Mineral Industry Research Organisation (MIRO)

MA/6/4/003: The use of quarry fines in hydraulically bound mixtures for construction applications

Guidance document

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EXECUTIVE SUMMARY

This guidance document covers the use of quarry fines in hydraulically bound mixtures (HBMs) for construction applications, specifically within pavement foundation layers.

This work was funded by the Minerals Industry Sustainable Technologies (MIST) programme in accordance with Thematic Priority 4: Optimising Resource Value (quarry product application).

A performance based approach is used throughout this guide, with reference made to the project technical report and associated findings which accompanies this guidance document. This document outlines the route for assessing the suitability of quarry fines (and other aggregate materials) for inclusion in HBMs for specified applications, with a range of traditional and alternative binders. Findings from laboratory research are discussed and guidance given on the design methods, and the performance and durability testing procedures necessary to ensure that durability requirements are met. Both environmental and non-environmental factors that could have an impact on the long-term performance of a HBM are also considered.

The document addresses the following areas;

- The materials and applications of HBMs
- Specification and compliance
- Design of a HBM for durability
- Application into pavement construction
- Trial sections

This guide does not provide specific guidance on issues such as layer thickness design and site specific considerations. Instead, it provides the signposts and background for readers to be able to access this information and relevant industry guidance, standards and specification documents. The guide concentrates on the application of HBMs into pavement foundation construction, with reference made to other applications areas where relevant.

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CONTENTS

GLOSSARY

Activator	Material which initiates hydraulic reactions
ASS	Air-cooled Steel Slag
BS EN	European Standard published by the British Standards Institution (BSI)
CBGM	Cement Bound Granular Mixture
CKD	Cement Kiln Dust
CEM I	Class 42.5N Portland Cement
CEM II	Class 32.5N Portland Cement (incorporating PFA)
DMRB7	Design Manual for Roads and Bridges, Volume 7: Specification for Highways Works
E_c	Modulus of elasticity (E) determined in compression, expressed in GigaPascals (GPa)
FABM	Fly Ash Bound Mixture
GBS	Granulated Blastfurnace Slag
GGBS	Ground Granulated Blastfurnace Slag
HBM	Hydraulically Bound Mixture
HL	Hydrated lime [$Ca(OH)_2$] also known as slaked hydrated lime
Hydraulic Binder	Cementing materials which harden in the presence of water
MCHW1	Manual of Contract Documents for Highway Works, Volume 1: Specification for Highway Works
MPa	MegaPascal equivalent to 1 Newton per millimetre squared (1 N/mm^2)
OWC	Optimum Water Content
QL	Quicklime
PI	Plasticity Index
PFA	Pulverized-Fuel Ash
R_c	Compressive strength
$R_{c\ vs}$	Coefficient of volumetric stability
R_{it}	Indirect tensile strength
$R_{c\ imm}$	Compressive strength after immersion in water
R_t	Tensile strength
Series 800	Series 800 of MCHW1
SBM	Slag Bound Mixture
SHW	Specification for Highways Works
SROH	Specification for the Reinstatement of Openings in Highways

1. INTRODUCTION

1.1 PURPOSE OF THE GUIDE

This document provides guidance on the application of quarry fines into hydraulically bound mixtures (HBMs) for construction applications, specifically within pavement foundation layers. This guidance document covers a range of potential materials, their scope for use, methods for assessing their characteristics and performance, and the general considerations and factors affecting their potential use.

Reference is given throughout the document to the findings from research and laboratory assessment carried out as part of this work. This work involved the development of HBM specifications containing a range of quarry fines and various binders, and subsequent mechanical testing to assess their performance and suitability for use in HBMs. Full data and discussion of the findings can be found in the technical report which accompanies this guidance document [MIST, 2008].

1.2 SCOPE OF THE GUIDE

The use of quarry fines within HBMs provides decision makers with an increased range of options for mixture design and provides an alterative, and potentially large, market application for these quarry 'by-products'. The use of these materials has potential benefits on both engineering and sustainability terms, and this document provides guidance on how these benefits can readily be achieved. Guidance is given to producers, buyers, contractors, designers and clients on the use of quarry fines in HBMs for construction applications, with specific attention being paid to use in pavement foundation layers. It is based on a review of existing literature and on extensive laboratory research carried out as part of this project.

All guidance in this document meets industry recognised standards and specifications and reference is given to the relevant documents for full details of the design methods and specifications where stated.

1.3 KEY DEFINITIONS

Unless otherwise specified, the term 'quarry fines' is used throughout this report instead of 'dusts', 'by-products', 'wastes', or 'rockdusts'.

- **Quarry fines –** Materials typically produced as a by-product of the blasting, crushing and screening processes at quarries. Fines are classed as aggregate passing the 4 mm sieve for use in concrete and related materials, and passing the 2 mm sieve for use in asphalt [BS EN 13043: 2002]. Anything larger than 4 mm is classed as coarse aggregate [BS EN 13043: 2002]

- **Hydraulically bound mixtures (HBMs) –** A mixture of aggregate or soil, with a hydraulic binder and, where appropriate, secondary constituents, which is designed to attain a structural integrity [BS EN 14227: 2004].

- **Hydraulic binders –** These are materials that can be used to bind aggregate or soil particles together. Some require an activator, such as lime, while others simply require the addition of sufficient water for activation. Hydraulic binders include cement, fly ash and slag.

2. HYDRAULICALLY BOUND MIXTURES

2.1 WHAT ARE HBMS?

HBMs set and harden by hydraulic reaction and their classification is based on the material treated (the type of aggregate or soil), the binder(s) used, the process by which it has been mixed, and the end performance requirements. By combining an aggregate with hydraulic binder(s), the strength, durability and volume stability of the material being treated can be tailored to specific requirements.

The use of HBMs in construction applications can have a number of advantages and some disadvantages;

Advantages

- HBMs provide the opportunity for a greater number of secondary and recycled materials to be used within higher value applications, rather than as unbound granular fill.
- HBMs reduce the demand on other construction materials, such as Type 1 aggregate.
- HBMs can be produced to the specific strength and/or stiffness required by a particular engineering project.
- HBMs can be used in a cold state and they gain strength and/or stiffness over a period of time. This slow curing time allows for a longer time frame for laying, compacting and (if required) pre-cracking.
- The high strength and stiffness values offered by HBMs allow for a reduction in the thickness of overlying layers in a pavement. This can help to reduce the cost of the overall project.
- HBMs allow for the re-use of excavated or demolition materials on-site. This reduces the need to import materials and it reduces the transport costs and distances of material that would have needed to have been brought to or taken away from site.
- The mixtures can be produced either in situ or ex situ and can be designed to have long term shelf lives. Plant required for laying and compaction are similar to those used for other materials, such as unbound mixtures and bituminous bound mixtures.
- HBMs can help organisations improve the sustainability of their projects and help them to meet or exceed client requirements for 'green' procurement [WRAP, 2005].
- The use of HBMs can have an energy saving effect on a project overall [ETSU, 1997].

Disadvantages

- Higher stiffness values offered by some HBMs may lead to cracking and deformation (for example, reflective cracking in the overlying asphalt layers). This can me mitigated by pre-cracking.
- The materials require compaction.
- The use of a roller compactor or padfoot may be required during laying and compacting of the fine grained material. This may increase the cost and/or time required for construction.

2.1.1 Considerations

There are a number of key considerations that need to be taken into account when assessing if the use of HBMs (including those containing quarry fines) is appropriate. These include;

- **Material resource efficiency** – will the HBM effectively replace or be superior to other traditionally bound or unbound materials? Will the potential requirement of high binder contents be an issue?

- **Economics** – Will the use of HBMs help to reduce or maintain the cost of the project, when compared to traditional materials?

- **Haulage** – Are the materials available locally? Will the costs associated with haulage outweigh the cost savings made elsewhere?

- **Technical** – HBMs offer a superior foundation layer and so reduce the requirement for a thick surface layer. What binder content is required for this and what are the required compaction techniques?

2.1.2 The binders

HBMs generally comprise an aggregate and binder(s), sometimes with an activator to activate the hydraulic reaction. Typically, HBMs are classed according to their binder type, with the most common being;

- Cement Bound Granular Mixture (CBGM) – bound using Portland cement

- Fly Ash Bound Mixture (FABM) – bound using fly ash (or pulverized fuel ash (PFA)) from coal burning power stations

- Slag Bound Mixture (SBM) – bound using granulated blastfurnace slag (GBS), an industrial by-product

HBMs are aggregate and binder mixtures that set and harden in the presence of water. Some binders only require the addition of a sufficient amount of water to 'activate' the hydraulic reaction, and harden, whereas others require an additional activator such as lime to start the process.

The speed at which this process occurs largely depends upon the binder used, the curing conditions and age. Typically, HBMs with cement as the binder (minimum of 3% content) can be classed as 'quick hydraulic' (QH), as they harden quickly. Whereas those with other binders, such as lime/PFA or lime/GBS, are classed as 'slow hydraulic' (SH), as they set and harden more slowly [Merrill et al, 2004].

The main binders and activators found and used within the UK are shown in Table 1.

Table 1: Traditional and alternative binders used in HBMs

Material	Availability	Binder	Activator
Portland Cement (PC)	**Traditional Binders** These binders are available and used widely in the UK and are covered by the appropriate BS EN standards and specifications for HBMs.	Yes	Yes
Pulverized Fuel Ash (PFA)		Yes	No
Granulated Blastfurnace Slag (GBS)		Yes	No
Ground Granulated Blastfurnace Slag (GGBS)		Yes	No
Quicklime (QL)		No	Yes
Hydrated Lime (HL)		No	Yes
Gypsum		Yes	Yes
Steel Slag		Yes	Yes
Cement Kiln Dust (CKD)	**Alternative Binders** These binders are not as widely used and available in the UK and are not covered to the same extent by the appropriate BS EN standards and specifications for HBMs.	Yes	Yes
Paper Waste		Yes	Not known
Red Gypsum		Yes	No
By-product Lime		No	Yes

2.1.3 HBM – Aggregates

Aggregates for application into HBMs can be crushed or uncrushed and should comply with BS EN 13242: 2002. The aggregate can be naturally occurring, recycled or manufactured, or any combination of these. HBM properties depend mainly on the properties of the aggregate and the interaction between the aggregate and the binder(s), which has to be considered during HBM design.

The suitability of an aggregate for application into a particular HBM is based upon the grading requirements specified in the relevant BS EN standard. It is also important to understand the characteristics and behaviour of the particular aggregate so as to be able to design mixtures that are suitable for their purpose. These issues are discussed further in Sections 3, 4 and 5.

Materials also need to be assessed on a source and application specific basis. HD35 within the Highways Agency's Design Manual for Roads and Bridges, Volume 7 (DMRB) [Highways Agency, 2001] provides advice on the use of a range of primary, secondary and recycled materials into HBMs, for pavement base and subbase applications. These materials include; blastfurnace slag, pulverized fuel ash, china clay sand, incinerator bottom ash aggregate, slate and spent oil shale, and many more.

2.1.4 HBM – Applications

HBMs have historically been used in construction applications in countries such as France, Holland and Germany, and to a lesser, but growing extent, within the UK. Since the introduction of harmonised European Standards and their adoption into the Manual of Contract Documents for Highways Works (MCHW), the scope for the use of HBMs has increased. HBMs are now increasingly being used for the construction of working platforms, liners, flood defences, trench reinstatement, erosion protection, major and minor roads, paved areas and heavy duty paving [WRAP, 2005].

The key application areas for HBMs include;

- **Trench Reinstatement** - The Specification for the Reinstatement of Openings in Highways (SROH) [Highways Authorities and Utilities Committee, 2002] permits several types of hydraulically bound mixtures for use in trench reinstatement. Confidence in the mixture's performance and its suitability for application into reinstatement projects, is typically determined by its Compressive Strength (R_c), which gives an indication of mechanical performance.

- **Pavement Construction** - The pavement design guidance associated with the DMRB [Highways Agency, 2001] permits a performance specification route for the design of pavement foundations. This provides details of the performance measurement of materials, and design values, and includes an indicative guide to the hierarchy of materials, according to performance. Series 800 of the Specification for Highways Works (SHW) [Highways Agency, 2007] is based upon European harmonised standards (BS ENs) for HBMs and stabilised soils for pavement subbase and base applications. Within pavement foundation guidance, it has been recognised that the potentially superior performance of HBM layers, when compared to traditionally used unbound materials, can now be factored into the overall pavement design and thus, allows for reductions in the thickness and strength of overlying layers [Highways Agency, 2006].

Figure 1: A HBM being compacted into a pavement foundation layer

- **Working Platforms** - HBMs are commonly used in the construction of working platforms. Here, the HBM used provides a stable and durable temporary working surface from which machinery, such as piling rigs and cranes, can operate. Working platforms are required where the natural ground conditions are unsuitable for the safe operation of construction plant. The working platform may be incorporated into the permanent design if drainage, the stress and load applied and regularity of use, maintenance and rehabilitation are considered during the design stage. This can reduce overall costs significantly [Kennedy, 2006].

- **Harbours and Flood Defences –** HBMs can be applied as earthworks and liners and can act as protective barriers when placed in layers to construct an embankment.

2.2 QUARRY FINES

Quarry fines typically consist of a mixture of coarse and fine sized aggregate particles, plus a clay/silt fraction (fines). These aggregate fines, in accordance with the BS EN 13242: 2002, are classed as less than 4 mm in size for use in aggregate applications such as concrete, and less than 2 mm in size for use in asphalt. However, particularly within quarry operations, the term 'fines' is often used to define all undersized material resulting from the blasting and crushing processes [Manning, 2004].

The British Geological Survey [2006] estimates that there are around 41 million tonnes of fine material produced by quarrying annually in the UK. This has increased over recent years due to changes in the demands and specifications for aggregates, resulting in changes to crushing and processing techniques. Currently, much of this material is stockpiled and the main applications to date have tended to be low value and low performance, such as in bulk fill and capping [British Geological Society, 2006].

Figure 2: Stockpiled quarry fines

In the UK, there is considerable variability in quarry fines, both locally and nationally. This is dependent on lithology and the crushing, screening and processing techniques applied. The range of quarry fines available in the UK are summarised in Table 2. Although not quarry fines, fine aggregate and fines from the production of Recycled Aggregates are included for completeness.

Table 2: Quarry fines types found in the UK

Lithologies	Example Types	Production
Sedimentary rock	Dolomitic Limestone Carboniferous Limestone Sandstone Gritstone	From the blasting, crushing and screening processes at quarries
Igneous rock	Granite Diorite Andesite	From the blasting, crushing and screening processes at quarries
Recycled aggregate	Various/mixed	Recovered construction, demolition and excavation waste (CDEW)
Superficial deposits	Silt/clay	Recovered from sand and gravel extraction processes

As HBMs are bound materials, they must possess strong aggregate interlock and/or a strong binder in order to be sufficiently durable, dependent on the specified performance requirements. Quarry fines are essentially a fine graded material with a general absence of coarse aggregate particles, so the desired strong aggregate interlock is likely to be missing. Therefore, in an unbound form, fines lack the ability to provide significant structural strength and stability. The lack of a strong aggregate interlock will also impact on the strength of the bound form. Therefore, issues such as ensuring that sufficient compaction is achieved need extra attention during the design stage (see Section 3).

By incorporating the fines with a hydraulic binder, the lack of potential aggregate interlock is overcome and material strength and stiffness can be designed effectively. Additionally, by using a finer aggregate, issues such as segregation during transportation from quarry to site are reduced. The finer material can also make compaction easier and can reduce the HBM's susceptibility to penetration by water.

2.2.1 Indicative suitability

As part of the research project, a range of quarry fines and hydraulic binders were sourced and assessed for suitability for application into HBMs for pavement foundation construction. Quarry fines materials were sourced to represent a range of lithologies and material types and were expected to produce HBMs with a range of performance and durability characteristics. Details of the research project are reported in the project technical report [MIST, 2008].

A variety of HBMs were designed and durability and mechanical performance testing was conducted.

Indicative strength values have been obtained from this testing and are shown in Table 3. All R_c values are for 2:1 height to diameter specimens tested at 28-days age.

Table 3: Typical compressive strength (R_c) results for tested HBM specimens

	Binder				
Generic Quarry Fine Lithologies	**4 to 6 % CEM I**	**4 to 6 % CEM II**	**PFA***	**CKD***	**GGBS***
Dolomitic Limestone	5 - 8 MPa	7 - 8 MPa	2 - 3 MPa	2 - 3 MPa	
Carboniferous Limestone				1 - 2 MPa	10 - 12 MPa
Andesite	6 - 9 MPa		5 - 7 MPa		
Grandodiorite	7 - 12 MPa	7 - 10 MPa			
Sandstone	5 - 7 MPa	5 - 7 MPa			
Silt (<0.063 mm grading)	1 - 2 MPa				4 - 6 MPa

N.B. CEM I is Class 42.5N Portland Cement and CEM II is Class 32.5N Portland Cement (incorporating PFA)
* Used with hydraulic lime (HL) as an activator

The results show that a range of strengths can be obtained from HBMs incorporating quarry fines and varying binders. The results are dependent on both the aggregate-binder bond and the characteristics of the aggregate parent rock. These figures are indicative and should be related to guidance found in industry standards and specifications (see Section 7)

Further details are available in the project technical report that accompanies this guidance document [MIST, 2008].

3. SPECIFICATION AND COMPLIANCE

3.1 FACTORS TO BE CONSIDERED

The development of a HBM design is an iterative process based on ongoing mixture design and laboratory testing in order to optimise performance and applicability into real-life settings. Assessment of the aggregate and binder mix, optimising the grading and establishing the minimum binder content are crucial to achieving a durable material suitable for use.

3.1.1 Short-term performance – Workability and trafficking

Pavement construction is subject to both relevant BS EN standards and specifications and the Manual of Contract Documents for Highways Works (MCHW), which draws upon these relevant BS EN standards and specifies that the structure must fulfil its role while also being durable and long-lasting [Highways Agency, 2007]. HBMs tend to cure and harden slowly (specifically non-cement bound materials), therefore, allowing for a long period of workability. Their strength gain is also typically slow and can provide the opportunity for re-working shortly after being laid, if necessary [Kennedy, 2006].

Even though HBMs tend to require more time to achieve full strength, it is possible for the trafficking of the newly laid surface to begin immediately, without the need for a lengthy curing period. This depends upon the cohesive properties of the aggregate and binder mix and it is important that a mixture design established to allow for immediate trafficking must also ensure that there is no detrimental effect on the long-term strength gain and traffickability of the pavement.

3.1.2 Long-term performance – Durability and degradation

The role of the pavement foundation is to distribute the applied vehicle loads to the underlying subgrade, without causing distress to the overlying layers. During the life of a pavement, the foundation layer has to be able to withstand a large number of repeated loads from traffic. In addition to this, it is also likely to experience forms of environmental degradation, such as the ingress of water and temperature fluctuations. It is therefore essential that the foundation can withstand degradation so that excessive deformation does not occur, which can lead to rutting or reflective cracking and erosion in the surface layers.

3.1.3 Economic viability

The economic viability of using HBMs in any construction project needs to be investigated prior to any decisions being made relating to material selection and mixture design. Issues such as the required binder content and expected manufacture and compacting techniques need to be taken into account. In addition, material availability and the associated transport costs need to be taken into consideration and weighed up against alternative material solutions.

HBMs offer a range of potential cost savings for construction projects. These include;

- The opportunity to reduce the demand for primary materials as they allow for the greater use of secondary and recycled materials. If available locally, this can also help to reduce costs associated with transportation.

- The typically higher stiffness values offered by HBMs compared to unbound materials, when used in the foundation layers of a pavement, can allow for a reduction in the thickness of the overlying pavement layers. This can have a cost saving impact on the overall project. This is particularly relevant where quarry fines are applied within HBMs due to the high stiffness values that they can provide.

The typically longer working and shelf-life than traditional materials means that they can be easier to lay and compact.

4. DESIGN OF HBMS FOR DURABILITY

4.1 FACTORS AFFECTING DURABILITY

The factors that affect HBM durability can be divided into those attributed to environmental conditions, such as temperature, water or other deleterious substances, and those associated with the material components of the HBM itself. If the durability of the HBM is inadequate, these factors can result in shortened in-service life spans, increased maintenance requirements, or, ultimately, failure of the pavement and costly remedial works.

4.1.1 Environmental factors

The key factors that affect the durability of a HBM are environmental and chemical. Environmental considerations include temperature extremes and changes, and the presence of water. Chemical considerations include exposure to deleterious substances or substances that may lead to expansive reactions. Dimensional changes to a HBM layer of a pavement can disrupt the overall structure and/or result in reduced performance of the layer itself. Specific causes of dimensional change can include;

- Thermal expansion/contraction – caused by excessive heat or cold
- Drying shrinkage – can be caused when a material is laid 'wet' and then dried during compaction; this is usually more associated with concrete than with HBMs
- Frost-heave – when the material expands due to frost and then shrinks when the frost disappears
- Freeze-thaw – when free water in the material weakens the structure during freeze-thaw
- Expansive reactions caused by excesses of damaging chemicals in the environment

4.1.2 Non-environmental factors

HBMs are only as good as their component parts and a mixture design should establish the optimum balance of binder, aggregate and water required to produce a suitable HBM for the intended use. In addition to the environmental and chemical factors, there are a number of non-environmental factors that have an impact on the durability of a HBM and should therefore be factored into the design stage (see relevant documents in Section 7), as shown in Table 4.

Table 4: Non-environmental factors affecting the durability of a HBM

Aggregate Factors	Binder Factors	Mixture Factors
Quality and content of fines	Curing rates	Grading
Particle density	Workability	Binder type(s) and content
Water absorption	Mechanical performance	Compaction (including density and air voids)
Resistance to fragmentation	Water requirements	Stiffness
Sulfate content	Chemical content	Resistance to permanent deformation
Stability	Potential for cracking and the healing of cracks	Permeability (both element and layer)

4.1.3 Drainage

Surface and subsoil drainage must be adequate to allow for the durability of a laid HBM to be maintained. Without adequate drainage the life-span and trafficking ability of the pavement will be restricted. This is particularly important during periods of high rainfall when the water table will be high [Britpave, 2007].

4.2 ASSESSING DURABILITY

The appropriate tests and requirements for determining the durability of a HBM are set out in Figure 4. The mixture design of a HBM is an iterative process based on specific and ongoing laboratory testing involving the assessment of both the sourced aggregate and the bound mixture as a whole. Through this iterative process, optimisation of performance can be achieved through grading analysis and establishing the optimum water content (OWC) and minimum binder(s) content.

Once an aggregate and binder(s) have been sourced, classification testing must be carried out to determine the physical properties of the aggregate and identify where potential problems may lie if they were to be incorporated into a HBM, for example, adverse chemical reactions. Subsequent mixture design should take into account both short and long-term performance considerations and should involve the optimisation of grading and binder content as a result.

Comprehensive assessment of the mechanical performance of the mixture is required to compare the HBM against the specified performance criteria. Subsequent assessment to identify the durability of the particular mixture design should also be conducted. Figure 3 outlines the procedure for this assessment [WRAP, 2008].

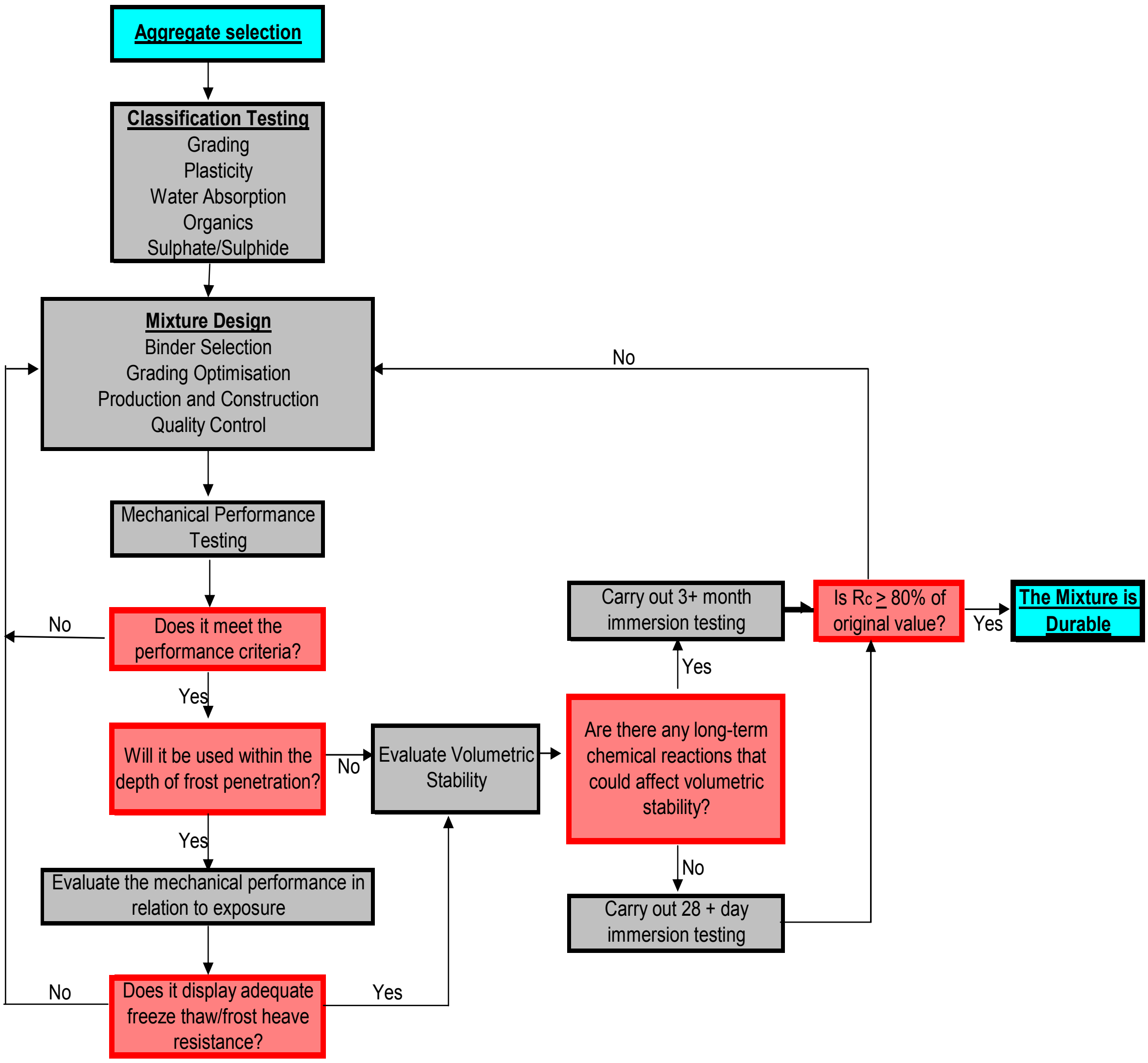

Figure 3. The procedure for testing the durability of a HBM [WRAP, 2008]

4.2.1 Classification testing

Classification testing determines the physical properties of aggregates and their potential suitability and performance if they are to be included in a HBM. Grading of the material is carried out in order to identify whether it is well-graded; i.e. it should have a good distribution of particle sizes from finest to coarsest, allow for efficient compaction by forming a matrix without voids, and achieve the required level of durability when placed in a HBM.

Grading must be carried out prior to any mixture design being developed, in accordance with BS EN 933-1:1997. Grading envelopes for CBGMs, FABMs and SBMs have been developed to provide guidance to producers, designers and specifiers [BS EN 14227: 2004]. These envelopes are used to assess whether or not an aggregate is suitable for its application by plotting the mass of material that passes each sieve size against the envelopes. Optimisation of the grading can be subsequently carried out to achieve this, often by adding other size fractions of the same aggregate or other materials. This ensures that the aggregate interlock is maximised and that a minimum number of voids are present in the final HBM.

In general, grading envelopes are narrower and more restrictive for higher performance applications, such as in pavement foundation layers, compared to general fill. Figure 4 shows the CBGM envelopes. Envelope A covers materials that are typically fine grained and are able to be suitably compacted. When an aggregate plotting within this envelope is used in a CBGM, the mixture is referred to as a CBGMA. Envelope B covers only well-graded coarser aggregate that has limited fines content. Similarly, a mixture containing this type of aggregate is referred to as a CBGMB

In general, quarry fines fall within Envelope A, or above. Above the limits of Envelope A, the HBMs are classed as treated soils [BS EN 14227-10 to 14: 2006].

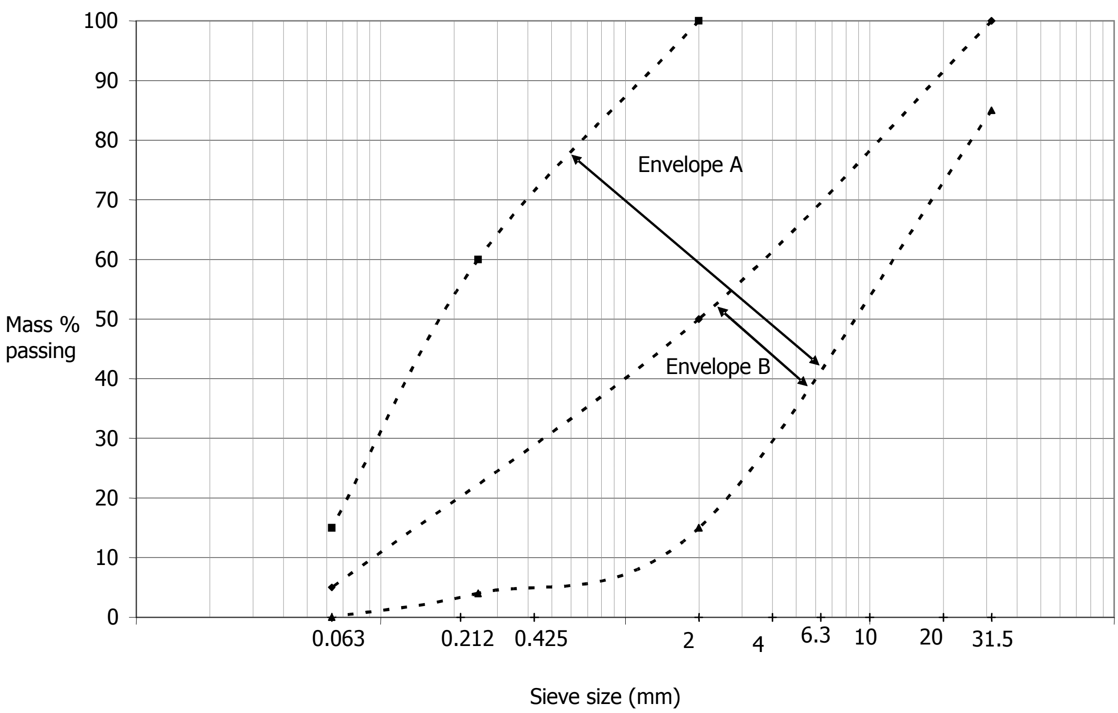

Figure 4: The grading envelope for a HBM (specifically a CBGM). BS EN 14227-1: 2006.

The suitability of an aggregate for use in a HBM also depends on its capacity for compaction, which is determined by assessing the dry density and optimum water content (OWC) of the material [BS EN 13286-1 to 5: 2003]. These factors influence the resulting strength and stiffness values when the material is manufactured into a HBM.

4.3 PERFORMANCE AND MECHANICAL TESTING

4.3.1 Introduction

Mechanical durability testing evaluates whether or not the HBM has the potential to withstand long-term deleterious conditions and maintain stability and the required level of performance.

The mechanical performance classification system for HBMs contained within Series 800 [MCHW1, 2007] and European Standards [BS EN 13286-41 to 43: 2003] can be divided into two systems:

- **System One** – based on an indirect method such as compressive strength, R_c, and
- **System Two** – based on a more fundamental combination of tensile strength, R_t, and modulus of elasticity, E_c.

Figure 5 shows the route for assessing the mechanical performance of a HBM in the laboratory.

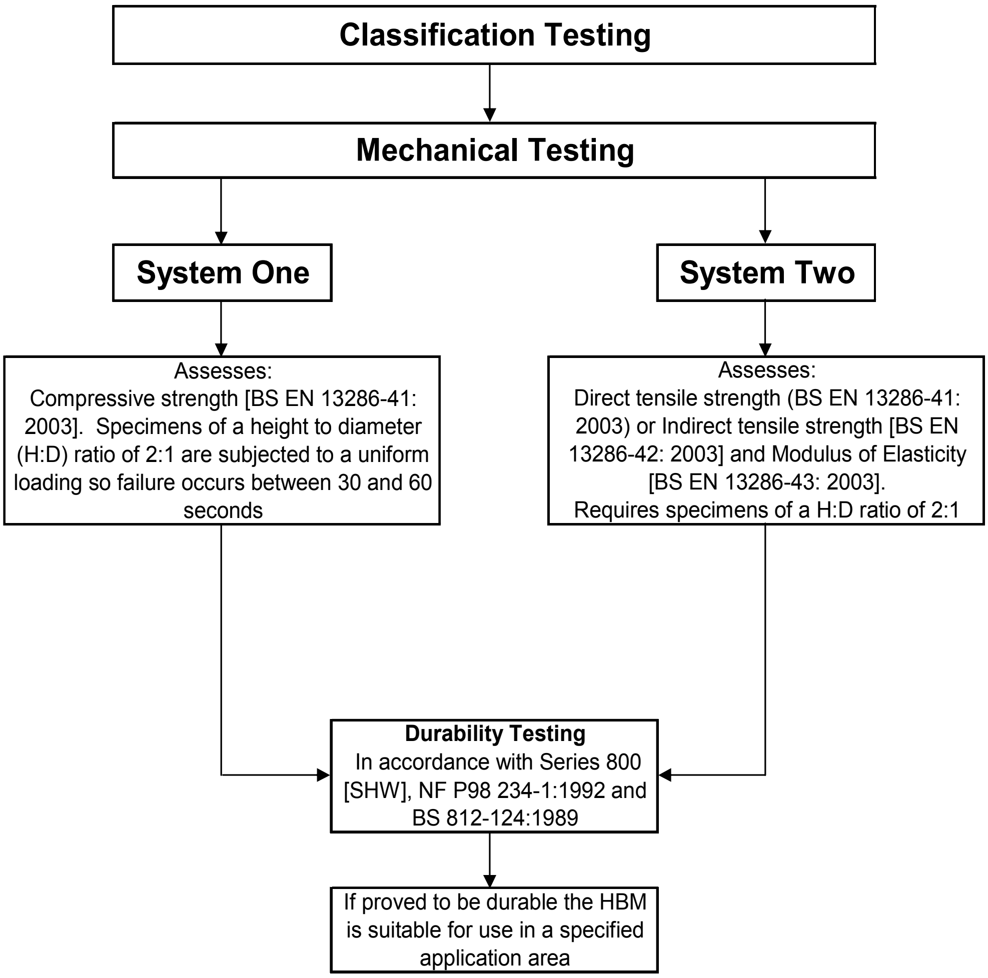

Figure 5: Routes for assessing the mechanical performance of a HBM (System One and System Two)

The preparation and testing of samples should be carried out in a way that reflects expected real-life conditions, such as, timescale, temperature and materials.

4.3.2 System One testing

A compressive strength value (System One classification) is often used as the basis for generic guidance. Care should be taken in relating strength gains, mixture design, material and application specific properties to the use of any generic guidance values as the overall performance of a HBM is dependant on many factors which cannot be accounted for in such generic values.

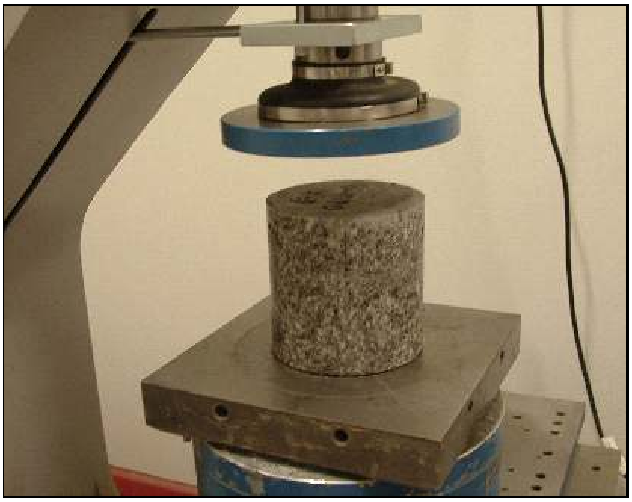

Figure 6: Compressive strength testing of a 1:1 height to diameter specimen of HBM

4.3.3 System Two testing

The tensile strength test is designed to model the forces exerted on a pavement layer in a direction perpendicular to the applied load, the strength datasets are expressed in MegaPascals (MPa). However, tensile strength (R_t) is difficult to determine experimentally, so is derived from the indirect tensile strength (R_{it}) using established relationships [BS EN 14227-1 to 3: 2004];

$$R_t = R_{it} \times 0.8\,(MPa)$$

The elastic modulus E_c (also known as static stiffness) measures the element's elastic stiffness modulus (defined as the secant stiffness at 30% of the peak force). The specimen is fitted with a collar (Figure 7) that measures the amount of specimen compression, in millimetres, during the application of the load to the top of the specimen. The results are expressed in GigaPascals (GPa). As the layer stiffness (E_l) is assumed to be 20% of the element stiffness (stiffness of the test specimen), it can be approximated simply using:

$$E_l(GPa) = E_C(GPa) \times 0.2$$

Figure 7: Strain collar fitted to a 2:1 HBM specimen during modulus of elasticity testing

4.4 DURABILITY TESTING

HBMs that exhibit compressive strengths in excess of 2 to 2.5 N/mm² are classed as bound materials, and are therefore, superior to unbound materials [Kennedy, 2006]. However, in recent years, durability recommendations for lower strength HBMs have emerged and these incorporate new methods of durability assessment.

Durability is currently assessed in Series 800 of the Specification for Highways Works (SHW) [Highways Agency, 2007] using the procedure given in clause 880.4. Specimens with a H:D of 1:1 are prepared and cured for 14 days in air. They are then cured for a further 14 days immersed in water. The compressive strength of these immersed samples ($R_{c\ imm}$) is determined along with that of control specimens ($R_{c\ control}$) cured for 28 days in air only. The mixture is classified as durable if the following applies;

$$R_{c\ vs} = \left(\frac{R_{c\ imm}}{R_{c\ control}} \right) \times 100 \ \geq 80\%$$

where:

$R_{c\ vs}$ is the relative volumetric stability (assumed to be durable if ≥ 80%)

The durability of a HBM should also be evaluated with regard to issues such as resistance to frost heave and freeze thaw. The duration of these tests should relate to the assessed potential for the material to be susceptible to long-term deleterious reactions. The strength of the aggregate within a HBM helps to determine its susceptibility to the weathering influences of the freeze-thaw process and the material's potential to lose or gain strength over time.

Table 5 summarises the durability testing procedures for HBMs.

Table 5: HBM mixture durability testing procedures

<table>
<tr><th>Durability Test</th><th>Standards</th><th>Procedure</th><th>Applicability</th></tr>
<tr><td>Volumetric stability</td><td>SHW Series 800, 2007</td><td>1:1 sealed specimens are cured for 14 days in air then immersed in water for 14 days at 20°C for CBGMs and 40°C for FABMs and SBMs. The resulting compressive strength must be at least 80% of the strength of control specimens.</td><td>This is a required test that must be carried out on all HBMs to be applied within pavement construction.</td></tr>
<tr><td>Freeze thaw</td><td>NF P98 234-1: 1992</td><td>2:1 specimens are cured for 28 days then soaked for 24 hours before being sealed. The specimens are then subjected to a cycle of air temperatures between -10°C and +10°C. The resulting compressive strength must be at least 80% of the average strength of the control specimens.</td><td rowspan="2">These can be used to assess durability when a HBM is to be used within the depth of frost penetration.</td></tr>
<tr><td>Frost heave</td><td>BS 812-124: 1989</td><td>2:1 specimens are cured for 28 days and then subjected to a range of temperatures from -7.5°C to +4°C whilst being partially immersed in water. Over 96 hours the linear expansion of the samples must be <13 mm.</td></tr>
</table>

5. DESIGN AND CONSTRUCTION CONSIDERATIONS

Pavement construction is subject to both relevant BS EN standards and the Specification for Highways Works (SHW), which specify that the structure must fulfil its role while also being durable and long-lasting. Details of the procedures to be followed when constructing a HBM are given in Series 800 of the SHW [Highways Agency, 2007].

The Highways Agency's Interim Advice Note IAN 73/06 [Highways Agency, 2006] provides guidance on the design of road pavement foundations and will eventually replace the existing requirements set out in HD 25/94 [Highways Agency, 1994a]. New foundation classes are to be presented in two forms, these are, 'performance designs' and 'restricted designs'.

- **Performance designs –** allow a wider use of the materials but require testing of the built pavement foundation in order to assess whether the design requirements are met. Stiffness is used as a measure of support offered by the foundation layer and it must meet specified target values. The foundation of a pavement is categorised into one of four categories based on stiffness which, when assessed alongside the California Bearing Ratio (CBR) of the subgrade, gives the minimum layer thickness for the foundation. Reference should be made to IAN 73/06 [Highways Agency, 2006] for the full design process.

- **Restricted designs –** these are typically applied to smaller schemes where material options and performance assessment methods may be limited. These designs are conservative and are limited to unbound mixtures or CBGMs, which allow for a level of uncertainty in design and construction.

The requirements for HBM specifications for use within pavement foundation layers are specified in the Series 800 of the SHW [Highways Agency, 2007], and in associated Notes for Guidance [Highways Agency, 2007b], which relate to the relevant and current harmonised European Standards.

There is this degree of uncertainty regarding the suitability of the fines, relating to their grading, so a laboratory test to simulate trafficking would be required. This is known as the IBI (immediate bearing index) test [Kennedy, 2006]. The IBI test is carried out at the mixture design stage and is essential for those materials that appear not to be conclusively well-graded and those where mechanical interlock may be reduced due to, for example, smaller aggregate particles. The process is simple and effective and full details on the test method and suggested IBI values are found in Britpave's guidance BP/14 [2005].

This guide does not set out to provide a design guide for pavement layers using HBMs. For full details of the procedures to be carried out when constructing, laying and compacting, it is recommended that the relevant Highways Agency specifications are consulted (see Section 7). Full details on layer thickness and layer design should also be based upon these documents.

5.1 LAYING OF THE HBM

HBM construction is versatile in terms of plant and materials and HBMs can be produced by either ex situ or in situ methods;

- **Ex situ –** The aggregate or soil are mixed with the hydraulic binder(s) in a stationary mixing plant before being placed and compacted. The plant used for these activities are the same that are used for traditional pavement materials, such as bituminous bound and unbound materials.

- **In situ –** The aggregate or soil are mixed with the hydraulic binder(s) in-place using plant such as rotavators, before being compacted. The main benefit of this approach is that existing site material can be used on site, rather than having to import materials to site.

The construction period of a HBM denotes the time that it remains workable at a given temperature. For example, the construction period for cement is 35°C hours, Therefore, a CBGM would be workable for one hour at 35°C, or five hours at 7°C.

The construction period for a HBM varies depending upon the type of binder used and also the presence of water. Table 6 details the indicative construction periods for HBMs containing different hydraulic binders.

Table 6: Typical construction periods for HBMs (adapted from Series 800) [Highways Agency, 2007]

Binder	Construction Period in °C hours (for example, cement bound HBMs would be workable for one hour at 35°C, or five hours at 7°C etc)
Cement alone	35°C hours
Fly ash and/or GGBS and then cement	35°C hours from the addition of cement
Fly ash activated by lime/gypsum (mix-in-plant)	70°C hours from the addition of lime/gypsum
GGBS and lime	200°C hours from the addition of GGBS
Fly ash and lime	800°C hours from the addition of fly ash
Lime alone	1200°C hours
GBS and lime (mix-in-plant)	1200°C hours from the addition of GBS
GBS activated by air-cooled steel slag (ASS) (mix-in-plant)	3000°C hours from the addition GBS
Other combinations	The workability period at 20°C is determined in accordance with BS EN 13286-45: 2003

The placement of HBMs should be avoided in cold weather, specifically below 3°C. This is due to the risk of frost and the potential for layer degradation.

Aggregates for use in HBMs should always be stored in a clean, dry and secure environment in order to prevent excessive degradation of the material or a significant change in the water content between mixing and application.

The HBM layer is laid and compacted and the resulting average bulk density of the layer should be no less than 95% of the average bulk density of the preceding laboratory specimens. Compaction of the layer should be carried out by a typical vibrating or pneumatic-tyred roller.

Figure 8: HBM being laid and compacted using conventional plant

The compacted HBM layer should not be allowed to dry out before the overlying layer(s) are laid. To prevent this from occurring, a curing membrane can be applied to maintain an appropriate level of moisture within the layer. Compaction should also be carried out at optimum water content (OWC) to achieve maximum density [Kennedy, 2006].

The application of quarry fines within HBMs requires specific attention during the laying and compaction process. Predominantly fine material may lead to coarse aggregate particles becoming segregated and 'floating' to the surface of the mixture. As a result, compaction may benefit from the use of a Sheepsfoot Roller or a Padfoot to mix the HBM during the process. Their use can help promote a strong aggregate interlock between the fines and any existing coarser particles, which can also help to reduce susceptibility to frost heave and permanent deformation.

Typically, HBMs can be open to trafficking immediately, provided that the IBI value, grading and aggregate are appropriate. If any of these factors are insufficient, immediate trafficking should be avoided for a period of one week (longer in cooler weather).

5.2 ON-SITE PRODUCTION CONTROL

Production control should be carried out continuously during the construction of a HBM layer within a pavement. It is vital that uniformity is ensured throughout the construction process and that aspects such as the OWC and grading and binder content are monitored. The water content must be monitored and adjusted where necessary to avoid the mixture becoming too wet or drying out too quickly.

If in situ methods of HBM construction are used, the rate of binder spread should be monitored. This can be done using a tray to catch the binder as a spreader passes over it and then the volume of binder caught being weighed to assess the rate and conformity of binder spread.

If ex situ methods of HBM construction are used, the rate of feed of the HBM component materials should be monitored. This is to ensure that there is no change to the grading, binder and activator additions or water content of the HBM mix, and that there is uniformity in the rate of feed.

5.3 CRACKING AND PRE-CRACKING

A key issue in pavement design and construction is the likelihood of reflective cracking occurring. This is when cracks develop in the foundation layers as a result of excessive loading or from environmental or non-environmental factors. These cracks can then migrate into the surface layers and lead to rutting and surface failure. When this happens, the whole pavement can fail and rehabilitation or reconstruction is required [Adaska and Luhr, 2004].

To prevent this from occurring, induced cracking, or pre-cracking, of the HBM foundation layer can be carried out. Induced cracking is required if the unconfined compressive strength of a HBM exceeds 8 MPa, as detailed in Series 800 of the SHW [Highways Agency, 2007]. Induced cracking is carried out with cracks being made at specified distances apart, and with a sand and bitumen material then being inserted into the grooves prior to final compaction (see Figure 9). In order for this practice to be successful, the HBM must not be allowed to dry before the overlying layer is laid and so a membrane can be applied to maintain moisture within the layer.

Figure 9: Induced cracking being carried out on a HBM subbase layer containing quarry fines

5.4 TRIAL SECTIONS

Trial sections are recommended to test traffickability prior to a full-scale project being carried out. This allows HBM specifications to be assessed on a site-by-site basis and for immediate and existing environmental and non-environmental influences to be taken into account.

An assessment of the ability of a HBM to withstand early trafficking should be determined in order to evaluate the potential risk of rutting and permanent deformation of the foundation layer, leading to the eventual failure of the pavement. Trial sections also allow for the assessment of the mixture when it is laid in large volumes and compacted using plant, rather than the scale encountered in the laboratory. On-site trial application means that issues such as traffic loading, water content, water pressure and variations in temperature and surface gradient can be taken into account.

Following the laying of a demonstration site, extensive laboratory testing and on-site testing should be carried out to test for compliance with specific application standards and specifications [Kennedy, 2006]. Representative samples from the full length of the laid HBM layer should be taken at regular intervals prior to final compaction and these should then undergo laboratory testing to System One and System Two (see Section 4.3). All sampling and testing should be carried out to the relevant BS EN standards.

On-site verification of the stiffness of the pavement can be essential, particularly when previously un-trialled HBMs have been used. Two methods for the determination of surface stiffness are (i) using a falling weight deflectometer (FWD) or (ii) using a lightweight deflectometer (LWD) (Figure 10). These processes measure the surface modulus and can be carried out easily and cause no disruption or damage to the pavement structure. The results from carrying out these assessments indicate the support being offered by the foundation layers to the pavement structure as a whole.

Figure 10: LWD testing being carried out on a pavement to assess the surface modulus

6. SUMMARY

This guidance document provides information for producers, buyers, contractors, designers and clients to increase confidence in the use of quarry fines in HBMs for construction applications, specifically in pavement foundation layer construction. It provides information on the materials available, indicative characteristics and performance parameters. From the guidance it can be seen that;

- Laboratory research on a range of quarry fines and hydraulic binder(s) has shown that these materials, when used in HBMs, are viable alternatives for construction and engineering applications [MIST, 2008].
- BS EN treated soil standards appear most appropriate for the specification of quarry fines within HBMs [BS EN 14227: 2004]:

  - **Part 10**: soil treated with cement (SC)
  - **Part 11**: soil treated with lime (SL)
  - **Part 12**: soil treated with slag (SS)
  - **Part 13**: soil treated with hydraulic road binder (covering proprietary products and recycling processes)
  - **Part 14**: soil treated with fly ash (SF)

- HBMs can be appropriately designed to provide a required strength/stiffness. They offer the potential for either rapid strength gain, in the case of cement treated materials, or at a slower rate, when other binders are used, such as slag and fly ash.
- The use of quarry fines within HBMs in the foundation layer of a pavement may lead to overall cost savings. HBMs provide a stiffer base than foundations constructed using standard materials and techniques, thus the overlying asphalt layers do not need to be as thick, reducing the other material costs. This whole structure and its life-cycle cost is an important issue to consider when assessing the suitability of applying HBMs within the foundation layer.
- The introduction of European harmonised standards for, and developments in the specification, testing and design of pavement foundations, means that HBMs can be economically competitive when compared to historic unbound materials, such as Type 1. This rise in competitiveness, accompanied with an increase in research and material understanding, will assist in a growth in the use of quarry fines in the aggregates market.
- The application of quarry fines within HBMs has the potential for increasing the sustainability of construction projects as it reduces the quantity of these materials stored in stockpiles and increases the value of the material in terms of potential application areas.

By using the performance approach to assessing the suitability of materials, this guidance document provides users with the confidence to consider the application of quarry fines within HBMs. Mechanical and durability testing has shown that the trialled mixtures are viable for application into road foundations, when assessed in line with current provisions, standards and specifications.

Attention should always be paid to the most recent European Standards and Highways Agency specifications and requirements. Assessment on a site specific basis should be carried out prior to any material being applied in a real-life setting. This can be done through the use of mixture trials and site trafficking trials. The durability requirements of a HBM should always be addressed in relation to the environmental and non-environmental factors that could have an impact on the performance of the material during its design life.

For more detailed information on the laboratory trials carried out as part of this project, please refer to the project technical report which accompanies this guidance document [MIST, 2008].

7. SOURCES OF FURTHER INFORMATION

Reference should be made to the following sources of information;

Title	Content
BS EN 14227: 2004 **Unbound and hydraulically bound mixtures – Specifications** • Part 1: Cement bound granular mixtures (CBGM) • Part 2: Slag bound mixtures (SBM) • Part 3: Fly ash bound mixtures (FABM) • Part 4: Fly ash (FA) for hydraulically bound mixtures • Part 5: Hydraulic road binder bound mixtures (HRBBM) • Part 10: Soil treated by cement (SC) • Part 11: Soil treated by lime (SL) • Part 12: Soil treated by slag (SS) • Part 13: Soil treated by hydraulic road binder (SHBB) • Part 14: Soil treated by fly ash (SFA)	Specifies the types, constituents and associated performance classes of a range of aggregates and soils treated with a range of different hydraulic binder types and contents.
BS EN 13242: 2002 **Aggregates for unbound and hydraulically bound mixtures for use in civil engineering work and road construction**	Includes the use of primary, secondary and recycled materials in HBMS. It includes the mechanical, physical and chemical test methods, and the associated limiting values. MCHW series 500, 600, 700, 800 and 1000 are based on this standard.
BS EN 13286: 2003 **Unbound and hydraulically bound mixtures. Test methods.** • Part 1: Test methods for laboratory reference density and water content – Introduction, general requirements and sampling • Part 2: Test methods for the determination of the laboratory reference density and water content – Proctor compaction • Part 3: Test methods for laboratory reference density and water content – Vibrocompression with controlled parameters • Part 4: Test methods for laboratory reference density and water content – Vibrating hammer • Part 5: Test methods for laboratory reference density and water content – Vibrating table • Part 7: Cyclic load triaxial test for unbound mixtures • Part 40: Test method for determination of the direct tensile strength of hydraulically bound mixtures • Part 41: Test method for determination of the compressive tensile strength of hydraulically bound mixtures • Part 42: Test method for the determination of the indirect tensile strength of hydraulically bound mixtures • Part 43: Test methods for the determination of the modulus of elasticity of hydraulically bound mixtures	Details the test methods for assessing the characteristics, physical and mechanical properties, and durability of unbound and hydraulically bound mixtures.

• Part 44: Test method for the determination of the alpha coefficient of vitrified blastfurnace slag • Part 45: Test methods for the determination of the workability period of hydraulically bound mixtures • Part 46: Test method for the determination of the moisture condition value • Part 47: Test method for the determination of California Bearing Ratio, immediate bearing index and linear swelling • Part 48: Test method for the determination of the degree of pulverisation • Part 49: Accelerated swelling test for soil treated by lime and/or hydraulic binder • Part 50: Method for the manufacture of test specimens of hydraulically bound mixtures using Proctor equipment or vibrating table compaction • Part 51: Method for the manufacture of test specimens of hydraulically bound mixtures using vibrating hammer compaction • Part 52: Method for the manufacture of test specimens of hydraulically bound mixtures using vibrocompression • Part 53: Method for the manufacture of test specimens of hydraulically bound mixtures using axial compression	
ETSU General Information Report 49 – Energy minimisation in road construction and maintenance	Discusses the energy benefits of using HBMs in road construction.
Interim Advice Note 73/06 – Design guidance for road pavement foundations (Draft HD25)	Guidance for the design and construction of road pavement foundations.
The Manual of Contract Documents for Highways Works (MCHW) – Series 500, 600, 700, 800 and 1000	The standards and specifications that all Highways Agency highways pavements must meet.
TRL Report 248 – Stabilised subbases in road foundations: structural assessment and benefits	A structural comparison of unbound and stabilised subbases and it provides guidance on thickness design and specification.
Chaddock and Roberts. PPR 127: 3/302_069 – Road foundation design for major UK highways	Specification guidance on the design of flexible, rigid and composite pavements, it provides foundation designs for the four foundation classes.
NF P98 234-1 (1992) - Tests related to pavements. Freezing behaviour of materials treated with hydraulic binders – Part 1: Freeze thaw test of stabilized gravel or sand.	The procedure for carrying out freeze-thaw testing on HBM samples.
Britpave BP/14 – The immediate trafficking of cement-bound materials	Guidance on assessing the immediate bearing index (IBI) of HBMs at the mixture design stage.

7.1 USEFUL WEBSITES

www.aggregate.com – Aggregate Industries
www.aggregain.co.uk – The AggRegain Specifier Tool (designed, developed and hosted by WRAP)
www.berr.gov.uk – Department for Business Enterprise and Regulatory Reform
www.bre.co.uk – Building Research Establishment
www.cement.org - The Portland Cement Association
www.ciria.org – Construction Industry Research and Information Association
www.concretecentre.com – The Concrete Centre
www.goodquarry.com – Part of the University of Leeds
www.highways.gov.uk – The Highways Agency
www.lafarge.com – The Lafarge Group
www.miro.co.uk – The Mineral Industry Research Organisation
www.mi-st.org.uk – The Mineral Industry Sustainable Technology Programme
www.qpa.org – The Quarry Products Association
www.standardsforhighways.co.uk – Standards for Highways
www.tarmac.co.uk - Tarmac
www.trl.co.uk – Transport Research Laboratory
www.viridis.co.uk – Part of TRL. Concerned with creating value from waste
www.wrap.org.uk – The Waste & Resources Action Programme

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