PUBLISHED PROJECT REPORT PPR792

Review of hydraulically bound materials for use in Scotland

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Prepared for: Transport Scotland, SCOTS
Project Ref: 2000-100

Quality approved:
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Contents amendment record

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<table>
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<th>Date</th>
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</tbody>
</table>
## Contents

Executive summary v

Abstract 1

1 Introduction 1
   1.1 Methodology 1
   1.2 Significance 2
   1.3 Definition 2
   1.4 HBM products 3

2 Hydraulically bound materials 5
   2.1 Recycled and secondary aggregates 5
   2.2 Recycled aggregates 6
      2.2.1 Reclaimed asphalt 6
      2.2.2 Recycled aggregate 6
      2.2.3 Recycled concrete aggregate 7
      2.2.4 Recycled glass 7
   2.3 Secondary materials 7
      2.3.1 China clay sand / Stent 7
      2.3.2 Coal fly ash (CFA) / Pulverised-fuel ash (PFA) 8
      2.3.3 Colliery spoil 8
      2.3.4 Foundry sand 9
      2.3.5 Furnace bottom ash (FBA) 9
      2.3.6 Incinerator bottom ash (IBA) 9
      2.3.7 Slag 9
      2.3.8 Slate aggregate 10
      2.3.9 Spent oil shale 10
   2.4 HBM production 10
      2.4.1 In-situ production 10
      2.4.2 Ex-situ plant production 12
   2.5 Summary 13

3 HBM specifications and test methods 15
   3.1 General 15
   3.2 UK and European based specifications 16
   3.3 Material property testing 19
      3.3.1 General 19
      3.3.2 HBM durability in pavements 20
      3.3.3 HBM durability in reinstatements 21

4 HBM construction and products 23
   4.1 HBM design for major roads 23
   4.2 HBM design for minor roads 24
   4.3 HBM in trench reinstatements 24
      4.3.1 General 24
4.3.2 Specifications 26
4.3.3 Limited findings on HBM use 27

4.4 HBM proprietary products 27
4.4.1 EcoFILL 27
4.4.2 Lafarge Aggregates and Bardon Composite Pavements 27
4.4.3 SMARTR PV1 28
4.4.4 SMR Premixd 28
4.4.5 Trenchmix 29
4.4.6 Trenchmod 29
4.4.7 Summary 29

4.5 Distresses with HBM paving applications 31
4.5.1 General 31
4.5.2 Methods to monitor HBM performance 31

5 Further trials 34
5.1 SROR trials 34
5.2 Research trials 34

6 Conclusions and recommendations 36
Acknowledgements 38
References 38
Tables

Table 2.1 – Recycled and secondary aggregates for highway works applications ........ 6
Table 3.1 - Type of HBM covered by EN 14227-1 ............................................. 16
Table 3.2 – Type of HBM covered by BS EN 14227-1, -2, -3 and -5............... 18
Table 3.3 - Permitted constituents of HBM mixtures for use in UK................. 18
Table 4.1 – Summary of Properties for Generic and Proprietary HBM Products .... 30
Figures

Figure 1.1 – Example of HBM processing plant and stockpiles.................................4
Figure 2.1 – Key elements of in-situ HBM production.............................................. 11
Figure 2.2 – In-situ HBM production for highway works ......................................... 12
Figure 2.3 – Plant production of HBM for highway works ......................................... 12
Figure 2.4 – Ex-situ HBM batch plant ....................................................................... 13
Figure 4.1 – Laying and compaction of HBM pavement layers................................. 24
Figure 4.2 – Trench excavation and reinstatements using HBM ................................. 25
Figure 4.3 – Framework for HBM use in trench reinstatements ................................. 26
Executive summary

The focus of this literature review is to gather information on the current state of practice on the application of hydraulically bound materials (HBM) in flexible pavements and trench reinstatements and give advice on their use in Scotland.

HBM is one of the most commonly used materials for pavement sub-bases where cement treated base (CTB) or cement bound material (CBM) are traditionally used. However, cement is not the only binding material currently used in HBM applications; binding materials such as fly-ash, lime and pozzolan are also used. Furthermore, the introduction of recycled and secondary aggregates (RSA) in HBM design has reduced the need to use primary materials, with demand for RSA increasing due to environmental and sustainability concerns.

The vast majority of RSA are recycled materials produced from construction, demolition, excavation waste and asphalt from road works. Secondary materials come in the form of by-products such as slag or fly-ash and can also be used as aggregates or earth-work materials. The inclusion of recycled and secondary materials in current UK and European standards and specifications has also greatly increased the demand for these materials.

Production of HBM for use in road works, as well as in other applications, is divided into two categories; in-situ and ex-situ production. The in-situ method processes the reclaimed material on site whereas the ex-situ method is performed in a central plant and requires treatment of the material at another location.

In addition to providing guidance on the application of HBM in major highways, work has also been done to provide guidance on the application of HBM on minor roads (residential or commercial roads) and trench reinstatements. HBM use in trench reinstatements follows the Specification for the Reinstatement of Openings in Roads (SROR) in which technical guidance on where HBM materials are permitted for use in Scotland is provided.

From this literature review, the following conclusions are made:

- HBM are defined as mixtures that set and harden by hydraulic reaction. They include:
  - cement bound materials (i.e. mixtures based on the fast setting and hardening characteristics of cement), and
  - slow setting and hardening mixtures made from industrial by-products such as fly ash (FA) and ground granulated blastfurnace slag (GGBS).

- HBM in the United Kingdom (UK) is classified under different grades, based on the strength of binding agent and aggregate gradation. Different grades of HBM include:
  - Soil cement
  - Cement stabilised soil
  - Lean concrete
  - Roller compacted concrete (RCC)
  - Cement bound granular material (CBGM)
  - Slag bound material (SBM)
  - Fly-ash bound material (FABM)
  - Hydraulic road binder bound material (HRBBM)

- The application of HBM is specified in Parts 1, 2, 3, 5, 10, 11, 12, 13 and 14 of BS EN 14227 and has to be produced, handled, transported, used and tested in accordance with the 800 series of the Specification for Highway Works (SHW). The
Road Authorities and Utilities Committee (Scotland) (RAUC(S)) provides technical guidance on the use of HBMs in trench reinstatements for Scotland.

- The advantages of using HBM are as follows:
  - HBM construction is popular and versatile in terms of availability of plant and materials.
  - HBM can be produced by “ex-situ” or “in-situ” equipment.
  - On-site materials, such as excavated soil or demolition wastes, can be re-used for some HBMs which, in turn, reduce the need to import virgin materials as well as avoiding aggregate fees and disposal costs.
  - The use of HBM is energy efficient because there is significant energy savings associated with cold mix technology. In addition, by-products of local power stations and metal works, such as fly-ash and slag, are incorporated in HBM design.
  - HBM has become a more attractive feature in several project bids because of its green procurement which meets many clients’ requirements.
  - HBM strength and stiffness increases with time especially with HBM mixtures which are slow setting and slow hardening.
  - Compaction process time is reduced when compared with un-bound mixtures, which also significantly reduces health and safety issues related to hand arm vibration syndrome.
  - HBMs can be used to up-cycle waste material which is initially not suitable for recyclable use.
  - The use of an HBM sub-base or base can significantly reduce the required thickness of pavement layers.

- The limitations of using HBM are as follows:
  - Fast setting HBMs provide good strength after initial construction but are prone to shrinkage during curing and, therefore, experience thermal stress cracks which, in turn, lead to reflective cracking in the asphalt surface.
  - Property requirements for the aggregate are selected by the user and are considered “open” in regards to strength, so that a poor choice as to the appropriate class of strength can lead to premature failure.
  - Lack of binder in HBM design contributes to poor strength and susceptibility to frost heave.
  - There is limited research on the use of HBM in trench reinstatements, particularly in weak pavements or roads in poor condition.

Although HBM use is covered by a European standard and is an approved material for general use, the limited research on HBM in utility trenches, especially in pavements that are below current design standards, raises concerns. Therefore, trials of HBM are recommended. In addition, trials will allow ranking of different binder types which can be of use to engineers selecting the appropriate class of HBM to use.
Abstract

The sub-base layer is very important in terms of the expected performance of any pavement structure. The sub-base is often the main load carrying layer of the pavement, as opposed to the base, and is designed to distribute the stresses and strains exerted from passing traffic loads down to the foundation. This distribution needs to be replicated in any reinstatement. Crushed aggregates are generally recommended for sub-base materials. There are two types of material which can be used in the sub-base layers: unbound granular materials and hydraulic bound materials (HBMs), the latter being a commonly used material for pavement sub-bases and bases. HBMs are defined as mixtures that set and harden by hydraulic reaction. They include cement bound materials (i.e. mixtures based on the fast setting and hardening characteristics of cement) and slow setting and hardening mixtures made from industrial by-products such as fly ash (FA) and ground granulated blast furnace slag (GGBS). The introduction of recycled and secondary aggregates (RSA) in HBM design has reduced the need to use primary materials, with demand for RSA increasing due to environmental and sustainability concerns. The preferred material for pavement applications is the slow setting HBMs. Although fast setting HBMs show good strength after initial construction, they often experience thermal stress cracks, due to shrinkage during the curing period, which are seen in the asphalt surface due to reflective cracking. The slower setting and hardening HBMs, with a reduced tendency to crack, lead to less reflective cracking and thus the possibility of reduced asphalt overlay thickness. The performance of HBMs can be monitored by extracting cores for analysis, as well as by using the Falling Weight Deflectometer to determine the stiffness of the HBM layers. Although current literature indicates that in general pavement construction and in some utility trenches, HBM materials have shown to perform well, there are concerns regarding its use in pavements that are below current design standards. Further research of HBM applications and adjacent pavement performance would need to be gathered and analysed in order to attain a better understanding of what materials and techniques work best. This further research could include pavement trials.

1 Introduction

1.1 Methodology

A literature review has been conducted to gather information on the current state of practice on the application of hydraulically bound materials (HBM) in flexible pavements and trench reinstatements for use in Scotland. The literature search contains views on the benefits and disadvantages of using HBM on major roadways throughout Europe, including Scotland. Particular attention is paid to types and performances of HBMs in trench reinstatements, including:

- Defining the material.
- Presenting the potential problems which occur when using HBM.
- Strategies used to minimise the occurrence of potential pavement distresses.
• Methods to monitor performance.
• Maintenance procedures used to resolve any potential issues.

Relevant specifications and design manuals are also reviewed for what is currently expected of HBMs. In particular, the relevant sections of the Specification for the Reinstatement of Openings in Roads (SROR) (RAUC(S), 2003), the Specification for Highway Works (SHW) (HA et al., 2011a) and HD 35/04 (HA et al., 2004) of the Design Manual for Roads and Bridges (DMRB) were studied for specific requirements that these products have to achieve.

1.2 Significance

There are two layers where HBM have been used:
• The sub-base layer, which is very important in terms of the expected performance of the pavement. The sub-base is often the main load carrying layer of the pavement, as opposed to the base, and is designed to distribute the stresses and strains exerted from passing traffic loads down to the foundation. This distribution needs to be replicated in any reinstatement.
• The base, which needs to be strong in order to prevent shear failure and structural, as opposed to surface, deformation, also known as rutting, in the overlying asphalt layer. In addition to providing strength, a well designed and constructed base will provide good drainage and prevent settlement.

In pavement design, the sub-base is usually unbound whilst the base is the lowest of the bound layers. However, the two types of materials which are most commonly used in the sub-base and base layers for trench reinstatements are unbound granular materials and hydraulically bound materials. Aggregates used in either type of material for these layers usually contain good interlocking properties; thereby, traffic loads are evenly distributed through the layer and the underlying layers. Crushed aggregates are generally recommended for these materials.

This report focuses on hydraulically bound materials only. Literature on research and practical experience of HBMs and their use in reinstated trenches was sought from the TRL library database and from the internet.

1.3 Definition

HBMs are not covered in the second edition of either the SROR (RAUC(S), 2003) or the Specification for the Reinstatement of Openings in Highways (SROH) (HAUC(UK), 2002). However, the third edition of the SROH (HAUC(UK), 2010) does include HBMs, which are described as follows:

"HBMs are mixtures that set and harden by hydraulic reaction. They include:
• cement bound materials (i.e. mixtures based on the fast setting and hardening characteristics of cement), and
• slow setting and hardening mixtures made from industrial by-products such as fly ash (FA) and ground granulated blast furnace slag (GGBS).

These materials comprise any HBM specified in BS EN 14227-1, -2, -3, -5, -10, -11, -12, -13 & -14, and shall be produced, handled, transported, used and tested in accordance with the SHW (Specification for Highway Works) 800 series. Although not called up in the SHW, the HBM types, SBM B4, FABM 4 and HRBBM 4 from BS EN 14227-2, -3, & -5 respectively are also included since they are
purposely suited for trench reinstatement work. HBMs therefore should be produced, constructed and tested in accordance with the SHW 800 series as if they were SBM B3, FABM 3 and HRBBM 4 respectively. Layer thickness and compressive strength requirements shall be in accordance with Table A9.1 except that the specified compressive strength requirement shall be deemed to apply at 28 days as detailed in Appendix A9.3.4. All of the SHW or BS EN 14227 HBM types are deemed approved for use as ARMs (alternative reinstatement materials) without a trial.”

The permitted use of HBMs within the third edition of SROR is currently being reviewed. HBMs are classified under different grades, based on the strength of binding agent and aggregate gradation. The different grades of HBM include:

- Soil cement.
- Cement stabilised soil.
- Lean concrete.
- Roller compacted concrete (RCC).
- Cement bound granular material (CBGM).
- Slag bound material (SBM).
- Fly-ash bound material (FABM).
- Hydraulic road binder bound material (HRBBM).

Each of these materials is usually produced in different classes, depending on cement content or strength. For instance, CBGM, FABM, and HRBBM all contain three different classes whereas SBM contains seven different classes. It is often found that, when cement is used as a binder for HBM, SBM is still used as a constituent material.

The use of HBM is regarded energy efficient (ETSU, 1997) because there is significant energy savings associated with cold mix technology. In addition, by-products of local power stations and metal works, such as fly-ash and slag, can be incorporated into HBM design.

1.4 HBM products

As far as practicable, the review has concentrated on products that are, or could be, available in Scotland and trials in ground and climatic conditions in, or similar to those in, Scotland. The internet was searched for proprietary HBM products that are on the market in Scotland. Any technical data sheets, COSHH statements, details of their application and of their performance were then sought for each product found. However, not that many products were identified that are significantly different from the generic equivalent. In addition, there is a wide diversity of performance likely from them due to the extensive list of different options, which means that any conclusions that are drawn from the investigation have had to be limited to specific products.
Hydraulically bound materials

Figure 1.2 – Example of HBM processing plant and stockpiles
(WRAP 2005a)
2 Hydraulically bound materials

2.1 Recycled and secondary aggregates

There is a wide variety of materials which are currently used in HBMs. Most notably is the use of recycled and secondary materials which reduces the production of primary materials. Historically it is well known that recycled and secondary materials have been used in highways and local roads, but recently there has been an increase in demand for these materials in other areas as well as highway construction due to environmental and sustainability concerns. In the UK, the use of recycled and secondary materials accounts for 30% of all aggregates sold in the UK (MPA, 2009). HBM is currently being promoted through the Scottish Government’s Zero Waste Plan which views all waste as a resource. The utility industry in Scotland generates approximately 680,000 t annually of waste of which 72% is diverted from landfill (Plant & Civil Engineer, 2012). Since 2006, a major push has been made for the use of sustainable low energy construction in Scotland and new guidelines were put in place which are based on reports TRL611 (Merrill et al., 2004) and TRL615 (Nunn, 2004). These reports are discussed in more detail in Chapter 0 whilst Sections 2.2 and 2.2.4 describes the different materials that fall under the category of “Recycled and Secondary Aggregates” (RSA).

According to the Waste and Resources Action Programme (WRAP), RSA accounts for almost 30% of the UK aggregates market in 2010 (MPA, 2009). Examples of high profile projects which have used recycled aggregates include the widening of the M25 motorway on the west side of London and the new spur road into Heathrow airport (WRAP, 2006a). Over 800,000 tonnes of recycles aggregates were used which accounted for 95% of the total unbound aggregates used on the project (Reid, 2011). According to the literature, one-third of the recycled aggregates came from the existing pavements and materials on site, and the remaining two-thirds came from demolition waste from London (Reid, 2011).

The vast majority of RSAs are recycled materials produced from construction, demolition and excavation waste and asphalt planings from highway works. Secondary materials come in the form of by-products such as slag or fly-ash and can also be used as aggregates or earthwork materials. The following materials are considered suitable for use in HBM (Sherwood, 1994) whilst Table 2.1 presents a summary of which RSA materials are suitable for different pavement layers:

- Demolition waste.
- Recycled concrete aggregate.
- Slate aggregate.
- Recycled asphalt.
- Pulverised fly-ash (PFA).
- Incinerator bottom ash (IBA).
- China clay sand.
- Air-cooled blast-furnace slag.
- Granulated blastfurnace slag (GBS).
- Burnt/unburnt colliery spoil.
- Basic oxygen slag (BOS).
- Electric arc furnace (EAF) slag.
### Table 2.1 – Recycled and secondary aggregates for highway works applications (HD 35/04)

<table>
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<th>Recycled / Secondary Aggregate</th>
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* Also has been classified as a recycled aggregate type (WRAP, 2006b)

### 2.2 Recycled aggregates

#### 2.2.1 Reclaimed asphalt

Reclaimed asphalt (also RA), also known as recycled asphalt pavement (RAP), can consist of milled or planed asphalt, as well as return loads or offcuts from bituminous layer joint preparation. Planed asphalt is a material removed from pavement layers using equipment fitted with milling cutters, whilst granulated asphalt is surplus or reclaimed asphalt material taken from bound pavement layers and reconstruction sites. The SHW (HA et al., 2011a) and the HD 35/04 (HA et al., 2004) state that RAP can be used in HBM design apart from reclaimed asphalt that contains any tar, which is not considered appropriate to be categorised as RAP. Similar to recycled aggregate, methods for processing RAP can be done in-situ or ex-situ with an estimated 5% used in new asphalt design and 95% used in fill materials (Barritt, 2003).

#### 2.2.2 Recycled aggregate

Recycled aggregate (RA) is defined as aggregate resulting from the processing of material previously used in construction (not including reclaimed asphalt, which is treated as a separate material) and has been approved in accordance with the SHW (HA...
et al., 2011a) and HD 35/04 (HA et al., 2004) for use in HBM. According to the SHW, recycled aggregates must contain no more than 1 % by mass of contaminants such as plastic, metal, wood, and plasterboard. Furthermore, recycled aggregates containing brick are more susceptible to freeze-thaw action and are more suitable for works such as general fill, capping and backfill. There are two methods of recycled aggregate production for highway works; in-situ and ex-situ production. More about these production methods is discussed in Section 2.3.7.

### 2.2.3 Recycled concrete aggregate

Recycled concrete aggregate (RCA) is defined in BS 8500-1 (BSI, 2006) as recycled aggregate principally comprising crushed concrete. RCA typically comes from demolition of roads, pavements, runways, and buildings. Based upon the SHW (HA et al., 2011a) and the HD 35/04 (HA et al., 2004), recycled concrete aggregates can be used in HBM design. RCA is readily available throughout the UK due to the volume of concrete in the roads, runways and buildings being demolished, and the existence of suitable reprocessing facilities.

### 2.2.4 Recycled glass

Due to the increasing pressure to find an alternative to virgin aggregates in highway works, the use of recycled glass has become a viable solution. Recycled glass is generally separated in recycling facilities or collected at bottle banks before being crushed or granulated. The principal materials that make up glass are quartz sand and sodium carbonate. Although not often used, recycled glass has the potential to be used as an aggregate in concrete or asphalt. One particular study looked at the inclusion of recycled asphalt in bitumen mixture with 30 % of the aggregate replaced with crushed glass (Nicholls and Lay, 2001). Analysis and compaction results showed that the performance of the glass-bitumen mixture was similar to that of the control (typical) asphalt mixture with no indications of issues with workability or compaction. The above results bode well for the continued use of recycled glass in bitumen mixtures and HBMs. Furthermore, the fact that both the SHW (HA et al., 2011a) and HD 35/04 (HA et al., 2004) approve the use of recycled glass in HBM, this industry will continue to grow.

### 2.3 Secondary materials

As stated earlier, secondary materials come in the form of by-products such as slag or fly-ash and can also be used as aggregates or earth-work materials. The following materials all fall under the category of secondary materials.

#### 2.3.1 China clay sand / Stent

The extraction of china clay (kaolin) from decomposed granite (kaolinitic granite) produces china clay sand as a by-product. High pressure jets of water are applied to weathered granite cliff faces which disintegrate the china clay. As the china clay collects at the bottom of the pit, water is pumped in and piped into a treatment plant where the clay then settles out. The china clay is then graded and washed before further use. China clay sand consists of two materials: stent and tip sand. Stent (waste rock) and tip sand (washed material) are produced during the extraction process. Stent in particular requires crushing and screening before application as an aggregate material. China clay sand has been approved by the SHW (HA et al., 2011a) and the HD 35/04 (HA et al.,
2004) for use in HBM, among other applications. Sources of china clay are located in the south west England where transport of this material to northern locations such as Scotland may prove expensive.

2.3.2 Coal fly ash (CFA) / Pulverised-fuel ash (PFA)

Fly ash is extracted from the burning of coal in coal-burning power stations and, when refined into pulverised-fuel ash (PFA), is similar in fineness to cement (HA et al., 2004). Historically, fly ash has been used as bulk fill for highway embankments. A typical example is the upgrading of a motorway junction outside Reading in the south of London where 85,000 tonnes of fly ash was used in the embankments (Reid, 2011). Fly ash is a siliceous material and does not swell when exposed to moisture. Some of the limitations of using fly ash are that it is a difficult material to compact especially when wet, and when compared with materials such as expanded clay, polystyrene or tyre bales, reduction in density is poor. However, fly ash supply is plentiful and is a cheaper alternative to other lightweight fill materials. Due to its Pozzolanic properties, fly ash can replace cement in concrete or binder in HBM. As is the same with recycled aggregates or RAP, fly ash in HBM can be processed in situ (to treat weak soils) or by plant, along with recycled aggregates. Studies on the use of fly ash in HBM bases have shown it to perform well initially under construction traffic and opening traffic and to continue to gain strength as the pavement is trafficked (Walsh and Williams, 2002).

2.3.3 Colliery spoil

Colliery spoil, also known as minestone, is produced from coal mining and consists of varying proportions of sandstone, shale, mudstone, and coal fragments. Therefore, colliery spoil properties can vary significantly. Colliery spoil consists of sulphates and sulphides which mean that its use in sensitive areas such as structural backfill is prohibited. Another limitation of colliery spoil is its susceptibility to freeze-thaw action and low particle strength, which suggests that it would perform poorly in an unbound sub-base. Colliery spoil is divided into two groups: burnt and unburnt colliery spoils. Burnt colliery spoil is defined as the residue following ignition of coal mine spoil heaps which results in partial to complete combustion of coal particles in the spoil, leaving calcined rock according to HD 35/04 (HA et al., 2004). Burnt colliery spoil is more useful than unburnt colliery spoil in terms of applications since all the combustible material is removed. Unburnt colliery spoil is specifically prohibited from selected granular fill within the SHW (HA et al., 2011a). Based upon the SHW and the HD 35/04 (HA et al., 2004), burnt colliery spoil can be recycled into:

- Hydraulically bound mixtures (HBM) for sub-base and base.
- Unbound mixtures for sub-base.
- Capping.
- Embankments and fill.

Unburnt colliery spoil can be recycled into:

- Hydraulically bound mixtures (HBM) for sub-base and base.
- Embankments and fill.

Some of the more high profile uses of colliery spoil include the use of spent oil shale (similar material to colliery spoil) in an embankment fill for a link road from the M9 to the Forth Road Bridge near Edinburgh Scotland. However, due to concerns about chemical variability as well as potential swelling and disintegration of the mixture from
sulphate attack, colliery spoil use is limited to bulk fill applications and its use as the coarse aggregate in HBM is unlikely to be approved (Reid, 2011).

2.3.4 Foundry sand

According to HD 35/04 (HA et al., 2004), foundry sand is a by-product consisting of uniform sized sands including various additives and metals due associated with its specific manufacturing process. Foundry sand is primarily used in block manufacture and asphalt with only a small proportion used in the construction industry and is located mostly in London, the Midlands, the North West and North East of England (DCLG, 2007). Based upon the SHW (HA et al., 2011a) and the HD 35/04 (HA et al., 2004), foundry sand can be recycled into HBM.

2.3.5 Furnace bottom ash (FBA)

Furnace bottom ash (FBA) is considered the coarser type of ash which is produced in coal burning power stations and occurs due to fusion of PFA particles as they fall to the bottom of furnace. FBA is porous in nature and varies in size, from fine sand to coarse aggregate. FBA has been approved in HD 35/04 for use in HBM (HA et al., 2004).

2.3.6 Incinerator bottom ash (IBA)

Burning of municipal solid waste (MSW) produces material which is discharged into a burning grate and once processed is called incinerator bottom ash (IBA). IBA is considered a heterogeneous material which may contain various proportions of brick, glass, ceramics, concrete, clinker, and ash according to HD 35/04 (HA et al., 2004). IBA is processed to remove metals and some unstable materials and is then screened to produce IBA aggregate. MSW incinerators can be found all over England. The SHW (HA et al., 2011a) and the HD 35/04 (HA et al., 2004) both approve of IBA use in HBM. Studies on the use of IBA in HBM base and sub-base layers have shown to perform well although the material should be overlaid as soon as possible to limit the exposure to traffic and weathering (Allen, 2002).

2.3.7 Slag

Slag is an industrial by-product of metal working processes and although there are many types of slag, the two most common are blast furnace slag and steel slag. There are many metal working operations in the UK, most notably Teesport and Scunthorpe in the north east of England and Port Talbot in Wales.

Blast furnace slag is considered to be a by-product rather than waste material by the EC due to its high value. Blast furnace slag is widely used as a coarse aggregate in asphalt production. In addition, granulated blast furnace slag is an alternative to cement in concrete and binder in HBM.

Crushed air-cooled phosphorus slag aggregate is somewhat lighter than conventional granular aggregate which exhibits very good soundness (high resistance to freeze-thaw deterioration) and good resistance to mechanical degradation together with good stability from their sharp, angular shape. However, their use occurs primarily in rural areas close to the remote locations where these slags are produced, at least in North American (University of New Hampshire, 2008).
Steel slag is also considered a by-product and is produced from the manufacture of steel from pig-iron. There are two types of steel slag; basic oxygen-furnace slag (BOS) and electric arc furnace (EAF) slag. EAF is typically more easily weathered than BOS due their chemical make-up which is a result of their respective manufacturing processes (Dunster, 2001; HA et al., 2004). Similar to blast furnace slag, steel slag is commonly used as coarse aggregate in asphalt especially in thin surface courses where it provides good skid resistance, as well as in HBM for bases and sub-bases (HA et al., 2004). It is also noted that steel slag undergoes weathering to ensure volumetric stability before being used in pavement applications. In particular, the weathering process involves hydration reactions of any lime (CaO) or magnesia (MgO), which can cause potential swelling of steel slag aggregate (Reid, 2011). There are numerous studies which show that slag performs well as coarse aggregate material used in asphalt mixtures and HBMs (Rockliff et al., 2002; Dunster, 2001).

### 2.3.8 Slate aggregate

Slate aggregate is the by-product of slate quarries primarily producing roofing slates and, as such, the primary UK source is north-west, south west and north Wales. It can be used in HBM providing it meets the appropriate material and grading requirements. However, it is not likely to be commercially available in Scotland.

### 2.3.9 Spent oil shale

Spent oil shale is a waste material of the oil industry in the Lothian region of Scotland, which has now ceased. Once the crude oil and naphtha was extracted from the oil shale, the spent shale along with other waste materials were deposited in heaps next to the refineries and mines and is somewhat similar to colliery spoils in nature. Spent oil shale is pinkish in colour and is referred to as Blaes (Winter et al. 2001). Similar to colliery spoils, spent oil shale must be well burnt and non-plastic for it to be used in most applications. Due to its approval to be used in HBM, among other applications, by SHW (HA et al., 2011a) and the HD 35/04 (HA et al., 2004), there is a strong demand for spent oil shale because of its usefulness as a cost effective fill and sub-base material. However, transport costs are high if the material is needed anywhere other than the northern part of the UK. As is the case with most oil refinery by-products, the cessation of oil production in the area means the supply of spent oil shale material is reducing.

### 2.4 HBM production

Production of HBMs for use in highway works as well as other applications is divided into two categories; in-situ and ex-situ production. The in-situ method processes recycled aggregates on site whereas the ex-situ method is performed in a central plant and requires treatment of the material at another location. The installation process of HBM material is critical to the success of the material. Not unlike asphalt, if HBM material is laid under poor weather conditions or is not laid to the design standards, the subsequent performance of the material is reduced significantly. Sub-Sections 2.4.1 and 2.4.2 describe these two production processes.

#### 2.4.1 In-situ production

Figure 2.1 presents a schematic illustrating the key elements involved in in-situ HBM production for use in flexible pavements. Binder is spread on soil and rotovalated or
mixed in-situ using on-site machinery; for trench reinstatements it will be mixed because it will have excavated to form the trench. HBM must be compacted as a single layer and, if cement is used, compaction has to be performed quickly after mixing, although this is less critical for slower-setting binders. As expected, poor compaction leads to low strength. In addition to these key elements, the in-situ method may also involve:

- Site investigation.
- Laboratory testing of old materials.
- Preliminary testing of mix design.
- Surface preparation by trimming and rolling to the finished profile.
- Cement or binder addition at a rate/m² in accordance with the mix design.
- Rotovation and addition of water to achieve optimal moisture content.
- Trimming and rolling of treated layer.
- Application of curing membrane.
- Density and strength measurements.

In terms of the benefits associated with using the in-situ method, huge cost savings are generated due to limited material transportation. Furthermore, when dealing with clayey soils, the in-situ method may be the only suitable method for mixing. In-situ production can also be performed in built-up areas where concerns of dust pollution are negated through the use of special machinery which enables a dust-free work environment. However, on-site production may only be economically viable for site areas greater than 10,000 m², which effectively excludes trench reinstatements, with HBM ready-mix materials considered the only alternative for such smaller-sized areas. An example of in-situ HBM production for highway works is shown in Figure 2.2.

Figure 2.1 – Key elements of in-situ HBM production
(Britpave, 2007a)
2.4.2  Ex-situ plant production

The types of aggregates used in HBM plant production must comply with BS EN 13242 (CEN, 2002). Plant-produced HBM is generally of higher quality than in-situ produced HBM due to better production control. The HBM plant process involves:

- Laboratory mixture design.
- Stockpile aggregate as opposed to in-situ aggregate.
- Mix in mobile or fixed plant.
- Transport to construction site.
- Tipping, spreading and compacting of the material.

Recycled materials and aggregates are taken from stockpiles and mixed with binder (such as lime, cement or fly ash) and water and then transported to site for laying and compaction. HBM can be compacted in multiple layers as required with the time to compaction being dependant on the binding agent (fast or slow setting binders). Figure 2.3 presents a schematic of how HBM is produced ex-situ.

![Figure 2.2 – In-situ HBM production for highway works](Britpave, 2004)

![Figure 2.3 – Plant production of HBM for highway works](Britpave, 2007b)
An example of an ex-situ site is shown in Figure 2.4. Recycled aggregates are available throughout the UK, primarily in areas with few resources of crushed rock, such as in the South and East of England, whereas the demand is lower in Scotland, the North and West of England, Wales and Northern Ireland due to plentiful resources of crushed rock.

![Figure 2.4 – Ex-situ HBM batch plant (WRAP, 2005b)](image)

### 2.5 Summary

In summary, the advantages of using not only HBM, but recycled and secondary aggregates in HBM, are as follows:

- HBM construction is popular and versatile in terms of availability of plant and materials.
- HBM can be produced by “ex-situ” or “in-situ” equipment.
- The equipment needed for laying and compacting HBM is similar to that used for laying and compacting unbound layers and bituminous bound products.
- On-site materials, such as excavated soil or demolition wastes, can be re-used for some HBM which, in turn, reduces the need to import virgin materials as well as avoid aggregate fees and disposal costs.
- By-products of local power stations and metal works such as fly-ash and slag can be incorporated in HBM design.
- HBM has become a more attractive feature in vying for project bids because of its green procurement credentials which can meet the client’s requirements.
- HBM strength and stiffness increases with time especially with HBM mixtures which are slow setting and slow hardening.
- HBM can be used to up-cycle waste material which is initially not suitable for recyclable use.

The installation process of HBM material is critical to the success of the material. If HBM is not laid as specified, the subsequent performance of the material is reduced significantly.
3 HBM specifications and test methods

3.1 General

Due to continued pressure from environmental agencies and government institutions, the need to use recycled materials is increasing, and the standards typically used to regulate construction materials are changing. The inclusion of recycled and secondary materials in current European and UK standards and specifications has greatly increased the demand for these materials. The most important specification for construction in the UK is the Specification for Highway Works (HA et al., 2011a) with detailed information on the use of hydraulically bound materials being provided in the 600 and 800 clauses. This specification covers work performed on primary and secondary routes, as well as other areas of construction. The revision of the SHW in 2001 enabled the use of RSA in highway works as well as other sectors, provided measures are taken to ensure quality control.

Standards for HBM applications were commissioned by the European Committee for Standardisation (CEN) in 2005 and are either already in place or are being prepared and have to be implemented in, currently, 32 European countries. Aggregates should comply with BS EN 13242 (CEN, 2007) whilst HBM s including water shall comply with BS EN 14227-12 (CEN, 2006). Specifications for cement bound granular mixtures (CBGM) are set forth in BS EN 14227-1 (CEN, 2004). A list of the current European standards in use for HBM pavement applications is:

- BS EN 13242 (CEN, 2007), Aggregates for unbound and hydraulically bound materials for use in civil engineering work and road construction.
- BS EN 13286 (CEN, 20030, Unbound and hydraulic bound mixtures – Test methods (20 parts).
- BS EN 14227 (CEN, 2004), Unbound and hydraulic bound mixtures – Specifications (10 parts).

As mentioned earlier, the SHW (HA et al., 2011a) and HD 35/04 (HA et al., 2004) provide information on different materials that can be used in HBM design and subsequent pavement applications. Application of HBMs in pavement construction is also covered in a number of Highways Agency specification documents which include:

- Interim Advice Note 73/06 (HA et al., 2006a), Design guidance for road pavement foundations.
- HA 74/07 (HA et al., 2007), Treatment of fill and capping materials using either lime or cement or both.
- HA 35/04 (HA et al., 2004), Conservation and the use of secondary and recycled materials.
- HA 26/06 (HA et al., 2006b), Pavement design.
- Specifications for Highway Works (HA et al., 2011a), in particular Series 600 (Earthworks) and Series 800 (Road pavements - unbound, cement and other hydraulically bound mixtures).
- Notes for Guidance on the Specifications for Highway Works (HA et al., 2011b).

According to the British In-situ Concrete Paving Association (Britpave), no British Standards are superseded by the European Standards for HBM because, prior to their introduction in 2004, the requirements for HBM were given in the SHW or other specifications based on the SHW. However, the European Standards significantly extend
the range of HBM because previously the SHW was limited to cement bound materials (CBM) (Bripave, 2005a).

3.2 UK and European based specifications

Many of the current HBM standards which are implemented in the UK are taken from standards set forth by CEN. Some of the European standards for HBM pavement applications adapted by the UK are listed above. A more detailed description of these standards is presented as follows:

- DD ENV 13282 (CEN, 2000), Hydraulic road binders — Composition, specifications and conformity criteria.

BS EN 14227-1 covers mixtures bound with cement conforming to the cement standard BS EN 197–1 (CEN, 2011). It also includes the combination of cement with ground granulated blast-furnace slag added separately at the mixing stage. Table 3.1 summarises the types of HBM mixtures covered by BS EN 14227-1 (CEN, 2004).

<table>
<thead>
<tr>
<th>Type of mixture</th>
<th>Suggested designation</th>
</tr>
</thead>
<tbody>
<tr>
<td>CBGM with permitted grading envelope “A” for the aggregate. This covers wide-graded mixtures encompassing sand mixtures and mixtures made from either crusher run, as-raised materials or demolition aggregates etc.</td>
<td>CBGM A</td>
</tr>
<tr>
<td>CBGM with permitted grading envelope “B” for the aggregate. This produces a 31.5 mm well-graded mixture</td>
<td>CBGM B</td>
</tr>
<tr>
<td>CBGM with tightly-graded mixture requirements producing either 20, 14 or 10 mm well-graded mixtures</td>
<td>CBGM C 0/20 or C 0/14 or C 0/10</td>
</tr>
</tbody>
</table>

BS EN 14227-2 (CEN, 2004) covers mixtures based on the hardening properties of slags produced as a by-product of the manufacture of iron and steel. Two types of slag bound mixtures (SBM) are included, designated A and B.

- The A mixtures are generally all-slag mixtures comprising two or more of the following: air-cooled blast furnace slag, air-cooled steel slag and granulated blast-furnace slag, although the use of non-slag aggregate is permitted. Apart from grading, there are no specified requirements for the various slags.
• The B mixtures use the combination of granulated blast furnace slag of specified properties, with either lime or a lime/gypsum combination or steel slag as a catalyst. They are faster setting and hardening compared with the A mixtures although considerably slower than cement bound mixtures.

BS EN 14227-3 (CEN, 2004) covers mixtures based on the hydraulic and/or pozzolanic properties of fly ash. Two types of ash are covered: calcareous fly ash (CaFA) and siliceous fly ash (SiFA). The type of ash depends on the nature of the coal burnt in the power station.

• CaFA is hydraulic in its own right and needs no additional constituents for hydraulic reaction. It sets and hardens at a similar rate to cement. However, it is not available in this country because the type of coal that produces such ash is not burnt in the UK.

• SiFA is a pozzolan and, thus, needs to be combined with lime for hydraulic reaction to take place. As with SBM, the lime/SiFA reaction is slow. If necessary, gypsum can be added to the lime/SiFA combination, or cement used instead of lime, but both these compromise the slow setting and hardening. In these cases, the mixtures set and harden similarly to the BS EN 14227-1 (CEN, 2004) mixtures. SiFA is widely available in the UK.

The setting and hardening of non-cement mixtures is slow compared with CBM and extremely protracted when ambient temperatures are lower than 5 °C. Therefore, careful consideration needs to be given to their use in the late autumn and winter months. However, in comparison with mixtures containing cement, the slower setting and hardening produces mixtures that:

• Exhibit extended handling time between production and compaction.
• Are immediately trafficable even under heavy traffic.
• Have a reduced tendency to crack, leading to less reflective cracking and thus the possibility of reduced asphalt cover.
• Exhibit autogenous healing (the ability to self-heal) when distressed in early life by traffic or earthworks settlement.
• Attain similar ultimate structural properties to CBM so that thickness design is similar to CBM.

BS EN 14227-4 (CEN, 2004) specifies the requirements for fly ash, both siliceous and calcareous, for use in HBM. BS EN 14227-5 (CEN, 2004) covers mixtures based on hydraulic road binders complying with ENV 13282 (CEN, 2000). These mixtures are factory produced blends primarily of SiFA or granulated blast furnace slag, usually but not exclusively with small quantities of lime and gypsum. As their name suggests, they are purpose-made hydraulic binders for road use producing HBM with extended handling time during construction. Their mechanical performance is similar to CBM at 7 days, as is their long-term performance. Table 3.2 summarises the types of mixtures covered by EN 14227-2, -3 and -5.
Table 3.2 – Type of HBM covered by BS EN 14227-1, -2, -3 and -5

<table>
<thead>
<tr>
<th>Type of Mixture</th>
<th>Part 1 Cement Bound Granular Mixtures (CBGM)</th>
<th>Part 2 Slag Bound Mixtures (SBA)</th>
<th>Part 3 Fly Ash Bound Mixtures (FABM)</th>
<th>Part 5 Hydraulic Road Binder Bound Mixtures (HRBBM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Graded slag without specified binder requirements</td>
<td>-</td>
<td>SBM A1 - A5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>31.5 mm wide graded mix (incl. sand mixes)</td>
<td>CBGM A</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>31.5 mm well graded mixes</td>
<td>CBGM B</td>
<td>SBM B1</td>
<td>FABM 1</td>
<td>HRBBM 1</td>
</tr>
<tr>
<td>0/20, 0/14, 0/10 mm well graded mixes with compacity requirement</td>
<td>CBGM C 0/20, 0/14, 0/10</td>
<td>SBM B2 0/20, 0/14, 0/10</td>
<td>FABM 2 0/20, 0/14, 0/11</td>
<td>HRBBM 2 0/20, 0/14, 0/12</td>
</tr>
<tr>
<td>Sand mixes with Immediate Bearing Index (IBI) requirement</td>
<td>-</td>
<td>SBM B3</td>
<td>FABM 3</td>
<td>HRBBM 3</td>
</tr>
<tr>
<td>Mixes with declared grading and other properties if appropriate</td>
<td>-</td>
<td>SBM B4</td>
<td>FABM 4</td>
<td>HRBBM 4</td>
</tr>
<tr>
<td>Treated fly ash mix</td>
<td>-</td>
<td>-</td>
<td>FABM 5</td>
<td>-</td>
</tr>
</tbody>
</table>

The above parts cover hydraulically treated aggregates. They are “open” regarding the property requirements for the “aggregate”, which have to be selected by the user or specifier by reference to BS EN 13242 (CEN, 2007). They are also “open” concerning strength, whereby the user or specifier selects the appropriate class of strength. Table 3.3 lists the permitted constituents for HBMs specified in BS EN 14227-1, -2, -3 and -5 (CEN, 2004).

Table 3.3 - Permitted constituents of HBM mixtures for use in UK (Britpave, 2005a)

<table>
<thead>
<tr>
<th>BS EN 14227</th>
<th>Aggregate</th>
<th>Cement</th>
<th>GBS</th>
<th>ASS</th>
<th>Lime</th>
<th>Gypsum</th>
<th>CaFA</th>
<th>SiFA</th>
<th>HRB</th>
<th>Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Part 1: Cement bound granular mixtures</td>
<td>BS EN 13242</td>
<td>BS EN 197-1</td>
<td>GGBS national regulation</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>Yes</td>
</tr>
<tr>
<td>Part 2: Slag bound mixtures</td>
<td>BS EN 13242</td>
<td>N/A</td>
<td>BS EN 14227-2</td>
<td>BS EN 14227-2</td>
<td>BS EN 14227-11</td>
<td>Requirements are open</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>Yes</td>
</tr>
<tr>
<td>Part 3: Fly ash bound mixtures</td>
<td>BS EN 13242</td>
<td>BS EN 197-1</td>
<td>BS EN 14227-2</td>
<td>BS EN 14227-11</td>
<td>BS EN 14227-3</td>
<td>BS EN 14227-4</td>
<td>BS EN 14227-4</td>
<td>N/A</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Part 5: HRB bound mixtures</td>
<td>BS EN 13242</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>ENV 13282</td>
<td>Yes</td>
</tr>
</tbody>
</table>
The next set of standards, shown below, cover the treatment of soils and thus require no reference to BS EN 13242 (CEN, 2002). In these, the term soil is wider than normal, covering natural material as well as industrial by-products and recycled materials.

- BS EN 14227-10 (CEN, 2004), Hydraulically bound mixtures — Specifications — Part 10, Soil treated by cement.
- BS EN 14227-11 (CEN, 2004), Hydraulically bound mixtures — Specifications — Part 11, Soil treated by lime.
- BS EN 14227-12 (CEN, 2004), Hydraulically bound mixtures — Specifications — Part 12, Soil treated by slag.
- BS EN 14227-13 (CEN, 2004), Hydraulically bound mixtures — Specifications — Part 13, Soil treated by hydraulic road binder.
- BS EN 14227-14 (CEN, 2004), Hydraulically bound mixtures — Specifications — Part 14, Soil treated by fly ash.


### 3.3 Material property testing

#### 3.3.1 General

The standards for HBM use in pavement applications have already been listed in Chapter 2. In addition, laboratory test methods are employed by countries throughout Europe as well as in the UK. Laboratory testing to determine density and water contents follow BS EN 13286 1-5, 2003 based on compaction method or sampling technique:

- BS EN 13286-1 (CEN, 2003), Unbound and hydraulically bound mixtures — Part 1, Test methods for laboratory reference density and water content — Introduction, general requirements and sampling.
- BS EN 13286-2 (CEN, 2010), Unbound and hydraulically bound mixtures — Part 2, Test methods for the determination of the laboratory reference density and water content — Proctor compaction.
- BS EN 13286-3 (CEN, 2003), Unbound and hydraulically bound mixtures — Part 3, Test methods for laboratory reference density and water content — Vibro-compression with controlled parameters.
- BS EN 13286-4 (CEN, 2003), Unbound and hydraulically bound mixtures — Part 4, Test methods for laboratory reference density and water content — Vibrating hammer.

Laboratory test methods vary from direct and indirect tensile strength tests, compressive strength test, modulus of elasticity, to California Bearing Ratio (CBR) test. The following test methods are listed:

- BS EN 13286–40 (CEN, 2003), Unbound and hydraulically bound mixtures – Part 40, Test method for the determination of the direct tensile strength of hydraulically bound mixtures.
- BS EN 13286–41 (CEN, 2003), Unbound and hydraulically bound mixtures – Part 41, Test method for the determination of the compressive strength of hydraulically bound mixtures.
Hydraulically bound materials

- BS EN 13286–42 (CEN, 2003), Unbound and hydraulically bound mixtures – Part 42, Test method for the determination of the indirect tensile strength of hydraulically bound mixtures.
- BS EN 13286–43 (CEN, 2003), Unbound and hydraulically bound mixtures – Part 43, Test method for the determination of the modulus of elasticity of hydraulically bound mixtures.
- BS EN 13286–47 (CEN, 2006), Unbound and hydraulically bound mixtures – Part 47, Test method for the determination of the California bearing ratio, immediate bearing index and linear swelling.

Manufacturing of HBM test specimens is done using different compaction methods following test methods:
- BS EN 13286–50 (CEN, 2004), Unbound and hydraulically bound mixtures – Part 50, Method for the manufacture of test specimens of hydraulically bound mixtures using Proctor equipment or vibrating table compaction.
- BS EN 13286–51 (CEN, 2004), Unbound and hydraulically bound mixtures – Part 51, Method for the manufacture of test specimens of hydraulically bound mixtures by vibrating hammer compaction.
- BS EN 13286–53 (CEN, 2004), Unbound and hydraulically bound mixtures – Part 53, Method for the manufacture of test specimens of hydraulically bound mixtures by axial compression.
- prEN 13286-54 (CEN, 2011), Unbound and hydraulically bound mixtures - Part 54: Test method for the determination of frost susceptibility - Resistance to freezing.

With regards to prEN 13286-54, this standard has yet to be approved. It is very important in terms of designing HBM, where studies have shown that lack of binder contributes to poor strength and susceptibility of pavement layers to frost heave. Therefore, consideration for these issues must be addressed during design.

### 3.3.2 HBM durability in pavements

Durability of HBM is important because failure in the HBM layer can result in poor performance of the adjacent layers in a pavement. Durability of HBM is determined by the aggregate and the mixture itself, and the expected performance of the material is a function of the application (expected mechanical performance), environmental conditions and position within the pavement. The aggregate must be durable to mechanical breakdown and the mixture must be volumetrically stable (Smith and Collis, 2001). The following (environmental and non-environmental) factors are likely to influence the durability of HBM (WRAP, 2007a):

- Volumetric changes (thermal expansion).
- Deterioration (including fragmentation) of unsound aggregate.
- Sensitivity of the HBM to water (frost heave).
- Chemical attack/aggressive ground.
- Adverse curing conditions (low temperatures, lack of water, drying shrinkage).
- The presence of organic material and clay which may limit strength gains (organic impurities interfere with the hydration reaction).
The Series 800 of clauses in the SHW (HA et al., 2011) and BS EN 13286-41 to -43 (CEN, 2003) are the specifications most often applied for durability testing. Series 800 uses a combination of aggregate threshold values, durability test criteria, and empirical datasets to determine the performance of the materials.

From these specifications, mechanical performance of HBM can be divided into two systems based on:

(i) an indirect method such as compressive strength, or
(ii) a combination of tensile strength and modulus of elasticity.

Performance analysis of HBM based on compressive strength is considered as generic guidance. Therefore, care must be taken when relating expected performance to generic values as many factors which affect HBM performance are not accounted for. Furthermore, curing time is crucial to the durability test because the permeability and strength of HBM change with time. For frost heave, HBM s with compressive strength of 4.5 MPa or greater are assumed to have good frost resistance according to the SHW (HA et al., 2011a). The volumetric stability test is in accordance with Clause 880.4 and is very important in identifying potential swelling in certain aggregates (primary, secondary, and recycled) which may contain some naturally occurring sulphides/sulphates.

In summary, the better the mechanical performance of HBMs, the more resistant they are to weathering. In particular, factors such as aggregate gradation, requirements for immediate trafficking and laying temperature, are critical to attaining acceptable durability.

### 3.3.3 HBM durability in reinstatements

All the factors described above are likely to be relevant the durability of HBMs when used in reinstatements. However, there are concerns regarding the use of HBMs in utility trenches when constructed in pavements that are below current design standards. This topic is discussed further in section 4.3.3.
4 HBM construction and products

4.1 HBM design for major roads

The application of HBM in major highways has been well documented in many studies (Chaddock and Atkinson, 1997; Chaddock and Roberts, 2008; Reid, 2011). The sub-base layer is very important in terms of the expected performance of the pavement. The sub-base layer is often the main load carrying component of the pavement and is designed to distribute the stresses and strains exerted from passing traffic loads, to the foundation. A strong road-base will prevent shear failure or deformation, also known as rutting, in the overlying asphalt layer. In addition to providing strength, a well designed and constructed road-base will provide good drainage and prevent settlement. Aggregates used in sub-base layers usually contain good interlocking properties, allowing traffic loads to be evenly distributed through the layer and the underlying layers. Crushed aggregates are generally recommended for road-base materials. There are two types of materials which can be used in sub-base layers: unbound granular materials and hydraulically bound materials. The use of an HBM sub-base or base can significantly reduce the required thickness of pavement layers. In addition, the compaction process time is reduced when compared with un-bound mixtures, which also significantly reduces health and safety issues related to hand arm vibration syndrome. The key elements for construction of HBM layers are as follows:

- Site investigation
  - Pre-construction assessment
  - Site preparation

- HBM Design
  - Identify binders
  - Find optimum moisture content for good compaction conditions
  - Confirm binder content
  - Assess strength gain and rate of gain
  - Drainage

- HBM Construction
  - In-situ (Sub-Section 2.4.1)
  - Ex-situ (Sub-Section 2.4.2)

- Quality control testing where testing is conducted on samples manufactured from mixed HBMs

- Grading of the surface to form a final level

- Sealing of the surface with a bitumen emulsion to maintain its moisture content during curing

Specifications for construction of HBM pavement layers can be found in TRL 611 (Merrill et al., 2004) and TRL615 (Nunn, 2004). Interim Advice Note IAN 73/06 (HA et al., 2006a) describes the current design methodology adopted by the UK Overseeing Organisations. The design thickness of HBM layers can be determined using IAN 73/06 for foundations and HD 26/06 (HA et al., 2006b) for pavements. Figure 4.1 illustrates the laying and compaction processes of HBM pavement layers.
4.2 HBM design for minor roads

In addition to providing guidance on the application of HBM in major highways, work has also been done to provide guidance on the application of HBM on minor roads (residential or commercial roads). TRL611 (Merrill et al., 2004), which followed on from TRL386 (Milton and Earland, 1999) where the HBM was made exclusively using cement, discusses the use of HBM in minor roads and, in particular, discusses ex-situ work as well as slow setting and hardening HBM materials. TRL611 broadens the scope to include HBM made from other hydraulic combinations including cement with either fly ash or GGBS, and lime with fly ash or GGBS. The use of RSA in HBM design is also examined and thickness designs are specified for roads carrying up to 5 MSA. However, there is some difference between the two TRL reports with TRL 611 being somewhat more conservative regarding HBM strength recommendations. Therefore, it is recommended by the WRAP guidelines for minor roads that, providing it is safe to do so, TRL 386 recommendations for CBM strength can be used for HBM which is designed to TRL 611 specifications (WRAP, 2005a). It should be noted that the guidelines provided by TRL 611 and TRL 386 are only for HBM design with asphalt surface courses.

4.3 HBM in trench reinstatements

4.3.1 General

According to WRAP (2005c), maintenance and utility trench works material accounts for 4.5% of the total construction, demolition and excavation waste generated in the UK. Since then, there has been a major push in the use of HBM in trench reinstatements. HBM use in trench reinstatements includes Alternative Reinstatement Materials (ARM), which is outlined in Appendix A9 of the SROR (RAUC(S), 2003). Two groups of materials make up ARMs: structural materials for reinstatement (SMR) and structural materials for fills (SMF). SMFs include excavated spoil, virgin materials, secondary recycled or waste
Hydraulically bound materials, or any combination thereof, that have been improved by re-processing, regarding and/or by the inclusion of a cementitious, chemical or hydraulic binder. SMFs are generally non-flowable and therefore normally require compaction and are only considered for use by trial agreement.

The SROR defines SMR as a group intended to include proprietary or alternative bound reinstatement materials that include cementitious, chemical, or hydraulic binder, or are inherently self-cementing. The group is divided into the following three sub-categories:

- Foamed concretes for reinstatements (FCRs).
- Flowable SMRs (FSMRs).
- Non flowable SMRs (NFSMRs).

FCRs use cement or proprietary binders generally as prescribed mixtures or foaming process, while FSMRs comprise any type and/or combination of aggregates and binders; both are flowable and should not require compaction. NFSMRs, like the FSMRs, can comprise any type and/or combination of aggregates and binders but are not flowable so require in-situ compaction (WRAP, 2007b). All SMRs except FCRs, require approval based on trials. Foamed concrete is the most commonly used SMR and some of its advantages include:

- Ease of application due to self-compacting and self-levelling properties.
- Lightweight and easy to excavate due to air voids introduced in foam.
- Early strength gain with re-surfacing possible within 12–18 hours after placement.
- Good load distribution, preventing the direct transmission of axial loads to the services.

In addition, studies (Jones et al., 2005) have shown that foam concrete can accommodate RSA providing it complies with the SHW specifications (HA et al., 2011a). An example of trench excavation and reinstatement using recycled HBM materials is shown in Figure 4.2.

![Figure 4.2 – Trench excavation and reinstatements using HBM](WRAP, 2009b)
4.3.2 Specifications

The SROR is the statutory document for street works in Scotland (RAUC(S), 2003) and it details where HBM is permitted for use (including road class and minimum depth), along with the technical guidance for use. The SROR is in the process of being updated with expected publication in 2013. In the current version, SMRs are only recommended for sub-base or base reinstatements and must pass the following compressive strength criteria, as specified by the SROR (RAUC(S), 2003):

- 2 to 10 N/mm² at 90 days for sub-base layers (100 mm to 150 mm) and all layers below the binder course (200 mm to 450 mm).
- 4 to 10 N/mm² at 90 days for base and sub-base layers (450 mm).

A similar code of practice is available for England by the Highway Authorities and Utilities Committee (UK) (HAUC(UK), 2002). Approved HBM that comply with BS EN 14227 (CEN, 2004) and also the SHW Series 800 clauses (HA et al., 2011a) do not require an approval trial to Appendix A9 of the SROH (HAUC, 2009) or, presumably, the SROR. A summary of HBM designation and corresponding BS EN 14227 standard is shown earlier in Table 3.2. A schematic illustrating the key elements involved in selecting HBMs and other sustainable materials for trench reinstatements is shown in Figure 4.2.

![Figure 4.3 – Framework for HBM use in trench reinstatements in England (WRAP, 2009b)](image-url)
4.3.3 Limited findings on HBM use

Although in general pavement construction and in some utility trenches where HBM materials have shown to perform well, there are concerns regarding its use in utility trenches within pavements that are below current design standards, i.e. insufficient bound material, thin sub-base, poor groundwater control, weak sub-base, etc. Such conditions are common within the local road network in Scotland. Essentially these concerns strongly relate to the impact on a carriageway adjacent to the trench containing HBM, i.e. it will be too strong and may behave like a concrete dyke, possibly preventing drainage paths and leading to moisture damage due to water ingress/ponding. Such concerns only highlight the fact that there has been very little research conducted to assess the performance of HBM relevant to the conditions described above. The subsequent use of trials is recommended to properly address these concerns.

4.4 HBM proprietary products

4.4.1 EcoFILL

EcoFILL is a HBM proprietary product primarily designed to be used as a utility trench backfill using processed arisings as the base aggregate content of the mix and fly ash as the binding agent. It is compliant with both British and European standards and can be used as an alternative to Type 1 sub-base without the need to carry out trials. The processing of EcoFILL includes certain key elements:

- Using a mixing plant that batches the aggregate by volume and binders by weight.
- Forced action mixing to ensure clay is broken down.
- Production control records.
- Moisture addition in accordance with BS EN 14227 (CEN, 2004).

In terms of manually handling this product, EcoFILL must be treated in the same way as concrete. To ensure superior performance, the product must be compacted to the same extent as SHW Type 1 material (in accordance with SROH Appendix A8.1), and exposure to excess moisture during compaction must be avoided. EcoFILL is manufactured at the optimum moisture content for compaction and can be stored for up to 14 days (336 hours) before use, providing the moisture content is not affected during this period. According to the product website, EcoFILL product testing is typically carried out by a UKAS accredited Laboratory (EcoFILL 40 Sustainable Fill Material, 2011). Online HAUC records of Appendix A9 trials showed that local authorities such as Herfordshire CC and West Sussex approved the use of EcoFILL for street works reinstatements (Database of Street Works Recycling, accessed 09/2012).

4.4.2 Lafarge Aggregates and Bardon Composite Pavements

Lafarge Aggregates and Bardon Composite Pavements are two of the biggest pavement construction companies in the UK. These two companies provide on-site production of HBM using local site materials or secondary aggregates, as well as specialist equipment and technical expertise in construction of HBM pavements. Lafarge Aggregates provide a variety of products including Axopave which can be used for HBM design as well as a variety of other pavement applications. Similarly, Bardon Composite Pavements offers a wide range of HBM including CBGM, Roller Compacted Concrete (RCC), FABM, SBM, and Bentonite Enriched Soil (BES). However, these companies look to offer a more large
Hydraulically bound materials

scale production of HBM and smaller projects such as trench reinstatements may not be suitable. No literature was found on the performance of these HBM materials.

4.4.3 SMARTR PV1

O’Keefe Limited are a company based out of London who have designed and developed an operation for recycling utility and construction waste for highway reinstatement use and varying pavement applications. The operation is called SMARTR - Stabilising Materials from Arisings – Re-grading and Treating for Re-use. The operation involves segregation, screening, grading, and manufacturing HBMs which comply with industry standards. Soil materials are stabilised using binders and arisings from trench excavations and other construction projects are treated for HBM use. The candidate HBMs go through rigorous tests in order to achieve compliancy with BS EN standards. Some of the testing includes:

- Waste Acceptance Criteria (WAC) contamination analysis (WRAP requirement).
- Sulphate/organic analysis.
- Particle size distribution.
- Moisture content and optimum water content by compaction test.
- Compressive strength.
- Immediate bearing index.
- Strength after immersion.
- Fines quality.
- Workability period.
- Frost susceptibility test.

The material that O’Keefe produces from SMARTR goes under the trade name of PAVIMENTUM or PV1. The HBM product should be used on the day of production, usually within eight hours of manufacture (www.o’keefe.co.uk). PV1 is classified as a CBGM1 material as it is produced in accordance with BS EN 14227-1 (CEN, 2004) and can be trafficked immediately after laying once compacted and surfaced. In particular, the compressive strength requirements of BS EN 13286-41 (CEN, 2004) are met with test results showing varying strength from 4 to 5.6 N/mm² at 28 days (www.o’keefe.co.uk). However, no information on trialled results on this HBM product has been found.

4.4.4 SMR Premixed

SMR Premixed is a proprietary recycling process utilising SMR soil stabilisers to manufacture HBMs. SMR Premixed has been available in the UK since 1999 and has a proven track record through numerous trials and local approvals across the highway network. SMR Premixed is considered an NFSMR material and is predominantly used as a reinstatement material for subbase and base layers. SMR Premixed is extremely easy and safe to use; excavated spoil is mixed with the right dosage of SMR and after 15 minutes of curing, the mix is ready for compaction. Once compacted, application of a wearing course can be placed immediately. A study by the Hampshire County Council Technical Advice Group showed that SMR Premixed had a consistent compressive strength of between 2 N/mm² and 4 N/mm² after 90 days. Subsequent testing of the pavement some two years later showed good results with performances equivalent to or greater to what is normally associated with conventional granular sub-base materials. In particular, this study showed that SMR Premixed meets the requirements of a C1.5/2 NFSMR as specified under Appendix A9 of SROH (www.smruk.com).
4.4.5 Trenchmix

Trenchmix is a slow setting slow hardening HBM which consists of PFA, lime, and recycled fines from a local recycling plant. Trenchmix is produced by a recycling company based in the West Midlands of England called Shropshire Recycling Services (SRS). The main component of Trenchmix is the surplus fines produced from the recycling plant while the PFA is sourced from a local coal burning power station. The presence of lime in the HBM mix acts as a catalyst to the PFA in providing the long-term strength. Once compacted, the HBM mix can support immediate surfacing and traffic loading. A laboratory investigation into the performance of the HBM showed promising results. However, full-scale road trials of the HBM product showed poor compressive strength and failure due to frost heave (Kennedy, 2002). Possible reasons for such a poor performance include lack of binder (lime or PFA) which contributed to a variable trial mixture. In 2002, the construction of a public sewer in rural Worcestershire by Wrekin Construction Ltd used Trenchmix as a trial (WRAP, 2007b). Due to the large variety of axle loading (cars, vans and heavy goods vehicles), this site was considered an ideal location for a trial. No problems were observed since the project was completed and the performance was noted as good.

4.4.6 Trenchmod

Trenchmod is a proprietary recycling process utilising on-site excavated material with soil stabilizers to manufacture HBMs. According to the product information, Trenchmod materials can produce strength in excess of Type 1 aggregate when compacted back into excavations. Trenchmod materials are independently tested by UKAS Laboratories to ensure it complies fully with the Highways and Utilities Committee on the use of HBMs. The quality of output is also guaranteed by testing before leaving the process area. The product remains as a granular material until it is laid and when compacted, a slow cementing action in the material is triggered, which significantly increases its strength. The material can be stored up to six weeks. Trenchmod material is very similar to handle as Type 1 and does not cause damage to tree roots or cause contamination of groundwater. Trenchmod is considered non-frost susceptible so it can be used up to the bottom of the base layer (www.keanes.co.uk). Trials using the Trenchmod process show that the material meets the requirements for SMR with a strength of between 2 N/mm² to 5 N/mm² and can, therefore, be used as a base (WRAP 2004).

4.4.7 Summary

Table 4.1 summarises the properties of generic and proprietary HBM products during construction and while in service. In particular, the length of time allowed between manufacture and placement, the ease of placement, and the minimum time between placement and overlaying / trafficking is noted for each HBM material. Durability of the HBMs in terms of compressive strength taken at either 14 days, 28 days or 90 days is also included. As already mentioned, for generic HBM materials to be considered for trench reinstatement works, they must meet the durability criteria specified by the SRO (RAUC(S), 2003). HBM mixtures designed and manufactured in accordance with the SHW (HA et al., 2011a) Series 800 clauses are approved for use without the need for trials which is set in the Appendix A9 of the SRO (RAUC(S), 2003). Finally, the properties of a HBM product that has been trialled or otherwise assessed by independent investigators is also included in Table 4.1.
### Table 4.1 – Summary of Properties for Generic and Proprietary HBM Products

<table>
<thead>
<tr>
<th>Properties during construction</th>
<th>Generic Products</th>
<th>Proprietary Products</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CBGM</strong></td>
<td>CBGM</td>
<td>DreamFillPV1</td>
</tr>
<tr>
<td><strong>FABM</strong></td>
<td>FABM</td>
<td>Trenchmix</td>
</tr>
<tr>
<td><strong>SBM</strong></td>
<td>SBM</td>
<td>SMR Premixd</td>
</tr>
<tr>
<td><strong>HRBBM</strong></td>
<td>HRBBM</td>
<td>Trenchmix</td>
</tr>
<tr>
<td><strong>EcoFILL</strong></td>
<td>EcoFILL</td>
<td>Trenchmix</td>
</tr>
<tr>
<td><strong>SMARTRPV1</strong></td>
<td>SMARTRPV1</td>
<td>Trenchmix</td>
</tr>
<tr>
<td><strong>Storage time (h)</strong></td>
<td>1-35</td>
<td>1-8</td>
</tr>
<tr>
<td><strong>Time to trafficking (h)</strong></td>
<td>1-70</td>
<td>12</td>
</tr>
<tr>
<td><strong>Ease of placement</strong></td>
<td>Compaction required</td>
<td>0.25</td>
</tr>
<tr>
<td><strong>Durability: compressive strength</strong></td>
<td>24-336</td>
<td>6 weeks</td>
</tr>
<tr>
<td><strong>Durability: compressive strength</strong></td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td><strong>Properties from trials</strong></td>
<td>24-336</td>
<td>24</td>
</tr>
<tr>
<td><strong>SMR Premixd</strong></td>
<td>0.25</td>
<td>6 weeks</td>
</tr>
</tbody>
</table>

**Properties during service**

<table>
<thead>
<tr>
<th><strong>Storage time (h)</strong></th>
<th><strong>Time to trafficking (h)</strong></th>
<th><strong>Ease of placement</strong></th>
<th><strong>Durability: compressive strength</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CBGM</strong></td>
<td>1-35</td>
<td>Compaction required</td>
<td>At 90 days = 2-4 N/mm²</td>
</tr>
<tr>
<td><strong>FABM</strong></td>
<td>1-70</td>
<td>Sub-Clause 813.17</td>
<td>At 90 days = 2-4 N/mm²</td>
</tr>
<tr>
<td><strong>SBM</strong></td>
<td>200-1600 depending on lime addition</td>
<td>Immediately once compacted and surfaced</td>
<td>At 28 days = 4-5.6 N/mm²</td>
</tr>
<tr>
<td><strong>HRBBM</strong></td>
<td>Complies with BS EN 13286-45 by 17 (20°C)</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td><strong>EcoFILL</strong></td>
<td>24-336</td>
<td>NA</td>
<td>At 90 days = 2-4 N/mm²</td>
</tr>
<tr>
<td><strong>SMARTRPV1</strong></td>
<td>1-8</td>
<td>NA</td>
<td>At 90 days = 2-4 N/mm²</td>
</tr>
<tr>
<td><strong>Trenchmix</strong></td>
<td>NA</td>
<td>NA</td>
<td>At 90 days = 2-4 N/mm²</td>
</tr>
<tr>
<td><strong>SMR Premixd</strong></td>
<td>NA</td>
<td>NA</td>
<td>At 90 days = 2-4 N/mm²</td>
</tr>
</tbody>
</table>

**Properties from trials**

<table>
<thead>
<tr>
<th><strong>Storage time (h)</strong></th>
<th><strong>Time to trafficking (h)</strong></th>
<th><strong>Ease of placement</strong></th>
<th><strong>Durability: compressive strength</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CBGM</strong></td>
<td>24-336</td>
<td>Compaction required</td>
<td>At 90 days = 2-4 N/mm²</td>
</tr>
<tr>
<td><strong>FABM</strong></td>
<td>NA</td>
<td>Sub-Clause 813.17</td>
<td>At 90 days = 2-4 N/mm²</td>
</tr>
<tr>
<td><strong>SBM</strong></td>
<td>NA</td>
<td>Immediately</td>
<td>At 28 days = 4-5.6 N/mm²</td>
</tr>
<tr>
<td><strong>HRBBM</strong></td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td><strong>EcoFILL</strong></td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td><strong>SMARTRPV1</strong></td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td><strong>Trenchmix</strong></td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td><strong>SMR Premixd</strong></td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>

**Durability: compressive strength**

- At 90 days = 2-4 N/mm²
- At 90 days = 2-4 N/mm²
- At 90 days = 2-4 N/mm²
- At 90 days = 2-4 N/mm²
- At 90 days = 2-4 N/mm²
- At 90 days = 2-4 N/mm²
4.5 Distresses with HBM paving applications

4.5.1 General

A pavement containing HBM layers or a composite pavement may develop different types of distresses throughout its service life. Some researchers maintain that composite pavements behave similarly to flexible pavements due to the performance of the asphalt layer (Von Quintus et al., 1979). CBM base materials often experience naturally occurring thermal stress cracks, due to shrinkage during the curing period, which are seen in the asphalt surface due to reflective cracking. Reflective cracking is the most widely recognised pavement distress associated with composite pavements (Von Quintus, 1979; Smith et al., 1984; NCHRP, 2004). To counteract this distress, HBM layers can be pre-cracked in order to control the location and size of surface cracks (Ellis and Dudgeon, 2001). In doing so, maintenance costs can be reduced and more importantly, reduces the asphalt overlay thickness. Specifications for pre-cracking are set forth in the SHW (HA et al., 2011a). Other techniques used to mitigate reflective cracking include use of crack relief layers and geotextiles (paving fabrics) (Adaska and Luhr, 2004).

As stated earlier, the setting and hardening of non-cement HBM is slow compared with CBM, especially during low temperatures. Therefore, careful consideration needs to be given to non-cement HBM use in the late autumn and winter months. However, in comparison with mixtures containing cement, the slower setting and hardening produces mixtures that have a reduced tendency to crack, leading to less reflective cracking and thus the possibility of reduced asphalt cover. HBMs also exhibit self-healing properties when distressed in early life by traffic or earthworks settlement.

Other major pavement distresses which can seriously affect the performance and structural capacity of composite pavements include fracture (cracking), distortion and disintegration. However, these distresses can be mitigated with the right structural design and application of a high quality HMA surface mixture, along with proper construction measures.

In regards to HBM use in trench reinstatements, there is very little information as to the effect of the new material on the surrounding pavement. This issue is of particular concern in roads which are performing below the current design standards.

4.5.2 Methods to monitor HBM performance

The performance of HBMs can be monitored and assessed using a number of different techniques. Below is a list of monitoring procedures which have been implemented in previous studies:

- Extract cores at varying service times (i.e. after 3, 6, 12 and 24 months) and perform:
  - visual inspection
  - density
  - compressive and tensile strength
  - moisture content

- Perform falling weight deflectometer (FWD) tests to determine the stiffness of the HBM.

The dynamic cone penetrometer (DCP) has been used for in-situ testing of HBMs but has limited application, in terms of ability to penetrate HBMs with a compressive strength...
greater than 3 MPa. However, this type of test is useful in terms of assessing the performance versus depth of penetration and therefore, it is mainly used directly after compaction before the onset of compressive strength gains (WRAP 2008).
5 Further trials

5.1 SROR trials

There is an approved system for confirming the suitability of alternative reinstatement materials for use in reinstatements in Appendix A9.5 of both the SROR (HAUC(S), 2003) and SROH (HAUC(UK), 2010). This outline scheme for approval trials requires three separate sites to be monitored in order to show that an otherwise unapproved material does have the required properties for general use. However, most HBMs are covered in one of the parts of BS EN 14227 (CEN, 2003, 2004, 2010, 2011, 2012) and, as such, are excluded from the need for such trials even though HBMs are not specifically referred to in the SROR (HAUC(S), 2003). Appendix A9 trials will only be required for formal approval if the HBM does not comply with the standard, either in terms of grading or binder, which is not expected to be the case very often.

5.2 Research trials

Given that HBMs do not generally require trials for approval for general use and that there is already a system for approving other mixtures, there are only three possible reasons for carrying generic trials of HBMs:


(b) Checking that the approval for general use of one or more of the classes of HBM was appropriate.

(c) Obtaining a clearer ranking of the different classes of HBM for one or more properties, presumably including durability.

There are no generic classes of HBM not covered by BS EN 14227 known to the authors and, if there were any, there potential availability would need to be reasonably wide-scale in order to justify a generic trial rather than leave it to individual producers to obtain Appendix A9 approvals. Similarly, no evidence has been found that any class of HBM has not performed adequately when installed correctly whilst there is evidence of satisfactory performance. However, in the case of HBM use in weak pavements, there is no evidence indicating good or bad performances. Therefore, with current knowledge, the only remaining reason for a generic trial is option (c).

The subsequent performance of different classes of HBM in pavements similar to those found in the local road network in Scotland would be beneficial, particularly for trench reinstatements. Some idea as to the relative durability and strength, when compared with the adjacent pavement, as well as potential drainage issues which may occur would be of use to engineers when selecting the appropriate class of HBM. Such a trial would, ideally, involve a series of sections along the same road with different binders, replicated across a series of road classes and/or soil types and/or climatic regions if possible. The properties of interest could then be measured and correlated for each factor (binder type, road class, soil type, climatic region and time). The change of properties with time would not be required if only the early life properties are of interest.

If durability is the main issue to be investigated, the sites would need to be monitored for a considerable time, if only once a year, in order to get data on the final durability, although there may be pressure to remove all sections once some had come to the end
of their service lives. In order to obtain some result over a shorter time, the change of properties with time could be used. The suggested property would be the stiffness as found from falling weight deflectometer (FWD) measurements because it is non-destructive. However, it would still take several years before meaningful results could be obtained.

Therefore, research trials could be usefully carried out, but results would not be available for several years if durability was the main interest.
6 Conclusions and recommendations

The report presents a literature review on the state of practice on the application of hydraulically bound materials (HBM) in flexible pavements and trench reinstatements. The literature search contains views on the benefits and limitations of using HBM on major roadways throughout Europe and worldwide. From this literature review, the following conclusions can be made:

- HBM are defined as mixtures that set and harden by hydraulic reaction. They include:
  - cement bound materials (i.e. mixtures based on the fast setting and hardening characteristics of cement), and
  - slow setting and hardening mixtures made from industrial by-products such as fly ash (FA) and ground granulated blast furnace slag (GGBS).

- HBM in the United Kingdom is classified under different grades, based on the strength of binding agent and aggregate gradation. Different grades of HBM include:
  - soil cement;
  - cement stabilised soil;
  - lean concrete;
  - roller compacted concrete (RCC);
  - cement bound granular material (CBGM);
  - slag bound material (SBM);
  - fly-ash bound material (FABM);
  - hydraulic road binder bound material (HRBBM).

- Application of HBM is specified in BS EN 14227-1, -2, -3, -5, -10, -11, -12, -13 and -14, and shall be produced, handled, transported, used and tested in accordance with the SHW 800 series. The SROR provides technical guidance on the use of HBM in trench reinstatements in the Scotland. A similar code of practice is available in the UK by the HAUC.

- The advantages of using not only HBM but RSA in HBM in trench reinstatements are as follows:
  - HBM construction is popular and versatile in terms of availability of plant and materials.
  - HBM can be produced by “ex-situ” or “in-situ” equipment.
  - On-site materials, such as excavated soil or demolition wastes, can be re-used for some HBM which in turn reduce the need to import virgin materials, as well as avoid aggregate fees and disposal costs.
  - The use of HBM energy is efficient because there is significant energy savings associated with cold mix technology. In addition, by-products of local power stations and metal works such as fly-ash and slag are incorporated in HBM design.
  - HBM has become a more attractive feature in vying project bids because of its green procurement which meets the client’s requirements.
  - HBM mixtures designed and manufactured in accordance with the SHW Series 800 are approved for use without the need for trials which is set in the Appendix A9 of the SROR.
  - HBM strength and stiffness increases with time, especially with HBM mixtures which are slow setting and slow hardening.
  - Compaction process time is reduced when compared with un-bound mixtures, which also significantly reduces health and safety issues related to hand arm vibration syndrome.
  - HBM can be used to up-cycle waste material which is initially not suitable for recyclable use.
The use of an HBM sub-base or base can significantly reduce the required thickness of pavement layers.

- The limitations of using HBM in paving and non-paving applications include the following:
  - Property requirements for the aggregate are selected by the user and are considered “open” in regards to strength, whereby poor choice of the appropriate class of strength will lead to premature failure.
  - Lack of binder in HBM design contributes to poor strength and susceptibility to frost heave.
  - In-situ HBM production may only be economically viable for site areas greater than 10,000 m², which effectively excludes trench reinstatements, whilst HBM ready-mix materials are considered to be appropriate for such smaller-sized areas.
  - The use of HBM in trench reinstatements can affect pavement drainage due to differences in gradation/permeability with the adjacent material.

- The use of generic and proprietary HBM have shown good results in terms of placement, compaction, and durability. Reports from both in-service and trialled sections show that HBMs are a viable alternative to traditional base and sub-base materials. However, there is limited research on the effects that HBM trench reinstatements have on the surrounding pavement.

In general pavement construction, HBM trials are not considered necessary because HBM is covered by a European standard and is an approved material for general use. However, it is recommended that trials be performed in order to provide more information on the performance of HBM in trench reinstatements.

Finally, the installation process of HBM material is critical to the success of the material. Not unlike asphalt, if HBM material is laid under poor weather conditions or is not laid to the design standards, the subsequent performance of the material is reduced significantly. The contractor in charge of the operation must ensure that the proper equipment is used during the transportation and installation processes. In addition, the crew entrusted to perform the tasks are expected to have undertaken the proper training that is needed with the laying of such materials.
Acknowledgements

The work described in this report was carried out in the Infrastructure Division of the Transport Research Laboratory. The authors are grateful to Michael McHale for carrying out the technical review and auditing of this report. Special thanks to John Barritt from WRAP for his help and advice with this report.

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