European standards:
- prEN14227-2, Hydraulically bound mixtures – Specifications – Part 2: Slag bound mixtures
- prEN14227-5, Hydraulically bound mixtures – Specifications – Part 5: Hydraulic road binder bound mixtures
- prEN14227-12, Hydraulically bound mixtures – Specifications – Part 12: Soil treated by slag
- prEN14227-13, Hydraulically bound mixtures – Specifications – Part 13: Soil treated by fly ash
- prEN14227-14, Hydraulically bound mixtures – Specifications – Part 14: Soil treated by hydraulic road binder

3 For purposes of brevity and understanding, the following terms are used in this document:
- EN European standard
- HBM hydraulically bound mixture
- SBM slag bound mixture
- FABM fly ash bound mixture
- HRBBM ‘hydraulic road binder’ bound mixture
- SS soil treated by slag
- SFA soil treated by fly ash
- SHRB soil treated by hydraulic road binder
- SL soil treated by lime
- FA fly ash (PFA)
- GBS granulated blast furnace slag
- PGBS partially ground granulated blast furnace slag
Table 1 describes the HBM types included in the ENs listed in 2.

It should be noted that the ENs for HBM do not cover production and construction requirements; these aspects will be covered in the SHW together with compliance requirements. In addition, it is possible, by selecting from a range of strength categories in the ENs, to specify the strength required for the selected mixture for the application/thickness concerned, rather like CBM 3, 4 and 5 (4 & 5 being higher strength CBM3) at the present time. For pavement design purposes, illustrative data for the HBM types listed in Table E1 are provided in Table E2.

Table E1: Brief description of HBM (other than CBM)

<table>
<thead>
<tr>
<th>HBM type</th>
<th>General description of HBM</th>
<th>Sub-types</th>
<th>Particular requirements</th>
<th>Strength classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>FABM1, HRBBM1, SBM 'B1'</td>
<td>Graded coarse and fine aggregate mixture</td>
<td>-</td>
<td>Aggregate properties selected from BSEN13242*</td>
<td>R_c or R_t,E</td>
</tr>
<tr>
<td>FABM2, HRBBM2, SBM'B2'</td>
<td>Graded coarse and fine aggregate mixture with compacity (term relating to void content – refer to EN) requirement</td>
<td>0/20mm</td>
<td>Ditto</td>
<td>R_c or R_t,E</td>
</tr>
<tr>
<td>FABM3, HRBBM3, SBM 'B3'</td>
<td>Fine aggregate (sand) mixture</td>
<td>-</td>
<td>Aggregate properties selected from BSEN13242*</td>
<td>R_c or R_t,E</td>
</tr>
<tr>
<td>FABM4, HRBBM4, SBM'B4'</td>
<td>Producer declared mixture</td>
<td>-</td>
<td>Producer declared grading &amp; other relevant properties</td>
<td>R_c or R_t,E</td>
</tr>
<tr>
<td>FABM5</td>
<td>Treated fly ash</td>
<td>-</td>
<td>See prEN 14227-3</td>
<td>R_c or R_t,E</td>
</tr>
<tr>
<td>SBM 'A'</td>
<td>Graded slag aggregate mixtures without specified requirements for GBS when used</td>
<td>1 - 4</td>
<td>Aggregate properties selected from prEN13242</td>
<td>Generally CBR but R_c or R_t,E can also be used</td>
</tr>
<tr>
<td>SFA, SS, SHRB</td>
<td>Treated soil</td>
<td>-</td>
<td>See prENs 14227- 12, 13 &amp; 14</td>
<td>CBR, R_c or R_t,E</td>
</tr>
<tr>
<td>SL</td>
<td>Treated soil</td>
<td>-</td>
<td>Stabilization</td>
<td>See prEN14227-11</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Improvement</td>
<td>Ditto</td>
</tr>
</tbody>
</table>

* EN for ‘aggregates for unbound and hydraulically bound mixtures
### Table E2: HBM properties for pavement design

<table>
<thead>
<tr>
<th>HBM type (ref Table E1)</th>
<th>Closest UK equivalent in terms of specified aggregate/soil &amp; performance</th>
<th>Recommended minimum strength categories for equivalence (MPa)</th>
<th>Static/ NAT material stiffness (MPa)</th>
<th>For analytical design purposes, suggested design stiffness from LR408 (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CBM5 CBM4 CBM3</td>
<td>T3 or C9/12</td>
<td>15000+</td>
<td>3000</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 &amp; B2</td>
<td>Staffs CC spec for GFA and Kent CC spec for HBM</td>
<td>T3 or C9/12</td>
<td>15000+</td>
<td>3000</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3, B3, B1 &amp; A</td>
<td>CBM2</td>
<td>T2 or C6/8</td>
<td>10000+</td>
<td>2000</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4, B4, 5,</td>
<td>CBM1</td>
<td>T1 or C3/4</td>
<td>2500 to 10000+ (aggregate dependent)</td>
<td>500 to 2000 (aggregate dependent)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SFA, SS, SHRB, SL</td>
<td>CBM1 (SL excepted)</td>
<td>T1 or C3/4</td>
<td>2500 to 10000+ (aggregate dependent)</td>
<td>500 to 2000 (aggregate dependent)</td>
</tr>
<tr>
<td></td>
<td>CLS-L &amp; CLS-H (LR248)</td>
<td>T0 or C0.4/0.5 or CBR 40</td>
<td>500+</td>
<td>200</td>
</tr>
<tr>
<td></td>
<td>Standard UK stabilized capping</td>
<td>7 day soaked CBR 15%</td>
<td>N/A</td>
<td>50</td>
</tr>
</tbody>
</table>

For comparison with Table E2, mechanical properties for HBM from UK experience are given in Table E3, including the aggregate type. *It is noteworthy that of the 10 illustrated, 7 used SRA!*
### Table E3: Actual laboratory mechanical properties for HBM

<table>
<thead>
<tr>
<th>Mixture reference</th>
<th>Composition</th>
<th>Mechanical Properties</th>
<th>Age in days</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>7</td>
</tr>
<tr>
<td>FABM 5 LR408</td>
<td>4% lime, 5% gypsum, 91% PFA 'agg'</td>
<td>Rc MPa</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rit MPa</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Et GPa</td>
<td>-</td>
</tr>
<tr>
<td>FABM 1 LR408</td>
<td>1.5% lime + 0.5% gypsum, 6% PFA, 93% Type 1 granite</td>
<td>Rc MPa</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rit MPa</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Et GPa</td>
<td>-</td>
</tr>
<tr>
<td>FABM 3 LR408</td>
<td>4% lime + 0.5% Na₂CO₃, 15.5% PFA, 80% china clay sand</td>
<td>Rc MPa</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rit MPa</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Et GPa</td>
<td>-</td>
</tr>
<tr>
<td>SBM 'B4' TRL PR/CE/145/99</td>
<td>1% lime, 20% GBS, 79% ABS</td>
<td>Rc MPa</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rit MPa</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Et GPa</td>
<td>-</td>
</tr>
<tr>
<td>SBM 'A' LR408</td>
<td>10% ASS, 20% GBS, 70% ABS</td>
<td>Rc MPa</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rit MPa</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Et GPa</td>
<td>-</td>
</tr>
<tr>
<td>SS A130</td>
<td>2% lime, 4% GGBS, 94% London clay</td>
<td>Rc MPa</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rit MPa</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Et GPa</td>
<td>-</td>
</tr>
<tr>
<td>FABM 3 Lab trial for Medway</td>
<td>2% lime, 14% PFA, 84% demolition sand</td>
<td>Rc MPa</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rit MPa</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Et GPa</td>
<td>-</td>
</tr>
<tr>
<td>FABM 2 AS2 Reconstruction Staffs CC</td>
<td>3% lime, 12% PFA, 85% planings</td>
<td>Rc MPa</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rit MPa</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Et GPa</td>
<td>-</td>
</tr>
<tr>
<td>FABM 2 Lab trial for Averham Bypass, Notts CC</td>
<td>2% lime, 13% PFA, 85% sand &amp; gravel</td>
<td>Rc MPa</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rit MPa</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Et GPa</td>
<td>-</td>
</tr>
<tr>
<td>FABM 2 Lab trial for EMA2000</td>
<td>2% lime, 13% PFA, 85% limestone</td>
<td>Rc MPa</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rit MPa</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Et GPa</td>
<td>-</td>
</tr>
</tbody>
</table>

**NOTE:** Rc denotes compressive strength, Rit indirect tensile strength (all NAT), Et elastic stiffness (all NAT except for Medway which is static compression). ASS denotes air-cooled steel slag, GBS denotes granulated blast furnace slag, ABS denotes air-cooled blast furnace slag.

**Observations on Tables E2 and E3:**

- All results apply to standard curing at 20°C
- Some LR408 mixtures included ‘enhancers’. These are not accelerators in the normal sense. Gypsum for example produces sulfatic strength development.
- Like CBM, mechanical properties are clearly a function of aggregate type and quality with stiffnesses of 1 GPa for treated soils, ~10 for treated sands and treated PFA, and an average of 20 for treated graded aggregate.

**When considering the use and application of HBM, the following should be noted and/or considered:**

- until greater UK experience is gained, it is recommended that HBM not containing cement shall be restricted in use to construction only during the period April to October. In addition, outside of this period, HBM layers shall be protected and insulated by the overlying layers;
- with the exception of treated soils, aggregate requirements including strength and fines content and quality will need to be considered. Ideally the aggregate needs to be hard, low in fines and non-plastic;
- concerning the types of lime in prEN 14227-11, it is imperative that full slaking of quick lime occurs prior to final compaction. If in doubt, it is suggested for mix-in-place treatment involving one mixing stage, that class 1 quick lime be used; with mix-in-place treatment involving 2-stage mixing with the quick lime added at the first stage only, either class 1 or 2 quick lime should be
satisfactory; and with aggregates treated in a central plant, the use of either class 1 quick lime or hydrated lime is suggested;

- in the case of SBM type B, the GBS properties shall be class 2 or better and PGBS shall be class C or D in accordance with EN14227-2;
- for design purposes, the 360 day mechanical properties using 20°C sealed curing should be used (note for compliance testing, earlier ages are used, refer to 10 below). Regarding specimen manufacture; typically refusal cylindrical specimens shall be used for mixtures using binders without cement, and refusal cylindrical or cube specimens for mixtures containing cement;
- any other requirements as specified in the EN for the HBM concerned e.g. immediate bearing index (to allow immediate trafficking, para 12); volume stability (para 13) and degree of pulverization (refer to EN) in the case of treated soils; and resistance to frost requirements (para 14);
- the permitted method of production; ‘mix-in-plant’ is recommended for HBM 1, 2, 3, 4 & 5. ‘Mix-in-place’ production can be used however for HBM 3, 4 & 5 and for soil treatment but it is suggested that layers shall be 50mm thicker than ‘mix-in-plant’ methods.

In line with the mixture design principles in LR408, it is suggested that the composition of unproven HBM should be based on mixture design testing carried out using 3 binder contents at 2 water contents usually OMC and 1,2xOMC. In the case of proven HBM, the composition can be based on past test results.

Until a history of use is established, the producer/supplier should provide evidence of mechanical performance development over either 1 year using 20 degrees C curing or, as a minimum, over 28 days using 40 degrees C curing for HBM without cement (c.f. over 28 days using 20 degrees C for HBM with cement). A schedule of testing similar to that shown in Table E4 is recommended for each combination of binder and water content. On the basis of this information, the contractor will then be able to declare the specimen manufacture and curing conditions and the age of testing for site control purposes, normally either 7, 14 or 28 days.

Not withstanding the results from 10, it is suggested at present that the minimum percentage proportions of constituents of HBM for use in base and sub-base should be in accord with Table E5. Note that the Table does not apply to HBM in capping.

Table E4: Suggested schedule of testing for laboratory mechanical performance of one combination of binder and water content

<table>
<thead>
<tr>
<th>Curing temperature</th>
<th>Age of test of sealed specimen (X denotes one result)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>7 days</td>
</tr>
<tr>
<td>40 degrees C</td>
<td>XXX</td>
</tr>
<tr>
<td>20 degrees C</td>
<td>-</td>
</tr>
</tbody>
</table>

NOTE: For guidance purposes for mixtures using binders without cement, refusal cylindrical specimens cured at 40°C and tested at 28 days have been found to be equivalent to about 80% of the 360 day strength/stiffness using 20°C curing. [For comparison purposes, for mixtures using binders containing cement, refusal cylindrical or cube specimens cured at 20°C and tested at 28 days have also been found to be equivalent to about 80% of the 360 day value at 20°C curing; and tentatively, for mixtures containing cement but in combination with reasonable amounts of PFA or GGBS, the 28 day strength at 20°C curing, could be equivalent to just 50% of the 360 day at 20°C curing.]
Table E5: Minimum proportions* of binder by total dry weight of HBM for use in base or sub-base (N.B. proportions for capping will be less).

<table>
<thead>
<tr>
<th>Binder</th>
<th>HBM types</th>
<th>A</th>
<th>1, B1, 2, B2</th>
<th>3, B3, 4, B4</th>
<th>5</th>
<th>SFA, SHRB, SS, SL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lime alone</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>4%</td>
<td>6%</td>
<td></td>
</tr>
<tr>
<td>HRB alone</td>
<td>3%</td>
<td>4%</td>
<td>5%</td>
<td>6%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GBS + lime***</td>
<td>8%</td>
<td>10%</td>
<td>N/A</td>
<td>6%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GBS + FA + lime**</td>
<td>9%</td>
<td>10%</td>
<td>N/A</td>
<td>N/A</td>
<td>6%</td>
<td></td>
</tr>
<tr>
<td>FA + lime***</td>
<td>10%</td>
<td>10%</td>
<td>N/A</td>
<td>6%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

NOTES:
*Minimum percentages apply to ‘mix-in-plant using weigh batching’. Indicated percentages should be increased by 1% for ‘mix-in-plant using volume batching’ and 2% for ‘mix-in-place’ production.

** minimum of 1% lime (or other activator) in HBM mixture but more recommended for volume batching (say 1.5%) and mix-in-place (say 2%).

*** minimum of 1.5% lime in HBM mixture but more recommended for volume batching (say 2%) and mix-in-place (say 2.5%).

Since setting and hardening is protracted, opening of HBM to traffic, site or otherwise, cannot be a function of setting and hardening as is the case for CBM in the UK but instead is a function of the immediate bearing capacity of the HBM. For immediate trafficking purposes, the immediate stability of the proposed HBM as measured by the IBI test in accordance with EN 13286-47 should follow the minimum recommendations in Table E6 subject to site verification. This data is based on French experience and if respected, the traffic should have no effect on the development of long term mechanical properties and performance of the HBM.

Table E6: Minimum immediate stability requirements for HBM (subject to site verification)

<table>
<thead>
<tr>
<th>HBM types A, 1, B1, 2, B2, 3, B3, 4, B4</th>
<th>FABM 5</th>
<th>SFA, SHRB, SS, SL</th>
</tr>
</thead>
<tbody>
<tr>
<td>IBI &gt; 40 (generally IBI test not required if crushed material constitutes 50% or more of the mixture)</td>
<td>CFA shall not be trafficked for 7 days. LFA shall never be directly trafficked and overlain by the next layer within 24 hours or 4 hours if gypsum is part of the mixture.</td>
<td>IBI depends on material being treated. Refer to relevant EN</td>
</tr>
</tbody>
</table>

For many years in the UK, strength testing after ‘immersion-in-water’ has been used as a measure of the volume stability of CBM should the aggregate or soil contain sulfates or be water susceptible or contain other deleterious material. In the case of SFA, SHRB and SS for sub-base or base use, it is suggested until greater experience is gained that this ‘resistance to water’ assessment be carried out after 7 days immersion following 21 days sealed curing, both periods using 40°C. The strength/stiffness of specimens subject to this curing should be compared to the strength/stiffness of specimens subject to sealed curing only at 40°C and should be greater than say 60% for use in sub-base and 80% for use in base.

In the case of frost resistance and thus use within the upper 350mm (or 450mm if the frost index is greater than 50) of a pavement, HBM complying with performance category C3/4 or greater or containing at least 8% binder addition (10% in the case of FA+lime) can be considered satisfactory as far as the UK frost heave test is concerned.
# ANNEX A: Summary of UK use of slow setting/slow hardening HBM based on slag and PFA

<table>
<thead>
<tr>
<th>Year</th>
<th>Material</th>
<th>Job &amp; traffic details</th>
<th>Construction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1987</td>
<td>FSBM (Flushing slag bound mixture - 85% phosphoric slag aggregate and 15% granulated blast furnace slag + sea water as activator)</td>
<td>Pembury by-pass, Kent - 500mm trial section - 13 million standard axles</td>
<td>320mm FSBM as sub-base &amp; base under 130mm surfacing</td>
</tr>
<tr>
<td>1997</td>
<td>FSBM (as above but activator changed to 3% 6mm-down steel slag)</td>
<td>Hale Street by-pass, Kent - 25 msa</td>
<td>350mm FSBM as sub-base &amp; base under 120mm surfacing</td>
</tr>
<tr>
<td>1997</td>
<td>Lime/GGBS treated boulder clay</td>
<td>A421 Tingewick bypass, Buckinghamshire - temporary diversion in service for 15 months</td>
<td>350mm layer as base and sub-base to 130mm bituminous surfacing</td>
</tr>
<tr>
<td>1997</td>
<td>GFA (Granular material treated by PFA and lime) using planings as aggregate</td>
<td>A52 reconstruction, Staffordshire - 8 msa</td>
<td>300mm GFA as sub-base &amp; base under 100mm surfacing</td>
</tr>
<tr>
<td>1998</td>
<td>FSBM (As for Hale St)</td>
<td>Wainscott Bypass, Kent - 45 msa</td>
<td>290mm FSBM as sub-base &amp; base under 180mm surfacing</td>
</tr>
<tr>
<td>1999 / 2000</td>
<td>GFA using granite aggregate*</td>
<td>Ramsgate Harbour Relief Road, Kent - 20 msa</td>
<td>320mm GFA as sub-base &amp; base under 130mm surfacing</td>
</tr>
<tr>
<td>2000</td>
<td>Lime/GGBS treated London clay</td>
<td>A130 Bypass (A12 – A127) DBFO project, Essex - 80 msa +</td>
<td>300mm enhanced capping</td>
</tr>
<tr>
<td>2000 / 2001</td>
<td>GFA using incinerator bottom ash (IBA) as aggregate</td>
<td>Burntwood Bypass, Staffordshire - 30 msa</td>
<td>350mm GFA as sub-base and base under 130mm surfacing</td>
</tr>
<tr>
<td>2002</td>
<td>Lime/GGBS treated boulder clay</td>
<td>A6 Clapham Bypass, Bedfordshire - 70 msa</td>
<td>250mm standard capping</td>
</tr>
<tr>
<td>2002</td>
<td>GFA using planings as aggregate</td>
<td>Lichfield Bypass, Staffordshire - 20 msa</td>
<td>330mm GFA as sub-base and base under 100mm surfacing</td>
</tr>
</tbody>
</table>

* only job that utilized primary aggregate.
Appendix F - Hydraulically bound mixtures for marine and fluvial construction works

An opportunity for increasing the use of recycled and secondary aggregate

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Preface/ Foreword

The technique and methods of stabilizing soil and aggregate including recycled and secondary aggregate for use in road construction can also be employed in marine and fluvial construction works. Thus the well known and well proven families of mixtures known as cement-bound materials (CBM) including soil cement (SC) and roller compacted concrete (RCC), and hydraulically bound mixtures (HBM) based on the use of lime, fly ash and hydraulic slag, have a role, albeit little known in the UK, to play in these non-road applications. They also have the advantage that they are not as ‘hard’ as concrete, and present a ‘softer’ aspect that blends into the environment (Figure 1).

Experience in this field of use is extensive in the United States and in some of our European neighbours such as Holland. This information note has been compiled with the purpose of providing a summary of this experience and describes a basis for the application of the technique in the UK. The note draws considerably on the bank of worldwide experience and data on cement stabilization both in road and non-road construction. The note however should be regarded as ‘provisional’ until and when greater experience is gained in the UK.

The note is inspired by and uses information and data from the many fine papers on the subject, especially those from the ACI (American Concrete Institute) and the PCA (Portland Cement Association). All of the figures that are included in the note are copies of PCA slides. This is gratefully acknowledged. Overall recognition is owed to the following:


1 GENERAL

1.1. Definitions/ descriptions

1.1.1. Cement-bound material/mixture (CBM)
A mixture of soil or aggregate and Portland cement with a water content compatible with compaction by rolling. After compaction and cement hydration, the mixture hardens to produce a hard, durable, impermeable and erosion resistant construction material.

1.1.2 Soil cement (SC)
Historically this was the first CBM. As well as the normal meaning of the word, soil can mean raw material close to or indigenous to the project and can include natural granular materials and secondary and recycled aggregates (SRA).

1.1.3 Roller-compacted concrete (RCC)
A relatively high strength version of CBM usually made from aggregate of near-concrete-aggregate quality, including SRA.
1.1.4 Hydraulically-bound material/mixture (HBM)
Includes CBM and thus SC and RCC, but also describes similar but slower setting and hardening products based on the cementitious properties of the combination of lime with pulverized fuel ash* (PFA) or other pozzolanic materials or with latent hydraulic materials like granulated blast furnace slag (GBS)**.

* PFA is the UK term for fly ash (the name used around the world to describe the material) that is captured in the precipitators of coal-fired power stations. PFA is a pozzalan which thus, in combination with a source of Ca(OH)2, behaves like cement, albeit more slow setting and hardening. In the UK, PFA is used widely in concrete.

** In the UK, the ground version of GBS, GGBS, is used widely in concrete.

1.1.5 Mix-in-plant method of construction
Method used for the manufacture of CBM, SC, RCC and HBM where the mixture is produced in a fixed or mobile central-mixing plant such as a continuous pug-mill type mixer or a pan-type concrete mixture.

1.1.6 Mix-in-place method of construction
Method used for the manufacture of CBM, SC, RCC and HBM in-place that employs cement-spreaders and pulverizing/mixing rotovators; also known as the ‘soil-cement’ process. The method can be employed in ‘mix-in-plant’ mode whereby the resulting mixture is ‘picked-up’ after mixing and taken to the place of use where it is compacted.

1.1.7 Optimum moisture content (OMC)
For a given degree of compaction, the moisture or water content above or below which reduced dry densities are obtained. In the context of this document, the OMC relates to the value determined using vibrating hammer compaction and the degree of compaction to that relative to refusal compaction by vibrating hammer.

1.2. Scope
This note covers the application of HBM in marine and fluvial construction work based primarily on the widespread experience of the faster setting CBM variety. There is less experience of the slower setting and hardening HBM, although many if not all of the principles described also relate to these other HBM. The note includes:
• The application of HBM in marine and fluvial engineering
• Requirements for constituents and HBM
• Mixture design
• Construction and field requirements
• Control and testing of construction.

Where applicable, the note makes reference to existing UK documentation for HBM in road construction and where possible refers to the relevant European standards. These references are listed in 1.4.

1.3. History
The use of HBM for marine and fluvial construction works developed in the US. This experience commenced in the early 1950s when during the construction of several major earth dams in the central plains area of the US, the Bureau of Reclamation (the Bureau) became concerned with the high cost of providing quality rock rip-rap for upstream slope protection of these dams. The Bureau therefore initiated research to study the suitability of soil cement for this purpose.

Based on laboratory studies that indicated soil cement made from sandy soils could produce a durable, erosion-resistant facing, the Bureau constructed a full-scale field trial section in 1951 on the south shore of Bonny reservoir in eastern Colorado. The particular location was selected so that the trial would be subject to severe conditions of waves, ice and an average of 140 freeze-thaw cycles per year. The trials consisted of stair-stepped horizontal layers of compacted soil cement facing. Each layer was 2.13m wide and 150mm thick after compaction and was constructed using the mix-in-place method of construction. This produced a minimum thickness of soil cement normal to the slope of 0.82m for the 105m long trial sections. (Figure 2)
Two types of local sandy soils were used. A fine silty sand which required 12% cement by volume and a silty, fine to medium, sand which required 10% cement. The average 28 day strengths were 7.9 and 6.1 MPa respectively. After 10 years, cores revealed that the strengths had doubled.

Although the construction plant would be considered quite crude by today's standards, the test section performed much better than anticipated with only minor erosion limited to the poorly compacted feathered edges of the layers and the lower layers where the mixing process produced less than the specified cement contents. After 10 years of observing the trial, the Bureau was convinced of its suitability and specified soil cement as an alternative to rock rip-rap for slope protection of the Merritt Dam (Nebraska) and the Cheney Dam (Kansas) in 1961. Soil cement was bid at 50% of the cost of rip-rap and saved $1 million for the 2 projects. In 1963, the Ute Dam (New Mexico) became the first major earth dam with soil cement upstream protection.

Since this early experience as rip-rap alternatives and upstream facings of dams, soil cement in the US has provided and continues to provide:
- slope protection for channels, spillways, coastal shorelines, and inland reservoirs
- and low permeability liners for water-storage reservoirs, waste-water treatment lagoons, sludge-drying beds, ash-settling ponds and solid-waste landfills including certain hazardous wastes.

Depending on conditions, including climate, water velocity and hard-object content in storm-water flow, US specifications include more stringent requirements for the soil/aggregate and strength. Where permeability is an important issue, careful material selection and mixture design is paramount. In such cases, fly ash (PFA) or other 'fine' material is sometimes a necessary constituent.

Application and experience is not limited to the US. The technique of HBM for marine and fluvial construction works, has spread to the rest of the world including all the major land masses of North America, Europe, South America, Australasia, Asia and Africa.

1.4. Standards/references

BSEN 197-1, Cement – Part 1: Composition, specifications and conformity criteria

DD ENV 13282:2000, Hydraulic road binders – Composition, specifications and conformity criteria

prEN 14227-11, Hydraulically bound mixtures – Specifications – part 11: Lime treated mixtures

prEN 14227-4, Hydraulically bound mixtures – Specifications – part 4: Fly ash for hydraulically bound mixtures

prEN 14227-2, Hydraulically bound mixtures – Specifications – part 2: Slag bound mixtures

prEN 14227-3, Hydraulically bound mixtures – Specifications – part 3: Fly ash bound mixtures


2 APPLICATIONS

This section illustrates the range of applications and principles for HBM in marine and fluvial engineering.
2.1 Shore and slope protection

As illustrated in the ‘history’ section above, HBM can be used for the protection of coasts and other slopes exposed to normal, even severe, wave action.

As explained, the HBM is placed in successive horizontal layers adjacent to the slope or core to form an outer protection ‘skin’. Measured perpendicular to the slope, the resulting ‘skin’ is typically 0.6 to 0.7 m thick or greater, and is formed using layers at least 2.5 m wide by 150 to 225mm thick. The 2.5m width of layer is normally used to facilitate the dump trucks that haul the HBM to the spreading operation.

Depending on mixing and compaction capabilities, the thickness of the layer can be 300mm. Thicker lifts will result in fewer horizontal joints and greater section modulus to resist breaking. The overall process is referred to as ‘stair-step slope protection’ (Figure 3).

This ‘stair-step’ protection can also be used for the protection of slopes of channels and river and stream banks exposed to lateral flows including debris-carrying rapid-flowing water.

Depending on the severity of the waves or flow and to prevent scour and undermining of the HBM, it may be necessary to place the first layer at least 1.5 m to 2.5m below minimum water level and to horizontally extend the first 1 or 2 layers further into the slope. The final layer can be continued over the top of the embankment for use as a road or pavement base layer.

The ‘stair-step’ process is used for slopes typically ranging from 1V:2H to 1V:3H.

For small reservoirs, ditches and lagoons where wave action and or rate of flow can be classified as mild, protection may consist of a layer of HBM placed parallel to the slope face. This method has been referred to as ‘plating’ where the compacted ‘plate’ is 150 to 225mm thick (Figure 4). Typically for placement purposes, the slope is 1V:3H or flatter although 1V:2H is possible. The ‘plate’ is normally formed in 1 lift.

Where a layer thicker than 225mm is deemed necessary, this can be constructed in 2 lifts but the minimum thickness of lift should be 150mm.

2.2 Liners

HBM has also experienced many decades of successful use as bottom liners for canals, water storage reservoirs, wastewater-treatment lagoons, sludge-drying beds, ash-settling ponds, and solid waste landfills. Typically linings range from 150mm to 300mm thick.

Water-tightness of HBM improves with age as hydration of the binder continues over time but if necessary, immediate water-tightness of the HBM can be improved by the addition of silt-size fines such as fly ash (PFA) to the aggregate such that it is possible to achieve permeabilities significantly less than $1 \times 10^{-9}$ m/sec. Provided acceptable strengths are reached then the lining will withstand damage by the anchors of vessels and operational and maintenance equipment and will remain functional.

HBM liners should be resistant to wastes including toxic pesticides, oil refinery sludges, pharmaceutical, rubber and plastic wastes. However certain wastes will be deleterious to HBM liners including acid wastes. It is imperative that various types of HBM should be tested for compatibility with the specific waste concerned prior to final design decision.

With reference to cracking, HBM will crack in time due to shrinkage and maybe foundation settlement. Cracks caused by foundation settlement can be minimized by proper preparation of the foundation. Shrinkage cracks can be minimized by proper curing.

Compared to cement alone, cracking is less pronounced with combinations of cement and pozzolan and even more so with lime/pozzolan combinations. The use of pozzolans has
the advantage of autogeneous or self-healing because of the cementitious reserve available from the longer reaction time between either lime or lime released during cement hydration and the pozzolan. This reaction can continue for many years after construction.

In the case of liquid reservoirs, filling immediately after final compaction can greatly reduce the likelihood of shrinkage cracking.

Field studies following the draining of reservoirs, have shown that cracks seal themselves with silt, clay and other sediments.

Where maximum seepage protection is required, say for impoundment reservoirs, composite liners of HBM and synthetic membranes can be used. For example, an HDPE membrane between 2 N^150mm layers of HBM has proved constructable and successful in use (Picture 5). The composite liner offers the following benefits;

- Provided the HBM is compatible with the liquid to be stored, the membrane will not suffer degradation
- The combination is strong and durable with the bottom layer of HBM providing a firm smooth surface and foundation for the membrane. The top layer of HBM protects the membrane from damage due to operational equipment, burrowing animals, vandalism and weather.

2.3 **Containment embankment structures**

Instead of just a facing, the entire cross-section of the structure can be constructed in HBM. In much the same way as the ‘stair-step’ form of construction, but in this case for the full-width, the embankment is built up in successive horizontal layers, typically 150 to 400mm thick, normally using HBM produced by the mix-in-plant method. The result is a monolithic HBM structure with compressive and shear strengths that can range from values akin to those achieved in earth embankments to values approaching structural concrete, depending on materials and the exact design expectations and requirements. If aggregates at or close to the site are suitable, substantial savings in materials can be realized compared to earth embankments. This may result also in cost savings and there may also be cost savings when compared to structures made using concrete such as dams.

In the case of dams, a monolithic HBM embankment structure will serve several purposes including slope protection and impervious core as well as shortening spillway and diversion structures. In addition, overtopping of the dam by water during floods or high water levels during construction, and more particularly when the dam is in use, will in general cause little if any damage. Excluding design issues that apply to dams in general whatever the construction material, the following will need consideration:

- the intersection of the HBM structure with adjacent material in order to prevent erosion, particularly below the HBM. Methods used include commencement of the HBM dam several layers below existing ground level or protection of the intersection with HBM rip-rap (see section 2.4).
- Where high waves can be generated, the bond between layers will need consideration
- The tailoring of the constituents of the HBM to satisfy the impermeability requirements of the structure.

Developments with slip-forming for facings, mean that monolithic HBM embankment structures can be built to near-vertical slopes by utilizing the slip-formed facing as a ‘shuttering’ for the placement and compaction of the HBM.

2.4 **Rip-rap**

HBM blocks can be used as rip-rap for shore and bank protection, scour and groyne protection. Typically the blocks might be 700mm by 700mm in plan and 400mm thick. Each will thus weigh about 400/500 kg. They can be easily constructed by mix-in-place methods as well as from plant-mixed material on an area close to where they will be required.
Basically a 400mm thick HBM layer is constructed and compacted and then while the HBM is still fresh, slots are formed in the layer preferably to full-depth. The slots can be formed using a ‘blade’ at the end of the hydraulic arm of an excavator or by a blade mounted on the tool bar of a dozer. The slots are spaced to produce a 700mm by 700mm grid. Light recompaction of the surface will be required after the formation of the slots taking care to preserve the discontinuities (emulsion can be introduced) at the slots.

Once the HBM has hardened, using a loading shovel or similar, the HBM layer can be loosened by commencing lifting at the outside edge of the grid. In so doing, the layer separates at the slots, producing ‘rip-rap’. The skill in the operation is recognizing when the HBM has achieved adequate strength to allow clean breakage at the slots and sufficient strength to allow handling, loading and transport to the place of use. In the case of cement binder, this may be within 3 days after compaction of the HBM layer but will vary according to the strength development and thus the time of year and the type of binder. Site trial will confirm the optimum time.

2.5 Miscellaneous applications

Although not always associated with marine and fluvial engineering, HBM can be used as backfill, as hardstandings for bulk material storage and in berms for bulk material storage. In certain cases, where high wear-resistance is required, the HBM can be protected by a layer of concrete or shotcrete or by the use of higher strength HBM or RCC. Thus for example with a berm, the interior zone may be constructed to a lower binder content and strength compared to the outer zone that is exposed to the elements and erosion.

3 REQUIREMENTS

- General

Based on practice and experience worldwide for the marine and fluvial construction works described above, the principal issues for HBM are erosion resistance and durability (Figure 6) and in certain applications, permeability. Structural requirements are generally low and in general will be satisfied by the binder content required for erosion and durability purposes.

As with concrete, it has been found with HBM that durability and resistance to erosion improve;

3 as the quality of the material being treated improves
4 and with increase in binder content and thus strength of the HBM.

This is a convenient and pragmatic situation since the requirements of the material to be treated can thus be specified on the basis of experience for the various applications and a simple strength test can be used in lieu of the more complicated tests required for erosion and durability assessment.

Putting to one side for the moment the specification of the soil or aggregate, for a given soil or aggregate, the strength of HBM in the field is not just a function of binder content but also of the density achieved in the placed HBM. Density in turn is a function of water content. The requisite binder content of HBM for marine and fluvial engineering works is therefore usually determined by means of a laboratory compressive strength test carried out on the mixture made at the optimum water content for compaction by rolling.

Testing is therefore identical to that employed for HBM in road engineering and involves the determination of the water content to achieve maximum compaction in the field under rolling and the amount of binder required at that water content to meet the required strength criterion and thus erosion and durability criteria.

Regarding the specification of the soil or aggregate, durability and resistance to erosion of HBM improve as the content and quality of the coarse element of the mixture increases and the plasticity of the fine element decreases. Thus where the HBM will be exposed to extremes of weather and erosion, it is necessary to
specify a minimum proportion of coarse material of maybe a specified quality and an upper limit on plasticity.

Where permeability is identified as an issue and where fines are lacking, then the use of finely divided material like PFA in the HBM is extremely beneficial because it is an inexpensive void filler. It is also extremely beneficial for another reason; it is a pozzolan and thus contributes to the strength development of the HBM.

In some of the applications described above, e.g. rip-rap, the speed of setting and strength development of the HBM is more important than for other applications. Thus the use of cement as the sole binder or part of the total cementitious content may be necessary.

- **Binders**

  Possible binders for HBM include:

  1.1.1. Cement complying with BSEN 197-1
  1.1.2. HRB (hydraulic road binder) complying with DDENV 13282;

  and the following, either used with the above or in combination with one another to produce a hydraulic combination (i.e. lime + PFA):

  1.1.3. Quick or hydrated lime complying with prEN 14227-11
  1.1.4. PFA complying with prEN 14227-4
  1.1.5. GGBS complying with prEN 14227-2
  1.1.6. Gypsum (natural and FGD gypsum) complying with prEN 14227-3
  1.1.7. Other materials such as CKD (cement kiln dust)

  1.1.8. Enhancers that include setting or retarding agents. Most HBM used for marine and fluvial engineering works have been made using either:

  1. cement alone or
  2. cement in combination with PFA or
  3. cement with lime and PFA.

  There is little if any reported experience with combinations without cement although it should be noted that similar long term strengths are possible with the use of the slower setting and hardening combinations, lime with PFA, and lime with GGBS. These combinations are useful where early strength is not important and extended handling times are required.

  Gypsum can be used with either of these combinations to produce a set and early strength development closer to cement. Such combinations are the basis of HRB, which is a factory-produced blend, typically of GGBS, PFA, lime and gypsum.

  CKD can perform a similar role to PFA since it is a cheap void-filler and cementitious particularly when used with cement or lime.

- **Aggregates**

  Depending on the application and design expectations/requirements, the scope is very wide. Exceptions include organic soils and materials, medium to high plasticity materials, and materials/aggregates that
contain substances that affect fresh properties like setting and hardening or that can have a deleterious effect, like sulfates, on hardened properties.

Granular materials are preferred as they pulverize and mix more easily and result in more economical HBM since they require less binder than finer materials. Typical materials include; silty sands, processed crushed or uncrushed sand and gravel, crushed stone, and, particularly in the context of this note, recycled and secondary aggregates.

For most applications but depending on exact end use and design requirements, aggregate gradation, plasticity and hardness requirements are not as restrictive as aggregates for conventional concrete, and for many, the normal minimum requirements would be, but not necessarily restricted to, as follows:

1. **100% passing 50mm but maximum aggregate size not greater than 20% of the layer thickness**
2. **not less than 50% passing the 4mm sieve**
3. **a minimum of 20% retained on the 4mm sieve where erosion is severe**
4. **avoidance of hard angular aggregate for HBM used compositely with synthetic membranes to avoid the possibility of puncturing the membrane**
5. **5 - 25% passing the 63 micron sieve***
6. **maximum plasticity index 8***
7. **aggregate strength - generally no requirement although in particularly harsh environments, it may be necessary to specify a Los Angeles requirement.**

* non-plastic fines can be beneficial. In uniformly graded material, PFA, CKD (cement kiln dust), and quarry dust serve to fill the voids in the aggregate structure, reduce binder content, and improve impermeability.

- **Water**

Water is necessary with HBM to help achieve maximum compaction of the layer and for the setting and hydration of the binder and eventual hardening of the mixture.

Potable water or other relatively clean water, free from harmful amounts of alkalis, acids, or organic matter, may be used.

Seawater has been used satisfactorily. The presence of chlorides in seawater may enhance early strength development.

**2.2 Compressive strength**

The required compressive strengths for some of the various applications described earlier are shown in Table 1 and are based on overseas experience gained over the last 50 years. In translating the requirements for the UK, allowance has been made for the different specimen size, manufacture and conditioning used abroad compared to practice in the UK.

It should be noted that the requirements are conservative to ensure a durable mixture. Should durability testing be carried out, using laboratory specimens exposed to cycles of both wetting-and-drying and freezing-and-thawing, it is highly likely that lower strengths and thus lower binder contents would suffice. For this reason, the strengths indicated should be viewed as target rather than minimum values.
Table F1: 28 day cube or 1:1 cylinder refusal (vibrating hammer) compressive strengths for HBM specimens cured in a sealed condition at 20°C for marine and fluvial construction works

<table>
<thead>
<tr>
<th>APPLICATION</th>
<th>Non-exposure to weather and erosion</th>
<th>Normal case</th>
<th>Strong current carrying heavy solid, severe wave action, inter-tidal zone</th>
<th>Rip-rap</th>
</tr>
</thead>
<tbody>
<tr>
<td>STRENGTH</td>
<td>4 MPa* (3 MPa)</td>
<td>8 MPa* (6 MPa)</td>
<td>12 MPa* (9 MPa)</td>
<td>12 MPa* (9 MPa)</td>
</tr>
</tbody>
</table>

* HBM made from cement alone. When cement is used with a similar amount or more of pozzolanic/latent hydraulic material, the required strengths values may be reduced to those shown in parenthesis. Where the binder contains no cement and thus the mixture is slow hardening, 28 day strengths using 20°C sealed curing days may yield strengths as low as 2 MPa or less. Unlike HBM containing cement, this is a severe underestimation of potential long term strength. It is suggested that when such binders are used, the above 28day strength values should still apply but the sealed curing should be carried out at 40°C for control purposes. The strengths achieved using this higher temperature are akin to 1 year strengths at normal temperature and thus indicative of ultimate properties.

2.3 Durability and volume stability

In addition to the strength requirements in Table 1 and depending on application, the integrity of the HBM may be checked for volume stability in the presence of water. The purpose of the test is to check the durability of the HBM and for disruptive soils/aggregates and sulfates. The check involves comparison of the strengths of specimens cured in water for the final 7 days of the 28 day period with the 28 day non-immersed strengths in the Table. Provided the immersed strength is 80% of the values in the table, the HBM is deemed satisfactory.

3.7 Permeability

Where low permeability is necessary, permeability testing of the hardened HBM should be carried out and compared with the necessary requirement. In the absence of permeability testing, then the combination of silt-sized fines and binder elements in the HBM should be no less than say 10% or even 15%.

Of equal importance is the bond and thus seal between layers. This is best achieved by ensuring that each layer is promptly covered by the next layer, that the mixture is not prone to segregation, and that the water content is maintained within tight limits of the optimum for compaction. From a segregation point of view, it is important there is sufficient sub-4mm in the HBM to allow the coarse aggregate (material greater than 4mm) to ‘float’ or be totally encapsulated within the mortar element. Fines content on the other hand should not be too high since instability under the roller may occur especially with mixtures on the wet side of optimum.

For 100% impermeability, as in liners for certain liquid wastes, then composite constructions of HBM with HDPE may be required.

3 MIXTURE DESIGN AND BINDER PROPORTIONS

2.2 Mixture design

The mixture design process for HBM using cement is described fully in BCA publication 46.048 and is recommended here, irrespective of whether the HBM contains cement, using the above recommendations for aggregate, soils and mixture requirements. In outline, the basis is as follows:

3. With the selected aggregate or soil in accordance with the end-use and permeability requirements, and using a guestimate for the likely binder content, determine the OMC of the mixture using at least 5 different values of water content.

4. Using the water content corresponding to the OMC, determine the necessary binder content by testing for compressive strength over a range of at least 3 binder contents. This should also be
carried out at say 1.2 OMC to check the effect of extra mixture water on strength before deciding the binder content.

5 Using the selected binder content, test for durability and volume stability using the immersion procedure described above and increase binder content if necessary or change aggregate/soil source

6 If necessary, carry out permeability testing on hardened specimens of HBM made at the selected binder content and OMC.

**Binder proportions**

Whatever the outcome of the mixture design process, binder contents and proportions should be not less than given in Table F2. These binder contents also define the starting point for the mixture design procedure.

Where the binder consists of 2 or more components, UK information on the optimum relative proportions is relatively scarce but some data exists for blends using lime/PFA and lime/cement. Table F3 should be viewed as illustrative and indicates optimum cement/PFA and lime/PFA proportions for equality, in terms of long term potential strength, with cement alone. Note that with lime/PFA but depending on mixing efficiency, the optimum ratio has been found to be about 1:4.

**Table F2: Minimum binder content according to construction method and binder constituents**

<table>
<thead>
<tr>
<th>Construction</th>
<th>OPC/ HRB</th>
<th>Lime</th>
<th>PFA/ CKD</th>
<th>GGBS</th>
</tr>
</thead>
<tbody>
<tr>
<td>In situ</td>
<td>4% alone</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>3% with</td>
<td>-</td>
<td>5%</td>
<td>or 3%</td>
</tr>
<tr>
<td>Ex situ</td>
<td>3% alone</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>2% with</td>
<td>-</td>
<td>4%</td>
<td>or 2%</td>
</tr>
<tr>
<td>In situ</td>
<td>-</td>
<td>3% with</td>
<td>10%</td>
<td>or 5%</td>
</tr>
<tr>
<td>Ex situ</td>
<td>-</td>
<td>2% with</td>
<td>8%</td>
<td>or 4%</td>
</tr>
</tbody>
</table>

*No recommendations can be given for the use gypsum, since there is little UK experience

**Table F3: Binder make-up and proportions to give same 1 year strength**

<table>
<thead>
<tr>
<th>AGGREGATE</th>
<th>cement</th>
<th>lime</th>
<th>PFA</th>
<th>Total binder content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fine only (&lt; 4mm)</td>
<td>10%</td>
<td>-</td>
<td>-</td>
<td>10%</td>
</tr>
<tr>
<td></td>
<td>6%</td>
<td>-</td>
<td>9%</td>
<td>15%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4%</td>
<td>16%</td>
<td>20%</td>
</tr>
<tr>
<td>Mixture of coarse and fine</td>
<td>5%</td>
<td>-</td>
<td>-</td>
<td>5%</td>
</tr>
<tr>
<td></td>
<td>4%</td>
<td>-</td>
<td>6%</td>
<td>10%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3%</td>
<td>12%</td>
<td>15%</td>
</tr>
</tbody>
</table>

**3 CONSTRUCTION AND FIELD REQUIREMENTS**

**General**

There are two methods for mixing HBM, either the mix-in-plant method or the mix-in-place method.

3 The former uses stationery mixers in which the aggregate, binder and water are combined (Figure 7). The resultant mixture is then transported to the point of use using dump trucks, where it is placed by either dozer, grader or paver, and then compacted by rolling.
4 The latter uses travelling mixing machines which mix-in-place. Using purpose-built machines, binder is spread on top of the material to be treated and thoroughly mixed-in with a rotovator. Mixing can consist of more than one pass of the rotovator. The mixed material is then compacted by rolling. Water, if necessary, is normally added by a spray-bar contained within the mixer-hood of the rotovator. The mix-in-place method can be used in ‘mix-in-plant’ mode (Figure 8) where the mixing is carried out away from the point of use, and the mixture then ‘picked-up’ and transported to the point of use as in the mix-in-plant method.

For both methods, compaction is carried out by either pneumatic-tyred or vibratory steel-wheeled roller or both in combination and should achieve 95% compaction relative to the density of the refusal strength specimens.

Provided the mixers are capable (forced-action mixers like continuous pug-mill mixers are recommended) the mix-in-plant method is recommended for multiple layer construction since it ensures more uniform mixing than the mix-in-place method and that the full depth of each layer contains binder. Also since material has to be brought in for each layer, it is easier to bring it in premixed.

However, depending on the importance and necessary integrity of the works and provided there is space, the mix-in-place method can also be used in ‘mix-in-plant mode’ as described above. With careful control, this can be as effective as the mix-in-plant method since the operations of picking up and subsequent spreading of the mixture results in more uniformity in the layer than would occur with the mix-in-place method carried out at the point of use.

It should be noted that the mix-in-place method can handle a wider range of materials because, in contrast with the mix-in-plant method, the problem of feeding material into the mixer does not exist. This can be problematic with the mix-in-plant method with aggregates/soils that do not flow easily or stick together.

More detail on the methods of construction can be found in BCA publication 46.048.

5.2 Construction times

Whatever the method used and end-use, construction should be carried out observing the times in table 4.

<table>
<thead>
<tr>
<th>BINDER</th>
<th>Under normal temperature conditions, time limit for compaction</th>
<th>Placement of next layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement or containing cement</td>
<td>Within 2 hours of cement introduction</td>
<td>Within 24 hours</td>
</tr>
<tr>
<td>HRB and binders with no cement but including GGBS, CKD and/or gypsum</td>
<td>Within 6 hours of binder introduction</td>
<td>Ditto</td>
</tr>
<tr>
<td>Lime with PFA</td>
<td>Within 24 hours of binder introduction</td>
<td>Within 3 days</td>
</tr>
</tbody>
</table>

In particular it should be noted that:

- compaction of each layer shall be completed within the times indicated but before excessive drying out of the layer occurs.

- prior to placement of the next layer, loss of moisture from the layer shall be prevented, certainly minimized. In certain instances, it will be necessary to regularly apply a fine spray of water to the surface of the layer. In no circumstances shall the next layer be applied to a dried surface.

- where impermeability and bond between layers is important, placement of the next layer shall be completed within the times indicated or a bond coat applied.
More detail on the methods of construction can be found in BCA publication 46.048.

5.3 ‘Stair-step’ and layered embankment construction

Construction for stair-step slope protection and layered embankment construction is as described in 2.1 and 2.2 respectively. Consideration however will need to be given to the compaction of the exposed edge to produce a dense durable face.

- Either the edges can be feathered, or
- Can be compacted simultaneously with the layer using a modified pneumatic-tyred roller (Figure 9), or
- Can be compacted using a modified vibrating roller (Figure 10).

  - ‘Plating’

Where less severe slope protection is required, ‘Plating’ which describes the laying and compaction of HBM parallel to the slope, can be placed by:

3 either pushing HBM up the slope by dozer
4 or by feeding HBM into a spreader that can travel up or down the slope

The former has been carried out on slopes as steep as 1V:2H whilst the latter method would normally be used for flatter slopes. In the case of the latter method, less energy is required to spread traveling down the slope.

Compaction should be carried out using self-propelled rollers if the slope is relatively flat or by winching a roller up and down steeper slopes (Figure 11).

Overall recommendations are as follows:

3 for slopes steeper than 1V:4H, the HBM should be premixed in a central plant or along the toe of the receiving slope/embankment and then placed on the slope
4 the receiving slope/embankment, should be firm and shaped to the required line and grade prior to HBM placement
5 as a minimum, grade stakes or more sophisticated methods of thickness control should be used employed to ensure correct thickness
6 95% relative compaction is required, thus the weight of roller needs careful consideration especially where the slope is steep
7 water curing should be used, employing a light fog spray to avoid ponding at the toe and possible wash-out of binder.

5.5 Liners

The basis of construction is as follows:

2 Single-layer liners can be constructed by either the mix-in-place or mix-in-plant method of construction.
3 Where the liner consists of 2 or more layers, then the mix-in-plant method is recommended.
4 Where preferred, bottom liners can be combined with a stair-step liner on the slopes.
For composite HBM/synthetic membrane liners, the bottom foundation layer of HBM is placed in the normal
fashion, the membrane installed, and the top protective layer of HBM also placed in the normal fashion using
premixed material (Figure 12).

5.6 Rip-rap

The construction process is described fully in section 2.4

3.1 Joints

Contraction and expansion joints are not required for HBM, but there will be construction joints. These will
be required whenever fresh mixture is placed against compacted mixture or when stoppages occur for
intervals longer than the ‘compaction’ time limits indicated in Table F4.

Construction joints should be vertical and consist of sound well-compacted material; thus constructed, they
will be able to accommodate without distress thermal movement should it occur. On the other hand,
feathered or sloping construction joints must be avoided since with temperature rise, lifting can occur as one
bay slides up and over an adjacent bay. Such occurrences will be a source of weakness in the HBM.

Construction joints are best constructed by using the roller to ramp-down the HBM at say the end of the
day. The layer should then be cut-back by mechanical blade to a sound and vertical face of fully compacted
HBM of the required thickness.

In summary the rules are:
3 In no case should fresh HBM be laid against compacted material unless the edge of the compacted
mixture is vertical.
4 In no case should fresh HBM be laid against uncompacted HBM that has been laid longer than the
‘compaction’ time limits in Table F4.

5.8 Curing

Compacted HBM should contain sufficient moisture for the full hydration of the binder. If allowed to dry out,
the mixture, particularly the surface, will become weak and friable.

During multi-lift work, drying out should be prevented by light spray application of water as described in 5.2.
This applies also to the edges of exposed ‘stair-step’ or other layered HBM.

At completion of the works, drying out of the final surface and edges of the HBM also needs to be avoided.
Again this can be achieved by applying water as above or by the application of a seal of resin-based material
or bituminous emulsion, although the use of seals may need to be avoided depending on end-use and
aesthetics. If positive seals need to be avoided, water spraying should be continued for as long as possible
but at least 7 days.

6 CONTROL AND TESTING OF CONSTRUCTION

6.1 General

The satisfactory performance of HBM for the applications described above depends on the construction of a
layer or structure that is of the correct dimensions and adequately strong.

Correct dimensioning is particularly necessary where the finished works consists of one layer of HBM since
thin layers can be distressed even during construction. In this case, careful control should be exercised over
the level of both the surface of the HBM layer and the bottom of the layer. This is relatively straightforward where the HBM is premixed but where the mix-in-place method of construction is used at the point of use, then the depth of mixing needs careful monitoring as well as the thickness of layer after final trim and compaction of the layer.

Strength also needs to be adequate for structural purposes but more importantly for the prime objectives of resistance to erosion and durability. The achievement of adequate strength in the layer is primarily a function of constituent consistency and batching as well as the density of completed HBM.

Aggregate consistency, water and cement content are relatively easily controlled during the batching and mixing process. The importance of aggregate consistency should not be underestimated since however good the batching and mixing of the cement, if the aggregate quality varies then so will the strength, up or down. This will have a detrimental bearing on erosion and durability.

The achievement of the necessary density is also a function of constituent consistency but additionally is affected by the compactive effort and the degree of support offered by the underlying structure.

6.2 Control, checks and test schedule

It is thus important to monitor all the above aspects to ensure that the HBM and structure will perform over the long term. The importance of the end-use will dictate the intensity of the control. As the project proceeds or as more experience is gained, then the frequency of tests and checks may be relaxed. Table F5 provides a check list of what needs controlling and what should be included in the specification for the works.

Table F5: Tests, controls and checks

<table>
<thead>
<tr>
<th>Test/control/check</th>
</tr>
</thead>
<tbody>
<tr>
<td>Receiving ground:</td>
</tr>
<tr>
<td>Stability, soft spots etc</td>
</tr>
<tr>
<td>Level and regularity (more applicable to mix-in-plant process since 'unseen' with mix-in-place method)</td>
</tr>
<tr>
<td>On the constituents:</td>
</tr>
<tr>
<td>Soil: grading, water content, plasticity, organics, sulfates and sulfur</td>
</tr>
<tr>
<td>Added constituents: Supplier certificate</td>
</tr>
<tr>
<td>Added constituents: Spread rates (mix-in-place) or batching records (mix-in-plant)</td>
</tr>
<tr>
<td>On the HBM:</td>
</tr>
<tr>
<td>Water content</td>
</tr>
<tr>
<td>Roller passes</td>
</tr>
<tr>
<td>Depth of mixing at all relevant stages (mix-in-place only)</td>
</tr>
<tr>
<td>Final HBM level</td>
</tr>
<tr>
<td>Final HBM thickness (mix-in-place only)</td>
</tr>
<tr>
<td>In-situ density</td>
</tr>
<tr>
<td>Compressive strength</td>
</tr>
<tr>
<td>Volume stability (normally just carried out at mixture design stage)</td>
</tr>
<tr>
<td>Impermeability (normally just carried out at mixture design stage)</td>
</tr>
</tbody>
</table>
Improving specifications for use of recycled and secondary aggregates in construction

**Figure 1**

HBM shore protection blending into surroundings

**Figure 2**

Stair-step soil cement shore protection, Bonny reservoir, Colorado, after 33 years of exposure to wave-action and freeze-thaw cycles
Improving specifications for use of recycled and secondary aggregates in construction

FIGURE 5
Composite HBM/synthetic membrane liner

FIGURE 5
HBM stair-step shore protection at high tide (just visible in middle of picture) exposed to severe wave-action and extreme weather
Improving specifications for use of recycled and secondary aggregates in construction