A **cement** and **concrete** industry publication

Hydraulically-bound Mixtures for Pavements

Performance, behaviour, materials, mixture design, construction and control testing

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Hydraulically-bound Mixtures for Pavements

Contents

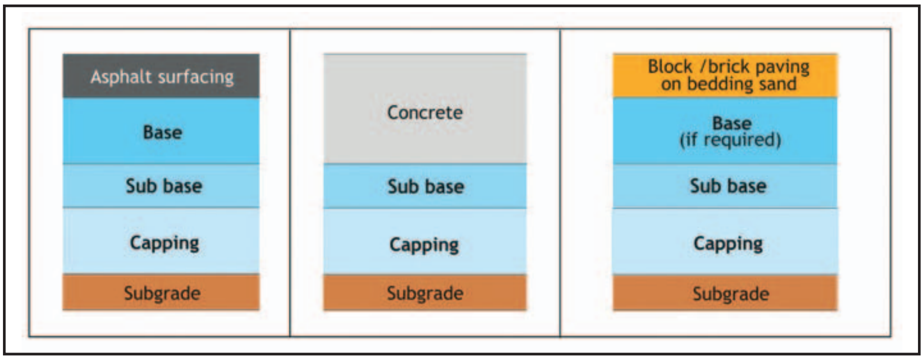
Glossary of terms

ASS	Air-cooled steel slag
BS EN	European Standard published by BSI
CBM	Cement-bound material
CBR	California Bearing Ratio
Cement	Portland cement to BS EN 197-1
E	Modulus of elasticity (also termed elastic stiffness or element modulus/stiffness)
EN	European standard
Fly ash	Pulverised fuel ash (PFA) also known as coal fly ash
gbs(&GBS)	Granulated blastfurnace slag
ggbs	Ground-granulated blastfurnace slag
GPa	Gigapascal
HBM	Hydraulically-bound mixture
HRB	Hydraulic road binder (factory blended hydraulic binder for road use)
IBI	Immediate bearing index (immediate CBR without surcharge rings)
Lift	Referring to layer, which depending on depth, can be constructed in one or more lifts
Lime	quick lime (CaO) or hydrated lime [$Ca(OH)_2$] also known as slaked lime
MCV	moisture condition value
MPa	Megapascal (or N/mm^2 or MN/m^2)
OMC	Optimum moisture content
PI	Plasticity index of a clay (difference between the liquid and plastic limits)
R_c	Compressive strength (normally determined on cylinders with a slenderness ratio of 1 or cubes)
R_{imm}	The ratio of the strength of specimens cured unprotected in water after an initial period of sealed curing, to the strength of specimens cured totally in sealed conditions for the same total time period
R_{it}	Indirect tensile strength (also known as the Brazilian or cylinder splitting strength)
S	Sulfur
SO_4	Sulfate

Foreword

This guide covers the stabilisation of naturally occurring soils or other materials to improve their mechanical properties and performance for use in capping layers, sub-bases and bases as shown in Figure 1. This document, to be in line with European standards and Highways Agency documents, covers treatment with cement and the full range of hydraulic combinations based on fly ash, granulated blastfurnace slag, gypsum and lime. The resulting materials are known as hydraulically-bound mixtures (HBM).

Figure 1
Construction layers (highlighted in blue) where hydraulically-bound mixtures are used (diagrammatic only)



After the introduction, which describes HBM and what they do, the guide describes the following aspects of HBM:

- binder selection
- soil/aggregate selection
- site investigation and preliminary assessment
- mixture design
- production and construction
- construction control.

Each part is designed to be stand-alone and self-contained. Thus for example, should the reader be familiar with the capabilities of the various hydraulic and pozzolanic materials, the first part can be glossed over, or, if guidance is sought solely on construction, then reference need only be made to the fifth and sixth parts. A construction summary is also included in chapter 6 where time does not permit digestion of the whole construction section.

Intentionally, the guide does not cover thickness design and specification, but should provide the background for the formulation of such application documents.

Much of what follows is of direct relevance to the treatment of contaminated materials where a process called stabilisation and solidification can be used to 'immobilise' contaminated materials as well as improving their engineering properties. Similarly, much is of direct relevance to pavement recycling work. However, these techniques are not the subject of this publication.

1. Introduction

1.1 What are hydraulically-bound mixtures?

Large quantities of imported natural aggregates are consumed for use as foundation materials on construction projects. In many cases the addition of cement to the materials already in the ground or available nearby would render them suitable for use and avoid the need to bring in other material. This treatment process is known as cement stabilisation.

Cement stabilisation is a process that combines soil, cement and water to produce a hard, durable paving material that can be used for the foundation or base of road and airport pavements, parking and storage areas. Cement can be used to treat most soils. In addition, deteriorating or failed pavements and roads can also be reconstructed by stabilising (or recycling) the existing pavement using cement.

Materials treated by cement are described variously as soil cement, cement-treated materials or cement-stabilised materials. Where aggregate is being treated, the resultant mixture may, depending on strength or national terminology, be referred to as cement-bound granular material, roller-compacted concrete (RCC), dry lean concrete, cement-bound granular base (CBGB) and cement-treated base (CTB). Whatever the terminology, they are all part of that family of paving materials known generically as cement-bound materials (CBM).

Figure 2
Stationary-mixing plant for the mix-in-plant method of construction.

CBM however are part of a larger family of paving materials known as hydraulically-bound mixtures (HBM) which all possess the advantages ascribed to CBM above. HBM describe soil or aggregate mixtures that use binders made from the following: cement, lime, gypsum, iron and steel slags, and fly ashes from coal-fired energy generation (fly ash is also known in the UK as pfa, which is the acronym for pulverised fuel ash). Such binders are known as hydraulic binders since they set and harden in the presence of water. HBM generally have a water content compatible with compaction by rolling. After compaction, the water is free to hydrate the binder or hydraulic combination and commence the setting and hardening process.

1.2 Why use hydraulically-bound mixtures?

Lower cost

HBM made from in-situ material, or borrow-material taken from elsewhere on the site or nearby, can be over 30% cheaper than the conventional approach of importing granular or other treated material. These savings arise from the use of existing resources and the resultant reduction in the cost of materials and transport. In addition, there may be less need to remove and dispose of material off site – this could also avoid landfill tax liability.

Fast construction

Modern construction methods make HBM quick and easy – thereby reducing contract duration.

Sustainable construction

Since HBM can be made from site arisings, recycled material or artificial materials, primary aggregate extraction is avoided. Traffic between aggregate sources and site can therefore be eliminated. There may also be a reduction in lorry traffic needed to dispose of the site material.

Improved performance

Depending on the aggregate being treated, the properties of HBM can be superior to those of unbound granular materials and often equivalent to those of bitumen-bound materials. Research has shown that HBM sub-bases could be laid up to 60% thinner than unbound granular sub-base, while producing an equivalent or better performance *(TRL 248)* [1]. Alternatively and technically better, it is often more advisable to keep the sub-base thickness the same and use the enhanced performance to reduce the thickness of the more expensive, overlying, pavement layers.

Proven long-term performance

HBM in its various forms have been used in road, airfield, port and other pavement construction for over 50 years. Among other stakeholders, HBM is permitted and used by the Highways Agency, BAA and Associated British Ports.

Figure 3
Grader laying and compaction of mix-in-plant produced HBM.

1.3 How treatment works

HBM is the result of combination between the material being treated and the hydraulic binder, which alters and improves the strength, erosion resistance, durability and volume stability of the soil or material being treated.

How cement works

Cement, here used to describe Portland cements, acts as a stabilising agent because, in the presence of water, the calcium silicates and aluminates in cement form hydrated compounds that subsequently produce a strong, hard matrix that glue the soil or aggregate particles together. The material that has been treated becomes part of this matrix. Cement can be used to stabilise many soils but is most frequently used to stabilise granular or non-cohesive soils where thorough dispersion of the cement is possible because of the non-sticky nature of the soil.

How lime works

Where cohesion prevents proper mixing, such as with medium- to high-plasticity clays, stabilisation is better carried using quick lime (CaO) or slaked or hydrated lime ($Ca(OH)_2$), hereafter just called lime, which initially makes the soil friable and more sand-like before reacting with the soil. Lime produces a high-pH environment, which dissolves the aluminates and silicates from the soil making them available for combination with the lime. The result is calcium silicates and aluminates and thus hydrates capable of setting and hardening as cement. If necessary, the strength of the structure can be enhanced by adding cement at a second mixing stage when the friability of the soil/lime mixture enables efficient mixing and dispersion of the cement as achieved with a granular soil.

Pozzolanic materials

Some soils contain reactive silicates and/or aluminates. These are known as pozzolanic soils or pozzolans. Also most clays and volcanic ashes are pozzolanic. Pozzolans react with freshly hydrated cement or lime to enhance the reaction.

Fly ash

Fly ashes, from coal-fired electricity generation plants are pozzolanic because they contain reactive silicates and aluminates. Such materials react chemically with lime and potentially respond better to lime than cement. It follows also that a lime/fly ash combination may be used as a binder and thus as an alternative to cement for the stabilisation of granular materials.

Hydraulic slags

The slag from iron production, known as blastfurnace slag, is a versatile construction material since it can be used as an inert aggregate or as a cementitious material or constituent in its own right, depending on how it is conditioned when discharged from the blastfurnace. If allowed to air-cool, an almost inert, hard, crystalline material is produced, which can be crushed to produce aggregate. If quenched rapidly in water, on the otherhand, a vitrified (glassy) product is produced, which has hydraulic potential. This latter product is known as granulated blastfurnace slag (gbs), which is naturally but slowly cementitious. Gbs ground to enhance its speed of reaction is known as ground granulated blastfurnace slag or ggbs.

Like fly ash above, ggbs is a well-known constituent of concrete, frequently used to enhance the properties of concrete as well as substituting for Portland cement. Also, like fly ash, gbs or ggbs can be used with lime as a cementitious combination for the treatment of granular materials.

Clays treated with slag and or fly ash

The lime/ggbs combination is also effective with clays, capable of matching the potential of the lime/cement combination. In this respect, ggbs may be better suited than fly ash since it is effectively a cement, whose hydraulicity or cementitious potential is enhanced by lime. Fly ash, on the other hand, being a pozzolan, only becomes hydraulic or cementitious in the presence of lime or a source of lime. Since clay is also a pozzolan, it should be apparent that the addition of another pozzolan, i.e. fly ash, to a material that is also a pozzolan, such as clay, is unnecessary. However, when the clay is of low plasticity or the natural silicates and aluminates in the clay are relatively unreactive, the addition of fly ash can be very beneficial.

Steel slag

It is possible to utilise the lime content in the slag produced from steel production for stabilisation purposes. This slag, known as air-cooled steel slag (ASS), is particularly suited, when combined with gbs, to the treatment of sands or combinations of fine and coarse aggregate.

Speed of reaction

Although the speed of reaction is slower than with cement stabilisation, the use of lime stabilisation or lime with fly ash or gbs or ggbs stabilisation is a perfectly viable and proven option. More importantly, however, the above discussion illustrates the wide range of possibilities with certain materials and that stabilisation has the flexibility to treat most available soils and materials.

1.4 European and British standards

BS EN 14227 [2] for HBM reflects the range of materials and binder options described above, and, in addition, permits a wide flexibility regarding performance.

The standard is in 10 parts. Broadly, half cover the treatment of processed aggregates complying with the BS EN for aggregates, and the other half the treatment of soils. For each, a wide spread of hydraulic binders or hydraulic combinations is covered. For example, there is a part that covers the treatment of aggregate with fly ash (or more accurately by a combination of fly ash with either lime or cement but with fly ash the main constituent of the binder) and a part that covers soil treated by fly ash. There are corresponding parts covering cement, lime, gbs and materials specifically called hydraulic road binders (HRB). HRB are factory-produced hydraulic binders specially formulated for road use. Typically, they are blends of ggbs and or fly ash with lime and gypsum or cement. Although unavailable in the UK, they are used extensively on the continent.

The scope of each part of the standard is much the same, however, covering:

- permitted constituents
- permitted mixture types (distinguished by aggregate type)
- laboratory mechanical performance classification.

It should be noted that the standard does not address production or construction issues or application. These issues are considered the responsibility of individual nations, the rationale being that the mixtures are products for users to apply in their own situation.

Regarding laboratory mechanical performance classification, the choice is also deliberately wide, to cover all European practice and needs. Performance can be specified by California bearing ratio (CBR), compressive strength or the combination of tensile strength and modulus of elasticity, each with a range of classes to cover any level in the pavement and traffic application.

2. Binder selection

As indicated in the introduction, a wide range of materials can be treated with hydraulic binders, although some binders or hydraulic combinations are more suitable for some materials than others. Furthermore, the viability of a certain material for treatment may be a function of application, e.g. capping, sub-base or base, and thus the strength and long-term performance requirements, as well as construction conditions and requirements. For example:

- construction trafficking requirements
- time of opening to in-service traffic
- time of year of construction.

Thus it is necessary to consider further what can actually be achieved in order to ascertain the viability for use of a certain soil, aggregate or binder.

2.1 Long-term performance

Whether cement, lime/cement, lime/fly ash, ASS/gbs or lime/ggbs, all HBM ultimately achieve similar structural properties. The long-term mechanical performance properties of HBM are essentially a function of aggregate type or the type of soil being treated. Typically, ultimate elastic stiffness is a good indicator of long-term performance and thus suitability for capping, sub-base or base use. This is shown in Table 1. Further information on elastic stiffness can be found in *TRL 408* [3] noting however that *TRL 408* quotes stiffness measured using the Nottingham Asphalt Tester.

Figure 4
Completed HBM layer with an aluminised resin-based seal coat.

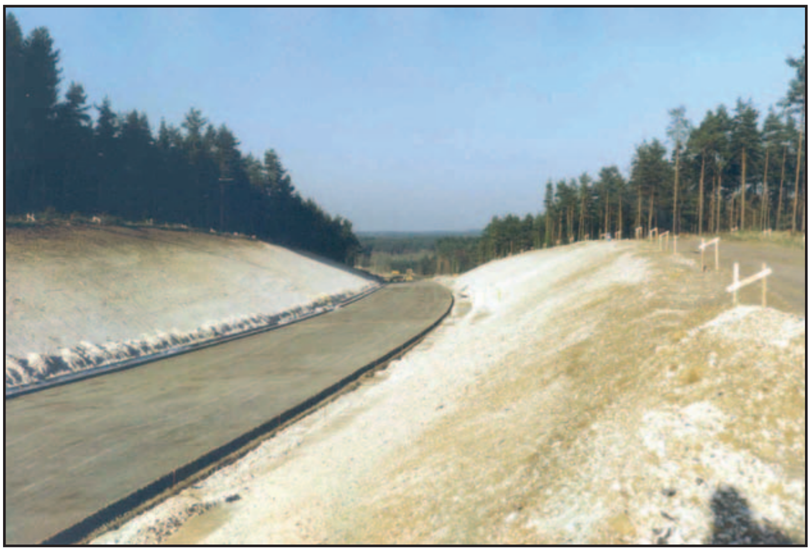


Table 1
Indicative ultimate static elastic stiffness and layer applicability of HBM as a function of soil/aggregate type and layer applicability.

Material to be treated	Medium-plasticity soils	Low plasticity soils, silty materials, flyash, chalk	Sands, planings, air-cooled slags, gravel, crushed rock
Ultimate static elastic stiffness (GPa) irrespective of hydraulic binder type	< 2	2–7	> 7
Layer applicability increasing from left to right	Capping ----------------------> sub-base----------------------> base		

However, depending on the binder, the rate of development of these long-term mechanical properties may be very different. As an example of the strength development, Table 2 compares the strength development of a well-graded hard granular material treated with lime/fly ash, cement/fly ash and cement.

Table 2
Strength development of cement/lime/fly ash combinations at 20°C using well-graded granular material as aggregate.

BINDER (percentages are tentative but indicative)	Compressive strength (MPa)					
	3 days	7 days	28 days	56 days	91 days	1 year
~ 5% cement	7	10	13	15	17	21
~ 3% cement + 7% fly ash	5	6.5	15.5	18.5	21.5	25
~ 2% lime + 8% fly ash	–	2.5	9	14	18.5	28

It should be noted that Table 2 illustrates the position at 20°C. However, the strength development of HBM is temperature dependent and Table 3 shows the comparative situation at 40, 20 and 10°C for a lime/fly ash-treated aggregate of similar proportions as that shown in Table 2 but made from a different fly ash and aggregate.

Table 3
Compressive strength development in MPa of lime/fly ash-treated aggregate at different temperatures.

Compressive strength (MPa)							
Temperature	7 days	14 days	28 days	56 days	91 days	182 days	1 year
40°C	3	5	10	11	–	–	–
20°C	1	–	2	–	6	9	11
10°C	0.5	–	1	–	4	–	7

Tables 1–3 together confirm that not only are the mechanical properties a function of aggregate type, but also the binder, and in the example used the source of the fly ash. It is important to remember that all fly ashes are different and the use of one for one job may not translate to another fly ash or job. Tables 2 and 3, which illustrate the use of the lime/fly ash combination, can also be taken to approximately illustrate the properties of HBM based on lime, ASS, gbs and ggbs.

From a pavement design point of view, the slower, more progressive rate of gain of strength of HBM made from slow setting and hardening binders, produces a layer with finer and self-healing cracks compared with cement. As a result, it should be possible to reduce the thickness of the overlying asphalt surfacing thickness compared with CBM.

2.2 Short-term performance

Coupled with this slower hardening and strength development, 'non-cement' HBM's exhibit a slower set and:

- have extended workability times compared with CBM, pavement quality concrete and hot-mix asphalt
- can be 'reworked' in the short-term (say 2 days for lime/fly ash, and even longer for ASS/gbs binder – *see Table 10*) to remedy construction faults.

Despite this slower set and hardening it is also possible to open such HBM to traffic immediately without the need for curing/non-trafficking periods. Treated fly ash is an exception and has special rules (refer to the section on trafficability in chapter 5). However, it is important to note that the short-term trafficability cannot be a function of strength, as is the case with CBM that are cured for 7 days, but instead has to be a function of the internal cohesion and friction (mechanical interlock) within the mixture. It follows therefore that it is necessary to establish 'the ability of such HBM to withstand immediate trafficking without detriment to the long-term development of strength and stiffness' in order to judge their suitability for immediate use.

Note that immediate use can also apply to CBM made from well-graded hard granular material and that with such aggregate, whether treated with 'quick' or 'slow' binders, suitability for immediate use can be assumed when there is at least 50% crushed material in the well graded aggregate (*BP/14*[6]). However, other aggregates and soils require laboratory examination of trafficability and the test used to ascertain this capability is known as the immediate bearing index (IBI) test (*BS EN 13286-Part 47*[4]). This test and requirements are considered in more detail in chapter 5.

Figure 5
Fresh HBM under site traffic.

In the majority of cases, whether the binder is quick or slow, the strength of HBM will be satisfactory for trafficking purposes. However, where significant early strength development is deemed necessary for frost resistance or when it is necessary to open the pavement early to very heavy in-service traffic, it may be necessary to avoid using certain HBM in late season and winter. This is to allow setting and hardening, and thus adequate strength development for frost resistance or trafficking purposes, to take place before the cold weather arrives. Note that this generally means:

- one to two months before the first significant frosts for binders based on lime/ggbs and lime/fly ash combinations (thus a preferred laying season of April to September inclusive)[1]
- 14 days to one month for cement or cement/fly ash or cement/ggbs or binders based on lime/fly ash/ggbs using a gypsum accelerator (thus a preferred laying season of March to October inclusive).

a. UK experience in winter with Flushing SBM (previously known as phosphoric slag), a mixture based on the combination of 'air-cooled phosphorus slag + GBS + ASS activator', has been good, but paradoxically this mixture is the slowest setting and hardening of all the mixtures considered in this document. Its successful performance, even in late season, is primarily a function of the quality of the constituents used and the fact that in late season, its early life performance is more akin to a good quality Type 1 granular sub-base.

2.3 Summary of binder applicability

To summarise, but subject to performance requirements and mixture design (refer to chapter 5), Table 4 is presented to help with binder selection.

Table 4
Binder options for HBM related to material, seasonal and construction trafficking requirements.

Aggregate	Immediate trafficability	Hydraulic binder options					
		Cement	Lime + cement	Lime	Lime + fly ash	Lime + ggbs	Lime (or ASS) + gbs
Well-graded hard material	Yes irrespective of binder	Yes	N/A	N/A	Yes	Yes	Yes
Sands	Subject to IBI test or, in the case of cement, use a 7-day non-trafficking period	Yes*	N/A	N/A	Yes	Yes	Yes
Poorly-graded / uniform hard material	"	Yes*	N/A	N/A	Yes	Yes	Yes
Well-graded weak rocks	"	Yes*	N/A	N/A	Yes	Yes	N/A
Chalk	"	Yes*	Yes	Yes	Yes	Yes	N/A
Brickearth	"	Yes	Yes	Yes	Yes	Yes	N/A
Low-plasticity clay	"	N/A	Yes	Yes	Yes	Yes	N/A
Medium-plasticity clay	"	N/A	Yes	Yes	N/A	Yes	N/A
High-plasticity clay	"	N/A	Yes	Yes	N/A	Yes	N/A
Fly ash	Refer to 'trafficability' in chapter 5	Yes	Yes	Yes	N/A	N/A	N/A
Effect of heavy rainfall during laying		Possible surface damage and removal of fines, including binder, from the surface					Possible but ASS + GBS with clean hard aggregate is particularly well suited.
Work in late season unless overlain immediately		Avoid unless R_{it}** > 1MPa before first frost		Not recommended			Possible but ASS + GBS with clean hard aggregate is particularly well suited.

* Where cement demand is high, fly ash or ggbs could be added before or at the same time to reduce cement content.
** Indirect tensile strength

3. Soil/aggregate selection

In combination with the previous chapter, it is also necessary to consider in more detail the ability on site to treat or process a material with hydraulic binder.

This section therefore examines:
- soil/aggregate suitability
- grading optimization
- mixer capability.

3.1 Soil/aggregate suitability

Materials that can be considered suitable for treatment to produce capping, sub-base or base fall into two categories -

Those materials that can be treated without preliminary processing:
- low plasticity clays
- silt-sized materials, such as brick-earth or fly ash
- granular materials ranging from crushed materials to clean sands or gravel–sand mixtures to variable mixtures of gravel, sand, silt and clay.

Materials that can be rendered suitable following pre-treatment or modification:
- uniformly graded materials
- medium- to high-plasticity clays
- materials containing either acids or organic matter or sulfates.

Considering uniformly graded materials, high percentages of binder are required for the stabilisation of such materials, either because the surface area of aggregate is large or because the binder needs to act as a void-filler. The addition of another aggregate or material that reduces the surface area to be coated or fills the voids will obviously reduce the binder demand. Fly ash can be useful for this purpose and it has the added advantage of its pozzolanicity and thus ability to react hydraulically with lime, or the calcium hydroxide liberated during cement hydration, therefore helping to reduce binder demand.

With regard to the more plastic clays, lime treatment is often usually sufficient for capping purposes and possibly, providing sufficient lime is added, for sub-base application. For this latter application, however, other binders or hydraulic components can also be added to the clay after pre-treatment with lime. The amount of lime needed can be as little as 1.5% by weight. The addition of lime renders the clay friable, making it suitable for subsequent treatment using cement or ggbs. More information on the action of lime on clay can be obtained from the British Lime Association.

Regarding soils or materials containing acidic or organic matter, such contaminants can delay the setting of the binder. If delayed set is a problem, the use of extra binder may neutralise the acidity of the material and reduce the retardation effect.

The other aspect of chemical contamination to consider is that of sulfate/sulfides and sulfate-bearing groundwater. These chemicals can cause the expansion and disintegration of hydraulically treated layers. However, sulfate attack is not usually a problem unless free water, other than that available in the treated material, is available. Research and practice indicates that certain soil types are more susceptible to sulfate/sulfide contamination, that extensive and detailed site investigation and testing is required, and that current knowledge suggests that lime/ggbs is the preferred combination where sulfates are an issue (*BP/16*)[7].

3.2 Grading optimization

As already indicated in Chapter 2, the ability to take traffic immediately even with cement treatment, is a function of aggregate type and grading. In addition and particularly in the case of high binder additions [for example with the lime/fly ash combination where the use of 3% lime + 12% fly ash may not be unusual when conditioned fly ash is employed] it is the overall grading of the total mixture that is important from an immediate trafficking point of view, particularly where heavy construction or in-service traffic is the norm.

For this reason, it is necessary to be aware that some of the European Standards for HBM, typically those not employing cement, have grading requirements for the total mixture, whereas that for cement alone as the binder has (mainly) grading requirements just for the aggregate.

Note that:

- With the lime/fly ash binder combination, the fly ash is powder-like and augments, or can be, the fine ‘fines’ element of the ‘aggregate’. As a result, this binder combination is more suited to the treatment of clean aggregates lacking in fine ‘fines’, such as planings, where the use of filler would be advantageous and even necessary. if cement were used In this case, the flyash content is decided primarily on the basis of grading optimisation for mechanical stability.
- A similar situation arises with lime/gbs or ASS/gbs combinations. Visually gbs looks like coarse clean sand. It can thus form part of the ‘< 4mm’ element of a mixture, and thus is better suited for use with a coarsely graded material.
- Where an aggregate or sand is poorly graded, it is likely that the addition of fly ash or gbs will be beneficial from grading and trafficability perspectives. Having thus made the decision to add fly ash or gbs, all that is then required to complete the mixture is to add a small percentage, 2% or 3% of lime or 3% or 4% cement, for setting and strengthening to take place.

Therefore as part of the soil/aggregate selection process, it is important to consider the grading specification, if there is one, for both the mixture and/or the ‘aggregate’. Since HBM with an excess of fines may have poor mechanical stability, this will help ascertain whether the mixture can accommodate a ‘large’ binder addition based on fly ash or gbs.

In this respect, the recommendations for grading should comply with the European standards (*BS EN 14227*) [2], which include HBM with grading envelopes capable of supporting immediate trafficking, preferably targeting the middle of the envelope, particularly at the bottom end. For other materials or where there is doubt or uncertainty, then it is necessary to carry out a laboratory test that simulates trafficability. This is known as the IBI test. This should be examined at the mixture design stage. For treated fly ash, where fly ash is effectively the aggregate, there are different rules (see section on Trafficability in chapter 5).

3.3 Mixer capability

A wide range of material can therefore be treated using a wide range of binders but successful treatment depends upon the ability to properly 'handle' the aggregate/soil and then properly mix the material and binder. A suggested guide is given in Table 5.

Table 5 shows that the mix-in-place method can process a wider range of materials, because in contrast with the mix-in-plant method, the problem of feeding the material into the mixing unit does not exist. However, decisions on choice of method must consider the quality of the final product given that the mix-in-place method can never match the quality of the mix-in-plant method using pugmill-mixing with weigh-batching, provided the latter method can handle the material (see section on 'choice of method' in chapter 6).

Figure 6
Mix-in-place method of construction (also known as in-situ stabilisation) showing the previously-spread binder, being mixed with the in-situ materials

Table 5
Guide to mixing capabilities for HBM.

Method of construction	Type of mixing unit	Suitability according to material type			
		Clean granular	Granular with up to 15% passing 63 µm	Fly ash, silts and cohesive material with up to 35% passing 63 µm and plasticity index (PI) < 10	Clays with PI > 10
Mix-in-plant or stationary plant or ex-situ process	Free-fall gravity	Possible but not recommended	No	No	No
	Pan or paddle	Yes	Possible but modification may be necessary to hoppers, aggregate feed and discharge	No	No
	Pugmill	Yes	Yes	Possible provided hoppers and aggregate feeds and discharge are properly designed	Possible but not normally practicable
Mix-in-place or in-situ process	Purpose-made rotovator mixer	Yes	Yes	Yes	Yes

4. Site investigation and preliminary assessment

This section considers the important issues of site investigation and initial assessment to determine whether to proceed to the mixture design stage. Initial assessment also considers the economic viability of producing HBM from the material concerned.

4.1 Soil survey

- If stabilisation of the in-situ soil is being considered, the primary purpose of the survey is to locate, identify and sample the various types of soil encountered so that they can be tested for suitability. Take samples of soil at such depths and frequencies as to be properly representative of the soils to be processed; to ensure this, the horizontal and vertical alignment of the pavement should be known beforehand. The frequency at which samples should be taken will depend largely on the number of changes in soil type over the proposed area of pavement and, particularly with clays, whether sulfates/sulfides are suspected.
- If soil or aggregate is to be imported from a borrow pit or transported from a cutting to an embankment or taken from stockpiles, the pit/cut/stockpile should be sampled at regular intervals throughout its area and at several depths.

The general principles to be observed in taking samples are described in *BS 1924* [5].

4.2 Economic viability

During this part of the process, the economic viability of treatment also needs investigation so that a decision can be made whether to proceed with laboratory testing.

An estimate of the binder requirement of many materials can be established from a visual examination of the material concerned. Indicative binder demands of materials suitable for the production of HBM for capping, sub-base and base are given in Table 6. This should allow an economic assessment to be made.

Table 6
Indicative binder contents taking into account batching efficiency and durability issues.

Aggregate	Application (indicative only)	Indicative compres-sive strength (MPa) or CBR	Indicative laboratory static elastic modulus (GPa)*** $_s$	Indicative additions (kg/m³) assuming components are added separately. Refer also to**					
				Cement alone	Lime+ cement	Lime alone	Lime+ fly ash **	Lime+ ggbs	Lime (orASS) + gbs
Well-graded & hard*	Subbase/base	4 +	~ 10	70	N/A	N/A	40+160	30+70	60+200
	Base	8 +	~ 15	90	N/A	N/A	50+200	30+90	60+200
Well-graded sand*	Subbase/base	4 +	~ 7	110	N/A	N/A	50+200	30+110	60+250
	Base	8 +	~ 10	140	N/A	N/A	60+240	30+140	60+250
Poorly-graded*	Capping	CBR 15%	-	60	N/A	N/A	N/A	N/A	-
	Subbase/base	4 +	~ 7	150	N/A	N/A	60+240	30+150	60+300
	Base	8 +	~ 10	200	N/A	N/A	70+280	30+180	60+300
Weak rocks*	Capping	CBR 15%	-	60	N/A	N/A	N/A	N/A	-
	Subbase/base	4 +	~ 7	150	N/A	N/A	50+240	30+150	N/A
	Base	8 +	~ 10	200	N/A	N/A	60+280	30+180	N/A
Soft chalk	Capping	CBR 15%	-	60	20+40	PNP	20+80	20+40	N/A
	Capping/subbase	~ 1	~ 2/3	120	30+90	PNP	40+120	30+90	N/A
Brickearth	Capping	CBR 15%	-	50	N/A	N/A	20+80	20+40	N/A
	Capping/subbase	~ 1	~ 2/3	120	N/A	N/A	40+120	30+90	N/A
	Subbase/base	4 +	~ 5	170	N/A	N/A	40+160	40+120	N/A
Clay of low plasticity	Capping	CBR 15%	-	50	30+30	N/A	30+80	30+30	N/A
	Capping/subbase	~ 1	~ 2/3	120	30+90	N/A	40+120	30+90	N/A
Medium plasticity	Capping	CBR 15%	-	N/A	30+30	50	N/A	30+30	N/A
	Capping/subbase	~ 1	~ 2	N/A	40+160	120	N/A	40+160	N/A
Clay of high plasticity	Capping	CBR 15%	-	N/A	N/A	70	N/A	N/A	N/A
	Capping/subbase	~ 1	~ 1	N/A	N/A	PNP	N/A	N/A	N/A
Fly ash	Capping	CBR 15%	-	50	N/A	50	N/A	N/A	N/A
	Capping/subbase	~ 1	~ 4	100	N/A	70	N/A	N/A	N/A
	Subbase/base	4 +	~ 7	140	N/A	100	N/A	N/A	N/A

Key
N/A – not applicable
PNP – possible but not proven?

Notes
* It is also important to consider the grading or nature of the material being treated to ascertain whether it can accommodate a 'large' binder addition based on fly ash or gbs. This is because an HBM with an excess of fines may have poor mechanical stability and may not support immediate trafficking without significant disturbance. This is undesirable for slow-setting, slow-hardening HBM.
** Assumes run-of-station conditioned fly ash. If lime and dry fly ash are factory-blended, total addition may be 50% of that indicated.
*** Also known as element modulus

4.3 Laboratory classification and chemical tests

If this initial assessment indicates that stabilisation is economically viable, laboratory tests should be carried out on the material to determine its uniformity.

Classification tests

Such tests should include classification tests for determination of particle size distribution for granular materials, and determination of liquid and plastic limits for cohesive materials or both if necessary. The laboratory preparation and testing techniques are described in *BS 1924*[5].

Chemical tests

As already discussed, it is advisable to test the material for organic or sulfate contamination, as described below.

Considering organics, use the test in *BS 1924* to detect the presence of acidic matter that could interfere with binder hydration. Even if the test proves positive, it may be possible to treat such materials by using higher binder contents. The strength tests carried out during the mix design process (*refer to chapter 5*) will indicate whether or not the potential interference can be overcome in this way.

Where sulfates/sulfides are suspected, current advice for fine grained materials is described in *BP/16*. This stresses the need for a desk-top study. This may eliminate the relevant soil/material before any sampling and laboratory testing is undertaken. Even if the decision is made to continue evaluation, extensive sampling for sulfate/sulfide testing is recommended before making the decision to proceed with mixture design and volume stability testing. This is discussed in more detail in the next chapter on mix design.

4.4 To proceed with the next stage?

The results of these classification and chemical tests may indicate that stabilisation is not viable. This may be as a consequence of chemical contamination, material variability, inability to handle the material or simply a matter of straightforward economics. There is therefore no value in testing further. However if the results are satisfactory, mixture design testing can be commenced.

5. Mixture design

For CBM, which traditionally have had a curing period of 7 days before trafficking, the primary objectives of the mixture design procedure has been to find the correct water content for compaction of the material by rolling, and the cement content required at that water content to meet the required mechanical performance. Equally important objectives have included durability and volume stability.

However, with the advent of the lime/fly ash, lime/ggbs and ASS/gbs binder combinations, where strength development is slower and curing periods not necessary, the ability of the mixture to support traffic immediately has also become one of the primary objectives of the mixture design procedure. As discussed earlier in chapter 3, this ability to support traffic is a function of the grading of the mixture.

5.1 Philosophy and basis of test procedure

Field compaction experience with HBM illustrates that:

1. There is an optimum moisture content (OMC) for compaction, above or below which reduced dry densities are obtained.

It has also been found that the mechanical performance (strength, bearing capacity or stiffness) of HBM is dependent upon binder content and dry density so that:

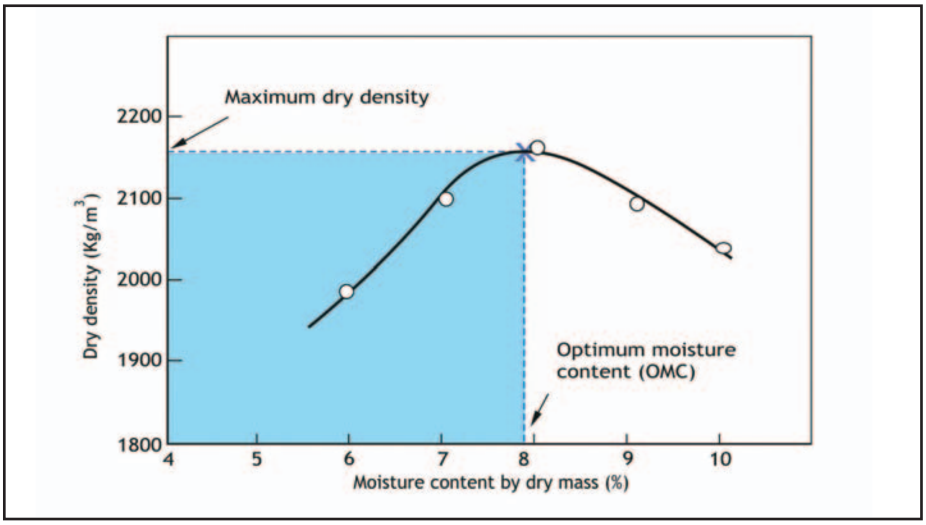
2. For constant binder content and water content, the mechanical performance increases as the dry density increases, and
3. For constant dry density and water content, the mechanical performance increases as the binder content increases.

These three relationships form the basis of the mixture design procedure for HBM.

Relationship 2 states that mechanical performance is dependent upon dry density, which in turn (relationship 1) is dependent upon moisture content. Thus mechanical performance strength and therefore binder content are dependent upon moisture content. It follows therefore that after grading considerations where appropriate, the first stage in the mixture design procedure must be to determine the water content.

To do this, the material, including an estimated quantity of binder, is compacted into a series of moulds over a range of moisture contents. Note that it is necessary to add the binder for the determination of OMC, since at the compaction stage, it constitutes part of the aggregate and thus affects the water demand for compaction. Following compaction, the dry density of the mixture contained within each mould is determined and plotted against moisture content. The OMC can then be established from the curve (Figure 7).

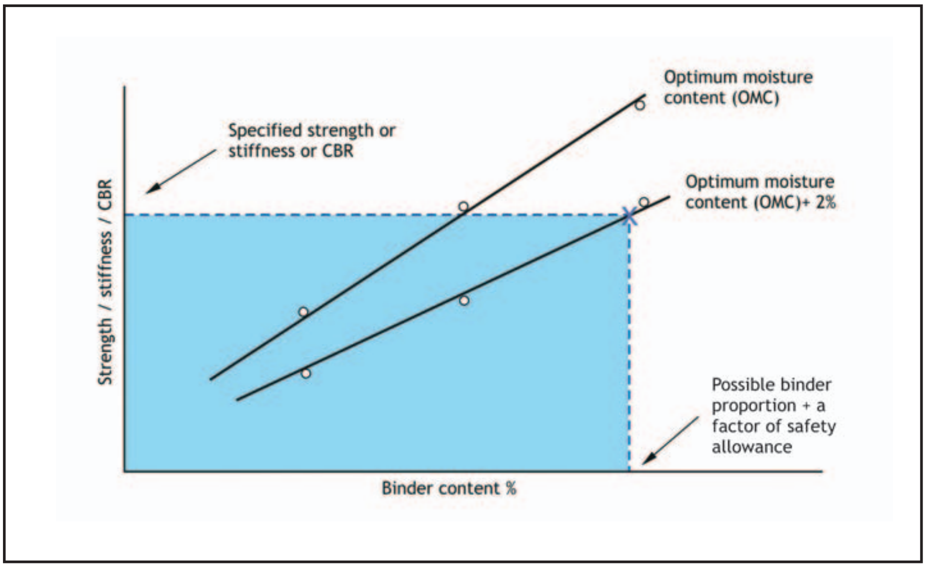
Figure 7
Example of dry density/moisture content relationship.



The second stage in the mix design procedure is to determine the exact binder content required. Using the value of OMC determined above, make specimens over a range of binder contents. After curing, test the specimens for strength, which is then plotted against binder content (Figure 8).

It is recommended that this stage is repeated using a higher moisture content, say OMC + 2%. As with concrete, the strength of HBM reduces at higher water contents or in other words higher water/binder ratios. It is necessary therefore to cater for situations where water content could be high either by design or accident. The binder content can then be chosen so that the control specimens will meet the specified strength requirements.

Figure 8
Example of strength/binder content relationship.



The third and fourth stages then examine trafficability and the aspects of durability and volume stability, respectively. However the ability to take traffic is probably better examined before the more time consuming and expensive stage 2.

5.2 Mechanical performance requirements

As the advent of slow-setting, slow-hardening HBM has meant a change in the mixture design process, so have developments in pavement design.

Previously, pavement design has been largely empirically based with the result that mixture design has concentrated on the laboratory examination of properties like CBR and compressive strength, properties that have little relevance from a performance point of view. However, in recent times a more analytical approach has been and is being employed. This has necessitated a change or addition to the properties normally measured, to include examination or the determination of fundamental mechanical properties such as laboratory tensile strength and modulus of elasticity, which have a direct bearing on performance and thus pavement design.

The two latter properties form the basis of the versatile design method reported in *TRL 615* [8], which is the basis of the current UK Highway Agency's pavement and foundation design documents. Associated with this, it should be noted that performance from a pavement design point of view is now characterised in the UK at 365 days and this necessitates measurement or the estimation (using 28-day testing) of mechanical properties in the laboratory at 365 days. Further information can be found in *TRL 408*.

Thus a set of results similar to that illustrated in Table 7 will be required for large important jobs.

Table 7
Suggested framework testing for laboratory mechanical performance for selected binder and water content.

HBM type	Curing temperature	Age of test of sealed specimen *					
		7 days	14 days	28 days	56 days	91 days	365 days
Without cement	40°C	XXX	XXX	XXX	–	–	–
	20°C	–	–	XXX	XXX	XXX	XXX
With cement	20°C	XXX	XXX	XXX	XXX	XXX	XXX

NOTE:
For mixtures using binders without cement, refusal cylindrical specimens cured at 40°C and tested at 28 days have been found, as a rule, to achieve between 80% and 90% of the 365-day strength/stiffness at 20°C. For mixtures containing cement, a similar relationship exists but between 28-day/20°C and 365-day/20°C.

* X denotes one result for one property be it modulus or strength

5.3 Test procedure

Carry out the testing in accordance with *BS EN 13286* and *BS 1924*.

Initially the material(s) should be at known, consistent and relatively low moisture content. This will usually require air-drying in the laboratory or, if necessary, oven drying, but the latter should be carried out only on clean hard aggregates. If cohesive material is oven dried, it will merely bake and produce hard lumps.

Stage 1 – Determination of optimum moisture content

Non-cohesive soils/aggregates

Make initial estimates of the likely required binder content and of the OMC for the mixture.

Depending on the level of mechanical performance property being considered, the binder contents indicated in Table 6 may be used at this stage with due regard to the table notes relating to the addition of binder constituents added separately at site or factory pre-blended. In any event, the binder content added at this stage should be not less than the minimum specified by the contract.

The estimated OMC for various mixtures is given below. The low figure of the range can be considered typical of mixtures made from cleaner/coarser material:

- Granular mixtures: 5–8% by dry weight
- Sand mixtures: 8–12% by dry weight
- Fine-grained mixtures made from chalk, silt or fly ash: 15–25% by dry weight.

Using the estimated value of OMC and two appropriate values above and two below, mix a quantity of water, less an amount equal to about 3% of the mass of dried soil or aggregate, into five separate samples of the material in order to bring the material to the required values. In the case of fine-grained materials, the moist material should be allowed to stand for 24 hours in an airtight container; with other materials the mixing with binder may proceed at once.

The likely binder content and the remaining water is then mixed into each sample of material.

In the case of granular or sand mixtures, mix the material, binder or binder constituents and water until a uniform mixture is produced. This applies whether the mix-in-place method or central-plant mixing is to be employed on site.

Where the mix-in-place method of production is to be employed, the following should also be observed:

- For chalks treated by lime followed by cement, ggbs or fly ash, experience suggests that the chalk benefits from adding the lime first since it seems lime seals or ‘case-hardens’ the chalk lumps making the chalk workable and stable. Evidence suggests that this improvement is relatively quick such that the second addition can proceed, say, 2 hours later, although the following day may be preferable to suit site programming.
- For non-cohesive materials treated by a combination of cement and, say, fly ash or ggbs (advantageous where the use of cement alone would mean a requirement for a large quantity of cement to be added in one operation), the cement should always be added second, approximately 2 hours after the first addition. If the cement is added first, there is the possibility that setting and hardening of cement will occur before or during the second addition (this is equally the case with cement added in two stages).
- For non-cohesive materials treated by separate additions of lime and either fly ash or ggbs, the order of addition is not an issue.

From each sample, carry out one density determination using the following methods of compaction:

- For HBM with performance specified by compressive/tensile strength or elastic stiffness, use vibrating hammer compaction in accordance with BS EN 13286-4.

- For medium and coarse-grained HBM with performance specified by CBR, use 4.5kg Proctor compaction in accordance with BS EN 13286-2.
- For fine-grained HBM with performance specified by CBR, use 2.5kg Proctor compaction in accordance with BS EN 13286-2.

Determine the sample mass and volume for each determination. The compacted material should be taken from the mould, and the moisture content of a representative sample of the material determined in accordance with BS 1924. Calculate the dry density for each determination, and plot a curve of dry density versus moisture content. The OMC (and also the maximum dry density if required) can be established from the curve (Figure 7). It may be necessary to establish further points near the peak of the curve in order to define the OMC clearly.

In the case of clean gravel and sand mixtures using cement, the results may not provide a clearly defined peak. This is because the lack of fines allows the thin paste of the wetter mixes to be pumped out of the material during compaction. However, experience has shown that for such materials the moisture content suitable for compaction in the field is in the region of 4% to 6% by mass.

Cohesive soils

Current practice and specifications mean that it is not absolutely necessary to determine the OMC of cohesive mixtures. Instead it is possible to go directly to the 'determination of the binder content stage' and prepare mixtures at selected moisture condition values (MCV) as described below in stage 2.

Stage 2 – Determination of the binder content

For the determination of the necessary binder content, prepare specimens for testing over a range of binder contents. The procedure and specimen manufacture depends on the setting of the binder and whether performance is specified by strength, stiffness or CBR.

- Examine at least three binder contents. One value should be at or near the binder content used to determine OMC, with an appropriate value below and another above.
- Select water contents corresponding to OMC and OMC + 2%, or, for cohesive mixtures, the corresponding MCV. For convenience and speed on site, the MCV test described in BS EN 13286-46 is frequently used to determine the suitability of a cohesive mixture for compaction. Typically, a MCV range of 12 to 8 indicates suitability, with MCV 12 corresponding to OMC and MCV 8 to OMC + 2%. These values are recommended for use in the laboratory for the determination of the binder content for cohesive mixtures.
- *For cohesive materials treated with quicklime alone*, add and mix the lime with the soil. The quicklime content indicated in Table 6 can be used. Sufficient water should be available at this stage to fully slake the quicklime by using a target MCV value of 10. Store the material overnight in waterproof bags.
- *For cohesive materials pre-treated with quicklime*, carry out the pre-treatment 24 hours in advance of adding the other stabiliser, storing the material overnight in waterproof bags. Again the quicklime content indicated in Table 6 can be used. Alternatively use an

amount that renders the clay friable. Normally 1.5% would be the minimum. Sufficient water should be available to fully slake the quicklime by using a target MCV value of 10.

- *For other hydraulic combinations*, follow the advice on order of treatment described in stage 1.
- Mix each combination of binder and water content, until it is uniform.
  - In the case of cohesive mixtures treated by lime alone, mixing should continue until 95% of the clay fraction passes the 28mm sieve and the degree of pulverisation is greater than 30% measured in accordance with BS EN 13286-48.
  - In the case of cohesive mixtures treated by cement alone, mixing should continue until 95% of the clay fraction passes the 28mm sieve and the degree of pulverisation is greater than 60%.
  - In the case of cohesive mixtures treated by lime followed by cement, ggbs or fly ash, 95% of the clay fraction should pass the 28mm sieve and the degree of pulverisation should be greater than 30%.

Note that the recommended degree of pulverisation is less for mixtures containing lime than for mixtures containing cement alone. This is because it is understood that the dispersion of lime continues after mixing. It should also be noted that the measurement of pulverisation may be difficult with mixtures with MCV less than 12 because of the sticky-nature of the mixture.

Performance specified by strength and/or modulus of elasticity

- For each mixture, make sufficient specimens using vibratory compaction to refusal in accordance with of BS EN 13286-51 to satisfy the requirements of the test schedule. For cement-containing mixtures, cubical or cylindrical specimens can be used. For non-cement-containing mixtures, cylinders must be used, and, because setting and hardening is slow, specimens of non-cohesive mixtures will need to be stored in their moulds. Moulds cut from plastic pipe with 10mm wall thickness have proved suitable for this purpose and comply with BS EN 13286-51.
- Cure the specimens in accordance with the specification, but usually in a sealed condition at 20°C for cement-based mixtures and 40°C for non-cement mixtures, for testing at ages in accordance with the test schedule. Test either in direct tension, compression, indirect tension or for elastic modulus as described in BS EN 13286-40, 41, 42 and 43, respectively.
- Using the average of each set of results, plot strength/modulus against binder content for the two moisture contents examined as shown in Figure 8. The binder content, with a margin to allow for method of mixing, type of mixer and expected site conditions (material variability and moisture content) can then be selected.

Performance specified by California bearing ratio

- For each mixture, make at least three CBR specimen in accordance with the CBR test in BS EN 13286-47 using:
  - the 2.5kg rammer (Proctor method) for fine-grained materials
  - the 4.5kg rammer (modified Proctor) for medium and coarse grained material.
- As described in the BS EN, prevent the specimens from drying out for three days, then soak them for four days, or as specified, and test to determine the CBR.

- Using the average of each set of results, plot CBR against binder content (as shown for compressive strength in Figure 3) for the two moisture contents examined. The binder content, with a margin to allow for method of mixing, type of mixer and expected site conditions (material variability and moisture content) can then be selected.

5.4 Trafficability

As described in Britpave document *BP/14*[6], UK experience indicates, with mixtures using either cement or slow-setting and hardening stabilisers, that provided the mixture is mechanically stable, the layer can be opened to traffic immediately. This can be established in the laboratory by CBR testing of the mixture immediately after specimen manufacture but without the use of surcharge rings. The resulting CBR value is termed the immediate bearing index (IBI).

This test or examination is necessary for most HBM except for well-graded mixtures made from crushed/angular/flaky material (refer to note to Table 8). It is a simple, quick and inexpensive test to carry out and is therefore perhaps best carried out as early as possible during the mixture design process before the more time-consuming and expensive mechanical property determinations.

The ability of HBM to take traffic immediately can normally be assumed provided the mixture meets the suggested IBI requirements in Table 8 noting that the IBI is determined on the bottom of the specimen. Further information on this important aspect can be found in *BP/14*, which also draws attention to the need for site verification of the laboratory work using pneumatic-tyred rollers and measurement of the surface stiffness of the layer.

Table 8
Suggested IBI_{bottom} values for immediate trafficking.

Material properties before treatment	Specimen compaction	Moisture content	Capping	Sub-base and base
Cohesive materials	Standard Proctor	OMC	> 10	> 15
Non-plastic material with 12–35% passing 80 microns µm	Modified Proctor	,,	> 20	> 30
Non-plastic material with < 12% passing 80 microns µm	,,	,,	Generally not necessary to treat for capping	> 40
NOTE: Well-graded mixtures consisting of angular/crushed material can be assumed to be satisfactory without the need for testing. Well-graded mixtures but with partly crushed/angular aggregate are generally satisfactory although if in doubt use the requirement in the last row. (More guidance is provided in *BP/14*[6])				

Where the mixture does not meet the requirements in Table 8, there are two possible courses of action:

- In the case of cement-based binders, exclude traffic from the layer for a minimum of seven days.
- In the case of lime-based binders, consider incorporating another material to improve the stability.

In the special case of lime-treated fly ash (where fly ash is considered the aggregate), the IBI test is not appropriate. For this mixture, experience suggests that direct trafficking is best limited to the construction period (i.e. before setting commences – refer to Table 10) and best avoided after setting unless overlain before setting by the next layer. This approach is also advisable for cement treated fly ash. Further data on treated fly ash can be found at www.ukqaa.org.uk.

5.5 Durability and volume stability

Experience with the UK Transport Research Laboratory frost heave test (*LR 90* [9]), indicates that CBM exhibit negligible heave when their compressive strength exceeds 2 or 2.5N/mm^2. In other words, the specimens still maintain their integrity at this strength and can be considered as bound materials and thus superior to unbound materials. In the past, therefore, and today, specifications for CBM have included or include compressive strength requirements at least in excess of 2 or 2.5N/mm^2.

With CBM and other HBMs designed to achieve a lower strength, such as a CBR values in the range of 15–50%, past practice has been to subject the mixture to frost heave testing and apply the maximum heave criteria – about 12mm – that is applicable to unbound materials. However, with such a degree of heave the integrity of the HBM is actually destroyed during the test, and it is impossible to know whether the HBM can still be considered 'bound' and thus perform as 'bound' in the pavement.

More recently, using data accumulated during the drafting of the European standards for HBM, it has been possible to formulate more relevant durability recommendations for these lower strength HBM. Among other requirements, this includes a limit for indirect tensile strength based on French and Belgian experience. The advice is shown in Table 9.

Table 9
Durability and volume stability recommendations/guidance for HBM (refer to text for details and age of test).

Mixture property	Medium- and coarse-grained aggregate	Fine-grained, i.e. clays and chalks (R_c typically ~ 1MPa)
Strength	R_c > 3MPa	R_{it} > ~ 0.2/0.25MPa
Immersed strength	R_{imm} > 80%	> 80%
Frost heave limits	Test not necessary if compliance with above	Aim for no heave but pragmatically < 2 or 3mm
SO_4 and S Limits	Limits not usually necessary	Yes, limits required – refer to BP/16

* R_c denotes compressive strength, R_{it} indirect tensile strength, and R_{imm} the ratio of the strength of specimens cured unprotected in water after an initial period of sealed curing, to the strength of specimens cured totally in sealed conditions.

It should be noted, that these recommendations apply to all HBM irrespective of the frost susceptibility of the aggregate or soil in the unbound condition.

The immersed strength requirement in Table 9 is also used to assess the volume stability of treated material. For example, if it is suspected that expansive clay minerals or other deleterious constituents (including sulfates/sulfides) are present in the material to be stabilised, and thus which may have a disruptive effect when water comes into contact with the HBM layer, it is advisable to carry out tests that examine the effect of immersion in water on strength and/or volume change of HBM under accelerated curing conditions (*BS EN13286-49*). HBM are then regarded as fit-for-purpose provided that specimens do not lose more than a certain percentage of their unconfined compressive strength and/or do not exceed a certain level of volume change, respectively.

These tests are considered mandatory as part of an overall durability assessment.

It is important to note that Table 9 does not include recommended ages for testing. This is deliberate since the time at which to test for durability has to be a function of the strength development of the mixture and therefore the characteristics of the binder.

Thus frost tests should be carried out when the material has attained a significant or high proportion of its ultimate strength. This might be at least 28 days for cement-containing mixtures cured at 20°C and the same age for most non-cement-containing mixtures but employing curing at 40°C.

In the case of immersion unprotected in water, immersion should not be carried out before at least 14 days sealed curing at 20°C for cement-containing mixtures and 40°C for non-cement-containing mixtures. Various immersion periods can then be employed from 14 days to as much as 2 or 3 months to give time for reactions to take place. For immersion, full non-protected immersion in aerated water at 20°C is suggested for cement-containing mixtures and 40°C for other HBM. The longer periods of immersion are recommended for soils or materials with complex sulphate/sulphur or special physical characteristics, like colliery or spent oil shale.

Additionally in the case of CBM characterised by CBR, it is possible to examine volume stability in the CBR mould (*BS EN 13286-47*) by applying a soaking procedure and monitoring heave to at least 28 days or until swelling reaches a plateau. However, this test is deprecated in some quarters, with the aforementioned volume change and immersion tests preferable.

6. Construction

6.1 Construction summary

This section summarizing the construction process assumes the reader has a basic knowledge of construction methods.

Primarily it describes mix-in-place stabilisation using two stabiliser additions. This so-called two-shot process has become very frequent but may not be familiar to experienced practitioners even though it draws significantly on normal stabilisation with just one stabiliser. However, where more detail is required on two-shot stabilisation, or mix-in-place work using one stabiliser or the mix-in-plant method, reference should be made to the subsequent sections. Otherwise, the reader may proceed to Chapter 7 on testing.

Production of the mixture may be carried out by mix-in-place or mix-in-plant methods. Non-cohesive materials and silty or low-plasticity soils can usually be treated using either method. However, cohesive soils are more difficult and are generally processed in-situ.

The following steps illustrate mix-in-place construction using lime at the first stage followed by another stabiliser at the second stage:

- To avoid final level problems, it is recommended that the site is prepared to the level required after stabilisation, using a roller and number of passes similar to that proposed by the stabilisation contractor.
- Spread quicklime over the soil at the specified rate.
- Rotovate the lime into the soil to achieve thorough mixing. Adjust the water content to achieve a target MCV of 10 and usually not more than 11 for cohesive mixtures.
- Lightly compact the layer to seal the top surface and leave to mellow for at least 24 hours.
- *Optional*: After mellowing, re-mix to achieve the necessary pulverisation. More than one pass may be required to achieve this. Lightly roll after the re-mixing.
- Spread the cement, ggbs or fly ash at the required rate and thoroughly mix into the soil layer. Check that the moisture content is close to OMC and not more than MCV 12 for cohesive mixtures The moisture content should be sufficient to achieve full hydration of the stabiliser, the required degree of compaction and low air voids to minimise subsequent ingress of ground water. Check the degree of pulverisation if not measured earlier.
- Fully compact within the time limits for the stabiliser used and trim to level.
- Seal with a curing membrane or place the next layer.

For mix-in-plant production, it may be possible for stabilisers to be introduced and mixed simultaneously. It is also possible to use a stationary pugmill mixer to mix the second stabiliser with cohesive material that has been pre-treated with lime using the mix-in-place method.

6.2 Methods

There are two methods by which HBM layers can be constructed:

- The mix-in-place (or in-situ) method.
- The mix-in-plant (or stationary plant or ex-situ) method.

Figure 9
Overall shot of mix-in-place stabilisation showing; powder spreader in the background, and from left to right; the prepared formation, water-bowser with hose connection to rotovator, previously-spread powder, mixing, roller, and finished layer with bitumen-emulsion cure coat.

The *mix-in-place* method can be used on either the in-situ soil or on a borrow material that is placed before stabilisation. Using purpose-built machines, the binder is spread on top of the material and thoroughly mixed-in with a rotovator. The mixture is then compacted by rolling. Water, if required, is normally added before or during the mixing process.

The *mix-in-plant* method uses stationary mixers in which the borrow material, binder or binder components, and water are combined. The mixture is then transported to the point of laying, where it is spread by dozer, grader or paver, and then compacted by rolling.

Figure 10
Paver-laying of mix-in-plant produced HBM.

The same principles apply to both methods:

- The material in the layer must be uniform.
- Construction joints should be vertical. (Note: expansion or contraction joints are not required in HBM layers.)
- Compaction should be completed within the 'construction period' given in Table 10 [in other words before setting commences] of the binder or hydraulic combination and while the mixture is in the optimum moisture condition.
- Loss of moisture must be avoided, and the layer protected from traffic (unless it is mechanically stable) and weather until the specified strength or bearing capacity is achieved.

Table 10
Construction period for HBM.

Binder	Construction period in °C hours
Cement alone	35 (~ 2 hrs at 20°C)
Fly ash and or ggbs then cement	35 from addition of cement (~ 2 hrs at 20°C)
Lime and gypsum activated fly ash (mix-in-plant only)	70 from addition of lime and gypsum (~ 4 hrs at 20°C)
Lime and ggbs	200 from addition of ggbs (~ 12 hrs at 20°C)
Lime and fly ash	800 from addition of fly ash (~ 48 hrs at 20°C)
Lime alone	1200 (~ 72 hrs at 20°C)
Lime and gbs (mix-in-plant preferred)	1200 from addition of gbs (~ 72 hrs at 20°C)
ASS activated gbs (mix-in-plant only)	3000 from addition of gbs (~ 1 week at 20°C)
HRB and combinations not listed above	Workability period at 20°C determined in accordance with BS EN 13286-45 multiplied by 17*

* 17 is the difference between 20°C and 3°C – with no strength development below 3°C assumed.

In the case of cement or lime-treated fly ash or mixtures based on the lime/fly ash combination, further information and documents can be found at www.ukqaa.org.uk. Similarly, advice on slag and slag-bound mixtures can be sourced from *Euromin* and or the *Slag Group of the Quarry Products Association*.

Before undertaking the construction of an HBM layer, the timing of the installation of drainage pipes and service ducts should be considered, as it is more difficult to dig a trench through an HBM layer than through a granular layer. When using the mix-in-place method, it is equally important to ensure that no previously constructed manholes protrude into the layer that is to be stabilised as they will be damaged by the rotovator.

6.3 Choice of method

There is a wide range of materials that can be stabilised to meet the requirements for either capping, sub-base or base, provided the correct choice of method and plant is made.

Table 5 indicated the capabilities of the methods of construction and the various mixing units available. It is clear that the mix-in-place method can process a wider range of materials because, in contrast with the mix-in-plant method, the problem of feeding the material into the mixing unit does not exist.

However, any decision on choice of method must consider the quality of the final product and the undoubted fact that the mix-in-place method can never match the quality of the mix-in-plant method using pugmill-mixing with weigh-batching, provided the latter method can handle the material. On those occasions when either method of stabilisation is possible, quality therefore must be an issue but the choice will also be determined by the availability of plant, the size and layout of the pavement, the depth to be stabilised and location of the material.

If the in-situ material can be stabilised, and depending on the quality required, the usual answer is to employ the mix-in-place method provided there is not a source of suitable material nearby that can be stabilised with a much smaller amount of binder. If there is a suitable source of material nearby, the answer is not so clear and depends on the factors mentioned in the previous paragraph.

Plant development is always taking place and, as long as the material can be properly compacted, the depth of layer is of secondary importance when deciding which method to use. However, where the specified thickness of layer exceeds the depth that can be processed by the available plant, it should not automatically be assumed that stabilisation is not feasable. Multi-layer construction can be employed using either mix-in-plant or mix-in place or a combination of methods, provided that:

- Due consideration is paid to the 'construction periods' detailed above and curing.
- The lower or lowest layer is able to carry construction plant.
- With the mix-in-place method, no material is left unprocessed at the layer interface and the previously constructed layer is not damaged by the subsequent work.

A combination of mix-in-place with mix-in-plant may be feasible when another binder addition follows lime pre-treatment.

For example, chalky or cohesive or silty material for HBM may be sourced from a 'cut'. The material can be treated with lime in the 'cut' becoming friable, excavated, and then deposited in a stockpile adjacent to a central mixing-plant in which it will be later treated with the second binder. This is common practice in France for capping and sub-base construction, where it is not unusual for the lime-treated material to remain friable in the stockpile for many months before subsequent treatment with the second binder.

6.4 Layout and general points

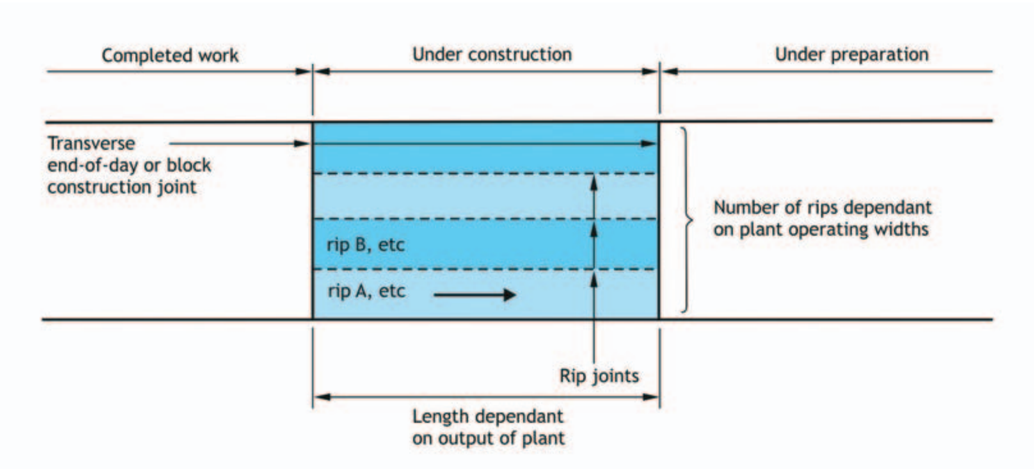
The shape of pavements normally falls into two categories, the strip type such as a road, or the square or rectangular type such as parking or storage areas. The paving procedure often employed for each type is illustrated in Figures 11 and 12. In the figures:

- a longitudinal or transverse construction joint refers to the junction between freshly laid or processed material and compacted (not necessarily hardened) material
- a rip joint refers to the junction between freshly laid or processed material and uncompacted material that may have been laid or processed up to one hour earlier.

Strip pavements

As Figure 11 shows, the construction proceeds in full-width blocks, starting with rip A, then rip B and so on. A feature of this type of pavement is the absence of longitudinal construction joints (as distinct from rip joints).

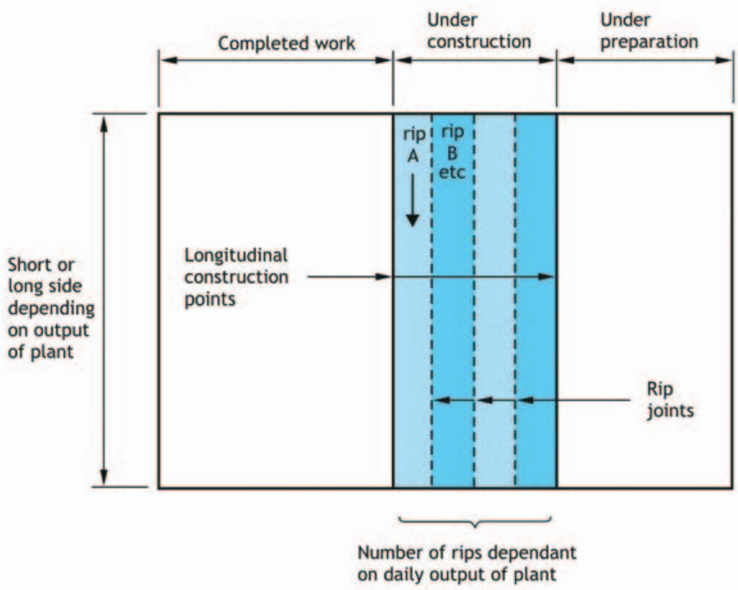
Figure 11
Suggested method of working for strip-type pavements.



Square or rectangular pavements

As Figure 12 shows, the construction proceeds in rips across the whole of one side, starting with rip A, then rip B, etc. In contrast to the strip type pavement, there are no transverse joints.

Figure 12
Suggested method of working for square or rectangular-type pavements.



General comments

The method of working described above for the two types of pavement applies equally to both the mix-in-place and the mix-in-plant methods of construction. In either case the operation should ensure the 'marrying-in' of one rip with another, i.e. A to B, B to C, C to D, and the careful use of plant so that no areas are left either unprocessed or uncompacted, or both. These aspects, along with the construction of joints, are discussed fully in the following sections.

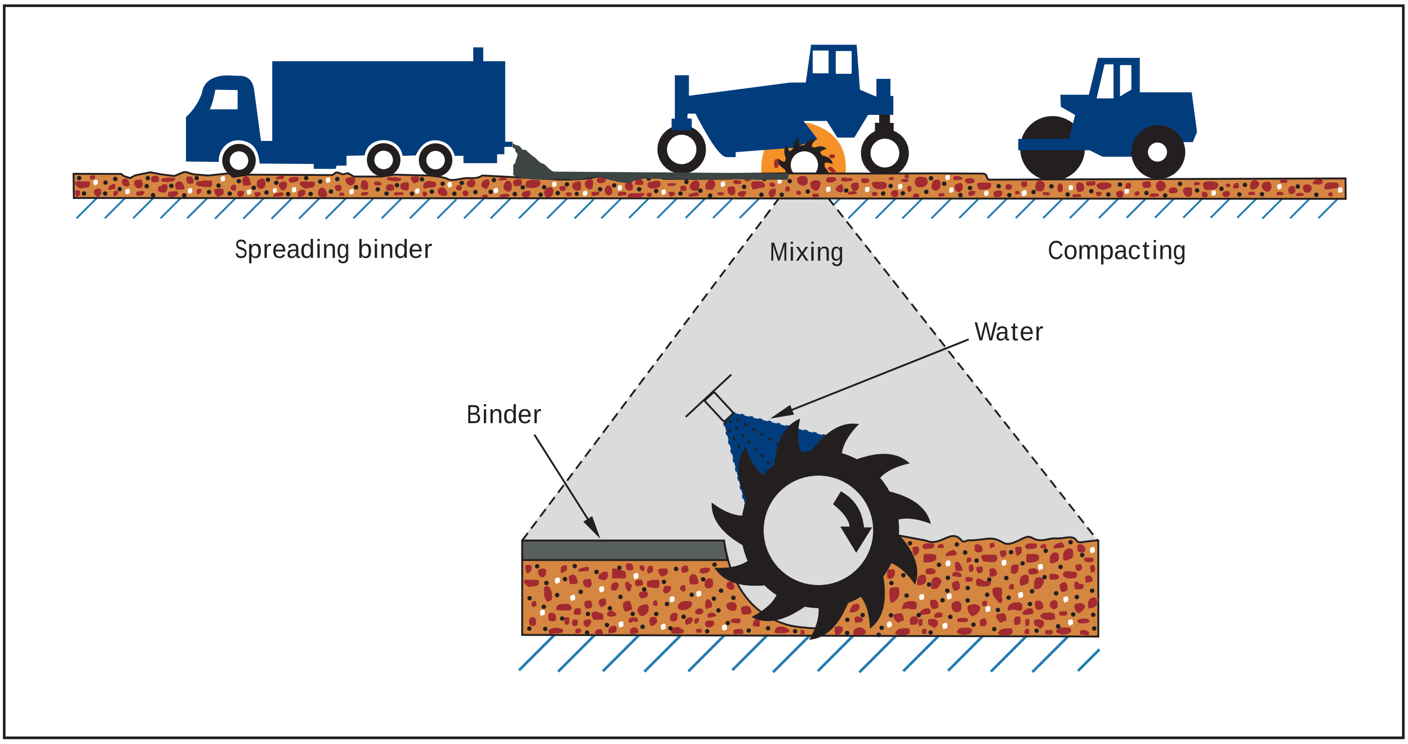
6.5 Mix-in-place method

The method consists of six stages:

- Site preparation
- Adjusting the moisture content
- Binder spreading
- Mixing
- Compacting
- Curing.

Compaction and curing are common to both methods of construction and are discussed after the section on mix-in-plant construction.

Figure 13
The basics of mix -in-place stabilisation



Site preparation

Mix-in-place stabilisation can be carried out on either in-situ or on borrow material.

For in-situ material, all organic material should be removed over an area extending 500mm beyond the outer limits of the area to be stabilised to ensure that the material to be processed is not contaminated.

Shape the ground and compact it so that the density and profile of the layer to be stabilised is compatible with that to be achieved after stabilisation. It should be noted that there will be 'bulking' of the layer following introduction of the binder and this will be greater if pre-treatment with lime is part of the operation. (Note: the degree of bulking can be determined at the mix design stage by comparing the compacted density of the material before and after treatment).

As there is little displacement of the soil during processing (this applies equally to a borrow material), it is important to take care over this stage because the level and density at the start of construction will determine the level and density at the finish. Also, any delays with the final compaction of the stabilised material, due to excessive grading, could result in drying out and setting problems. As a consequence there could be problems in achieving the required density and/or finish and/or performance.

If material is to be pre-treated with lime, this operation should be carried out at least 24 hours before the next stage.

The preparation of the layer to receive a borrow material prior to treatment is no different from that required for any road construction material and thus the usual care should be paid to compaction and soft spots, surface levels and drainage, as well as standing water or any other unsuitable materials.

The required depth of borrow material can then be placed and compacted so that, as above, the density and profile of the layer to be stabilised is compatible with that required after stabilisation.

Adjusting moisture content

Water can be added either by the jets within the mixing hood of the rotovator or by a spray bar attached to a water bowser. If the jets in the mixing hood are used, the water is added during the mixing passes. If a spray bar is used, the water can be added either before binder spreading or between mixing passes. If the water demand is large, a combination of both methods can be used.

Both methods have their merits but probably the more satisfactory way is through the jets in the mixing hood of the rotovator provided the jets remain unblocked at all times. The main advantage of this method is that all the water is introduced during the mixing of the binder with the material to be stabilised, thus ensuring that all of it is used in the mixture. Some rotovators are equipped with water tanks, but the capacity of these is often inadequate. Thus rotovators usually work in tandem with water tankers to which they are connected by hose.

Water bowsers can be equipped with a spray bar either at the rear of the tank or offset to one side clear of the wheel tracks. The latter is preferable since there are no wheel-ruts in which the water can collect and cause uneven distribution. Either way, problems of run-off, especially with fine-grained materials, are experienced on sloping sites and careful control is required to ensure a uniform distribution of water throughout the material. Adding water to clean coarse-grained materials causes fewer problems, since the material is sufficiently open-textured to prevent ponding and run-off.

Depending on the material and the time of year, the water required to achieve the optimum water content can be considerable. When planning the stabilisation operation, it is important to ensure that both the means of water dispensing and the capacity of the units are capable of supplying in the region of 20 litres/m^3 for each 1% required rise in moisture content.

Whichever method is employed, it is important to ensure that the addition of water does not unduly delay the stabilisation process. The water should be distributed uniformly throughout the material, and under no circumstances should the water dispensing plant be allowed to remain stationary over one spot. This would result in an over-wet area that can be corrected only by complete removal.

Binder spreading

The binder is spread using mechanical spreader units. These are generally dedicated self-propelled units but are sometimes incorporated within the rotovator. It is important to ensure that the binder is spread uniformly both in the transverse and longitudinal directions noting that the greater the uniformity of binder spreading, the greater the uniformity of mixing.

Figure 14
Mix-in-place method of construction showing powder spreading and water-bowser in tandem with rotovator for water addition through spray-bar in hood of rotovator.

The equipment deposits a layer of binder on the ground, shielded by a skirt to minimise dust. Operations should be curtailed in windy weather.

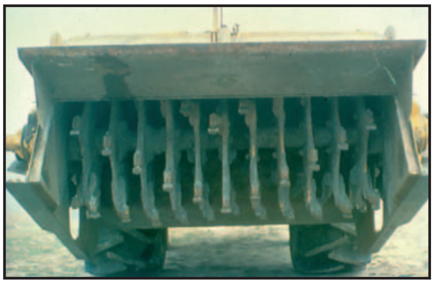
The binder is usually metered by volume, although some spreaders can control spread rate by mass in a similar way to that operated on binder belts in a central mixing plant. The dosage can be adjusted to the distribution required and is unaffected by the working speed, although a constant slow speed in the region of walking pace is recommended to ensure good control over line of working.

The units are usually filled directly from a bulk delivery lorry. When planning the programme of work it is important to remember that spreader units with a carrying capacity of, say, 10 tonnes, take 20–25 minutes to be filled, but only 5–10 minutes to discharge. It may be more efficient to employ two spreaders so that one can be spreading while the other is being charged.

Mixing

It is important that all materials are thoroughly mixed together. More than one pass of the mixing equipment may be required to ensure this, but the number of passes should be kept to a minimum, consistent with uniform mixing, so that compaction and finishing can be carried out with as little delay as possible. Mixing should be continued until the stabilised material is of uniform colour and texture over the whole area and to the full depth of treatment.

Where more than one mixing pass is required, levelling and compaction between passes will assist in achieving final levels and the correct depth of stabilisation. As with binder spreading, it is important to ensure that no areas are left untreated, and the rotovator should therefore overlap slightly into completed work, whether fresh or otherwise.



Above: **Figure 15**
Close-up of rotovator with hood raised to show mixing arms and picks.

Right: **Figure 16**
Rotovator with rotor mounted between axles. These types of rotovators can be 'fitted' with an internal powder-storage hopper, which dispenses the blanket of powder on the ground about 300mm in front of the rotor hood.

Plant

Mixing is carried out using powerful and purpose-built machinery.

Such machines usually have one transversely mounted single shaft rotor, which carries a large number of tines and is lowered into the mixing position by hydraulic rams. The rotor is enclosed in a hood within which the material is mixed as the machine moves forward. Some machines have the rotor mounted at the rear, although it is more common to find the rotor mounted between the front and rear axles.

All machines today are capable of mixing comfortably to depths of, say, 250mm although 300 or 350mm is feasible, which is probably the limit for compaction and measurement of compaction.

Some mixers also incorporate powder spreading features. Normally they consist of an on-board hopper, capable of holding about 4 tonnes of powder and a dispenser that discharges a uniform amount of powder on the ground immediately in front of the rotor, thus minimising dust.

Two binder applications

Where two stabilisers are required to be spread and mixed, either the same day or on successive days, say, the mixture resulting from the first addition should be compacted to the same degree as required after the second addition. This is necessary in order to maintain the correct depth of mixing and binder dilution and secondly to provide a seal to minimise moisture change.

Edge restraint

Mix-in-place rotovators cannot normally work against forms, kerbs or other edge details for two main reasons. Firstly, because of the design of the rotovator, a narrow strip of material adjacent to the edge detail would be left unmixed. Secondly, there is the possibility of serious damage to the edge detail because of the mass and power of the rotovator.

It is therefore common practice with mix-in-place stabilisation to stabilise material beyond the specified limits at the edges of the area to be stabilised, to provide support for the work within the specified limits. In the case of stabilisation of an in-situ material, this support will already be present, but when using a borrow material, this should be spread over an area extending 500mm beyond the specified area.

Construction joints

Contraction and expansion joints are not required for HBM layers, but there will be construction joints, either in the longitudinal direction of working or the transverse direction or both, depending on the shape and size of area and the method of working. Joints can be a source of problems if not constructed properly and their frequency should be minimised.

For square or rectangular areas, the method of construction entails working the full length of one side and gradually moving across the area in rips, so there will be no transverse joints. However, a longitudinal joint will be formed at the beginning of each day's work. To ensure that the joint is vertical, the new day's work should be commenced by overlapping slightly into the existing work as with the binder spreading.

Conversely, in the construction of strip-type pavements, the stabilisation operation is usually carried out in full-width blocks of two or more 'rips', where the junction between 'rips' is no older than one hour. Therefore, there will be no longitudinal joints, but a transverse joint will be formed between adjacent blocks of work. As with rectangular areas, care should be taken over the construction of this joint, and, if possible, it is advisable to initially use the rotovator at right angles to the normal direction of working, thus forming a vertical joint between the old and freshly treated material.

6.6 Mix-in-plant method

The mix-in-plant method consists of six stages:

- Site preparation
- Mixing the material, binder or hydraulic combination and water
- Transporting the mixture to the point of laying
- Spreading the mixture
- Compacting
- Curing.

Site preparation

The preparation of the layer to receive the HBM is no different from that required for any pavement material, and attention should be paid to its compaction, surface levels and profile. HBM should never be laid on frozen or softened material, or on standing water or any other unsuitable materials.

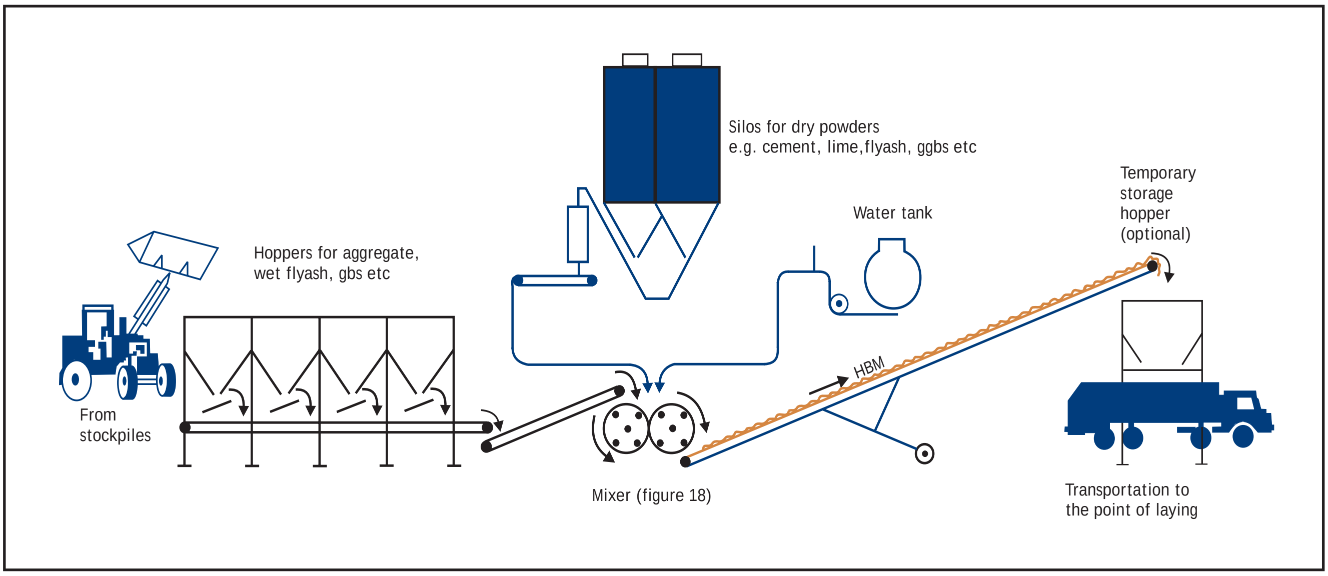
Unless the HBM is obtained from a permanent stabilisation plant, the location of the mixing unit will be determined by local conditions. Whatever the case, it is important to ensure that the distance from the plant to the site is such that compaction can be finished within the 'construction period' of the mixture.

Although it is important to minimise segregation during stockpiling of the material for stabilisation, it is inevitable that there will be variations in grading and moisture content throughout the stockpile. Account should be taken of this at all stages during the handling of the material prior to its introduction to the mixing plant.

Mixing

Depending on the specification, HBM can be produced in batch or continuous mixers and the proportioning of the ingredients can be by mass or volume. Figure 17 shows the key elements of a typical mixing plant.

Figure 17
The key elements of the mixer for the mix-in-plant method of construction.



Below: **Figure 18**
A close-up of a continuous pug-mill mixer showing the mixing trough, shafts and blades.

The essential characteristic of a mixer is that it should have a mixing action capable of producing a uniform material. A positive mixing action is recommended (Figure 18) because HBM contains very little water, can often be relatively lean in binder and can be made from 'dirty' aggregates. Therefore uniform dispersion of the binder throughout the mix is not as easily obtained as with, say, a structural concrete mix of average workability. Depending on the raw material, this may be virtually impossible to achieve with tilting or rotating drum mixers.

On larger jobs a good output from the mixer is also necessary, since the laying plant will require a sub-stantial and steady supply of material to ensure uninterrupted forward movement. This is essential to achieve a good surface profile with minimal joints.

Transporting the mixture to the point of laying

When spreading the material, it is important that the layer is uniform in grading and moisture content. If the material segregates and/or the moisture content is on either the dry or the wet side of the design moisture content, it will be difficult to achieve good compaction and hence the strength or bearing capacity of the laid material will be lower. This will affect the performance of the material in the field.

Therefore, it is essential during transportation of the material from the mixer to the site that segregation of the mix is minimised and that the material can be protected from the weather. Even if the haul distance is short, a breakdown could occur during transportation or with the laying plant. Protection should therefore be available. Steel-lined, end-tipping lorries equipped with covers are recommended. They should be of sufficient number to ensure uninterrupted forward movement of the laying plant.

Figure 19
Sheeted-lorry delivering mix-in-plant produced HBM for grader-laying. Note how discharge is carried out 'on-the-run' to minimise segregation and aid spreading.

(This is a historical photo with questionable health and safety practices by todays standards, however it demonstrates delivery of HBM well.)

Spreading

Objective

The main objective is to achieve a layer of consistent material and depth in the field.

Plant

A variety of plant can be used. Pavers are recommended since there is good control of sur-charge, compaction and surface regularity. However, it is important to keep the receiving hopper charged with material at all times to limit segregation.

Above: **Figure 20**
Dozer-spreading of mix-in-plant produced HBM.

Right: **Figure 21**
Grader-laying of mix-in-plant produced HBM.

Dozers and/or graders can be used, but unless laser guidance is employed, more care needs to be taken, as it is more difficult to achieve the required surface levels and profiles.

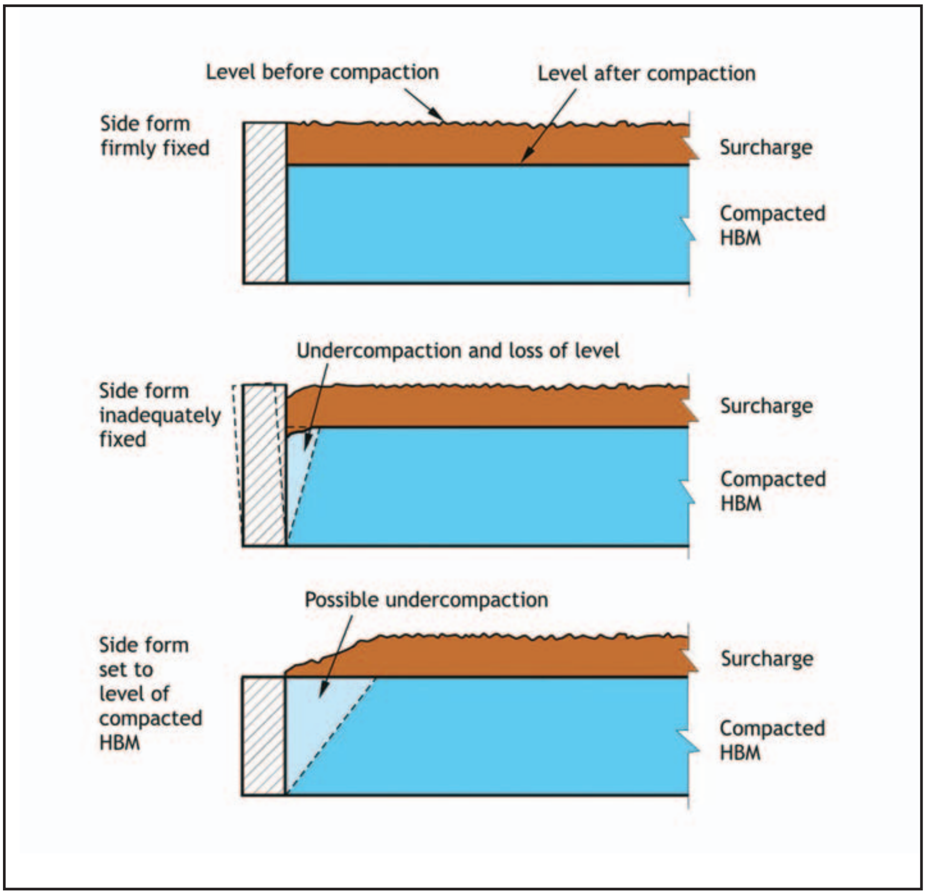
An advantage of spreading by dozer or grader, however, is that the operation can be arranged so that the plant does not run on the underlying layer, thus preventing its disturbance. A further advantage is that the spreading operation can be carried out on a broad front thus eliminating longitudinal joints.

Edge restraint

Provide edge restraints in order to ensure full compaction at the edges of the HBM layer (Figure 22).

If forms are used for this purpose, they must be firmly fixed to resist lateral and vertical displacement during compaction. In addition to affecting the surface regularity of the layer, such displacements cause lack of compaction at the edges. Alternatively, kerbs or other edge details may be used.

Figure 22
Surcharge and edge restraint issues showing problems caused by inadequate fixing and lack of surcharge.



When no edge restraint is used, the material should be spread over an area slightly larger than that specified. The excess material provides the edge support so that the material within the treated area can be compacted to specification.

Normally it is sufficient to spread the material over an area extending 300mm beyond the specified area. However, it must be remembered that some materials are less stable than others and spread easily under compaction; allowance must be made for them.

Surcharge

To produce a given thickness of compacted layer, the material should be spread to an adequate surcharge.

When forms are used, it is recommended that they are set to the required level of the surcharge, because this facilitates spreading and allows the surface profile to be checked easily after compaction by measuring the level of the layer below the top of the forms. It also helps to prevent material being inadequately compacted adjacent to the forms. Kerbs or other edge details can be used to similar effect.

Figure 23
Paver-laying of mix-in-plant produced HBM.

When pavers are used, some compaction may take place during spreading, so less sur-charge will be required. However, even when using pavers, some materials may require a surcharge of 25% or more, so preliminary trials should be carried out with every mixture to determine the correct surcharge.

With dozer or grader laying, compaction is an integral part of the laying and levelling operation. Ideally, the layer should be left about 10mm high after main compaction. The excess should then be trimmed and bladed forward for incorporation further down the works (it is *not* discarded), so that finishing rolling can be carried out without the need to fill low spots, as these can become a source of weakness in the layer. This can be particularly problematic with fine-grained HBM.

Construction joints

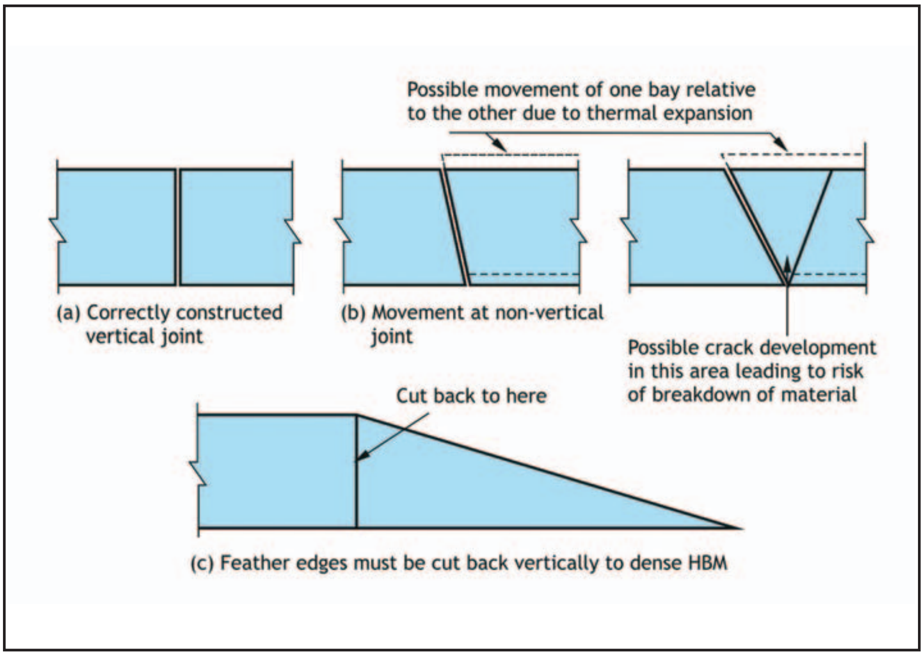
Contraction and expansion joints are not required for HBM layers, but there will be construction joints, either in the longitudinal direction of working or the transverse direction or both, depending on the shape and size of area and the method of working. Joints can be a source of problems if not constructed properly, and their frequency should be minimised.

The laying operation should be organised so that longitudinal joints against compacted (not necessarily hardened) material are avoided. This is impossible with square or rectangular pavements, but with strip pavements full-width working, usually necessitating two or more 'rips', should be employed to eliminate the need for longitudinal joints.

Figure 24
End-of-day shot of paver-laid material, cut-back to a vertical-face of fully-compacted material in preparation for next day's laying. Previously the end of the layer had been 'ramped-down' by the rollers during compaction.

Transverse joints in strip pavements are unavoidable, but it is essential they are vertical. Feathered or sloping joints should not be constructed since they are a source of structural weakness and can give rise to 'blow-up' as one bay rides up and over another due to expansion. Joints should be formed by laying heavy baulks of timber or well-secured forms against which the roller can work. The roller should be used parallel to the joint to ensure that maximum compaction is achieved.

Figure 25
Formation of transverse joints with mix-in-plant produced HBM.



Alternatively the mixture can be ramped down at the end of the day. The layer should then be cut back to achieve a sound and vertical face of properly compacted mixture of the required thickness.

In summary, the rules for the construction of both longitudinal and transverse joints are as follows:

- In no case should fresh material be laid against compacted material unless the edge of the compacted material is vertical.
- In no case should fresh material be laid against uncompacted material that has dried out or been laid for a time greater than the recommended construction period in Table 10 for the binder.

6.6 Compaction

Similar principles govern treated material as that material without binder:

- The HBM or treated layer should be compacted by rolling at OMC to maximum density.
- Likewise, the plant suitable for compacting an untreated material is suitable for compacting the same material when treated with binder.

Whatever type of roller is used, attention must be paid to compaction at joints, adjacent to kerbs, channels or side forms, and around box-outs created for gullies and manholes.

The compaction operation should always be completed within the 'construction period' of the binder being introduced to the material.

Types of roller

In general, the following compaction plant has been found to be suitable for HBM:

- vibrating rollers
- multi-wheeled, pneumatic-tyred rollers
- smooth-wheeled, dead-weight rollers.

Vibrating rollers are used for HBM more than any other type of roller. Ensure the correct frequency and amplitude of vibration is used, and select the appropriate diameter and mass of roll relative to the type and thickness of material being compacted. Advice should be sought from the manufacturer of the roller. Always use vibrating rollers without vibration for the first couple of passes in order to 'bed down' the material.

Pneumatic-tyred rollers are recommended for sands and other fine-grained materials. By correct adjustment of tyre pressures, shear planes can be avoided, and a well-closed, uncrazed finish can be achieved.

Figure 26
Compaction plant – vibrating roller.

Smooth-wheeled, dead-weight rollers should be used with caution since their mass can cause them to sink into the uncompacted material and cause ridges and undulations. This problem can be overcome by first going over the material with a light roller or vibrating roller without vibration to bed down the material. This type of roller is not recommended for jobs with a small daily output or for use in awkward areas since the areas may be too small to enable these rollers to work efficiently.

Rip joints

Where either HBM is being laid through a paver or where the mix-in-place method is being used, it is important that the material at the edge of a rip is well married-in to the adjacent rip. In order to achieve this, the roller should compact each rip so that a narrow strip (usually 300mm is sufficient) is left uncompacted until the adjacent rip is stabilised or laid. In this way the junction between the two 'rips' will be indistinguishable, well married-in and compacted and hence unlikely to give problems in the future.

Figure 27
Correct rip-joint construction with paver- laid HBM. Picture shows un-compacted edge strip of previously-laid material, which will then be compacted with the adjacent 'rip' being laid in picture in order to maintain level, full compaction and homogeneity across the 'rip' joints.

Level control

Surface irregularities, if any, will be shown up during the rolling operation and should be corrected at this time.

Level control with mix-in-place hydraulically-bound mixtures

Grading work will be necessary for mix-in-place stabilisation. If all the preceding construction stages have been carried out correctly, especially the initial preparation of the material to be stabilised, this work will be minimal. However, one feature peculiar to mix-in-place stabilisation is the formation of a hollow at the start of each rip and a mound at the end. This is brought about by the nature of the mixing action during which the material is picked up as the mixing plant moves forward, is mixed, and then deposited about 500mm later. It is not a matter for concern but grading work will be necessary to provide the correct levels. Care is needed with fine-grained materials.

Level control with mix-in-plant hydraulically-bound mixtures

Normally surface irregularities cause little problem with the *paver-laying* of mix-in-plant CBM, and the important finishing rolling and curing can be carried out without delay. Where high spots are identified, these can be trimmed and the area re-compacted. In the case of low spots, the surface should be well scarified before filling to the correct level. The layer should then be re-compacted in the normal way. Experience has shown that if this scarification is not carried out, especially with fine-grained materials, the infill material does not bond to the main part of the layer.

With *dozer or grader-laying* of HBM, the need to fill low spots should be avoided by aiming to produce a layer about 10mm high after main compaction. The excess should then be trimmed and bladed-forward for incorporation further down the works (it is *not* discarded), so that finishing rolling can be carried out without the need to fill low spots, which can become a source of weakness in the layer.

Finishing rolling

Carry out finishing rolling to ensure that the surface is sealed, free from roller marks and free from roller cracks, which normally result from heavy vibrating rollers over-stressing the surface of the layer.

Multi-wheeled pneumatic-tyred rollers are recommended for this purpose because of the ability to change tyre pressures while on the run although it should be noted that high tyre pressures can also over-stress the surface of the HBM layer. This means that roller marks can be removed and the surface of the layer can be moulded back together to give a tightly sealed surface. These rollers are particularly useful for ‘tightening’ the surface after the use of vibrating rollers and have the added benefit of permitting compaction to be carried out at lower water content than is possible with vibratory compaction alone. This effective reduction in water/binder ratio results in higher strengths for the same binder content or permits a reduction in binder content.

Light rollers and vibrating rollers without vibration have also been used for finishing, but they are not as effective or always successful.

Figure 28
Compaction plant – finishing-rolling using a pneumatic-tyred roller (PTR). This type of roller is ideal for removing surface shear cracks produced by vibrating rollers, for producing a smooth surface and, at the same time, checks the ability of HBM layers, slow-setting particularly, to take immediate traffic.

6.7 Curing and protection

With the exception of medium- and coarse-grained aggregate treated with the ASS/gbs combination, which are less susceptible to distress caused by inadequate curing and protection, the following advice should be followed.

Properly produced and compacted HBM will contain sufficient moisture for the hydration of the binder. However, as with concrete – and even more importantly because of the small amount of water in the mix – loss of moisture has to be prevented in order to allow full hydration and thus strength to occur in the top part of the layer and to prevent, with fine-grained mixtures, cracking and crazing of the surface.

Figure 29
Example of a good seal to the HBM layer that will prevent drying out and thus poor strength development of the surface of the HBM.

Unless the material is to be covered immediately by another pavement layer, a seal coat should be applied. Curing is usually carried out by the spray application of a 40% bitumen emulsion applied at not less than 0.5 litre/m^2 to seal the surface, or aluminised compound, or the very frequent application of water spray. The latter has to be used where two or more lifts are employed and bond is required between the lifts.

As discussed in chapter 5, some HBM can be opened to traffic immediately provided it has the necessary grading and aggregate and or IBI value and in the case of the emulsion seal coat, sand or grit is applied to prevent removal by the wheels of traffic.

Figure 30
Application of grit to prevent removal of bitumen-emulsion seal coat under traffic.

In the case of cement-based HBM of poor grading and/or where the IBI value is insufficient or in the absence of such data, traffic should be kept off the layer for a period of seven days or even longer in cooler weather. For treated fly ash, refer to *Trafficking* in chapter 5.

The production and placement of HBM in late season is not recommended and risky (refer to Table 4 for advice). However, if unavoidable, work should not be carried out at temperatures below 3°C unless the temperature is above freezing and predicted to rise to above 3°C and the completed layer is to be protected, preferably with the next pavement layer, the same day or before the next predicted frost.

6.8 Rectification and reinstatement

Rectification

Shallow low spots in HBM layers can be remedied after hardening. The remedy depends upon the type and the subsequent number of layers to be placed upon the HBM layer.

Two or more layers to follow

Where the HBM layer is to be covered by two or more layers, shallow low spots are best ignored since the depression will be evened out during placement of the subsequent layers. Areas damaged by weather or traffic can be similarly ignored, provided that all loose material is removed and the resulting depression is shallow. Whatever the structural importance of the layer, this method is perfectly adequate and can be carried out by the contractor without a delay to the planned programme of working and without affecting the surface regularity of the wearing course.

One layer only to follow

Where shallow depressions exist in a HBM layer that is to be covered by pavement quality concrete or a thin bituminous surfacing, the low spot cannot be made even by the placement of this top layer without causing final surface regularity problems. In this case the layer should be first brought to level with bituminous material. The same treatment is recommended for damaged areas provided, as above, all defective material is removed and the resulting depression is shallow. The maximum size of aggregate in the repair material should be compatible with the depth of repair. This method of repair should also be used for shallow repairs in HBM layers directly below small unit paving such as concrete blocks.

For deep repairs to HBM layers, complete removal of the defective area is structurally the most satisfactory solution. The edges of the sound material should be made vertical and the defective material replaced with fresh mixture or similar material and well compacted. If absolutely necessary, high spots can be reduced by scabbling or other approved methods. Whatever method is used, it is important that the body of the layer is not damaged structurally.

Reinstatement

Reinstatement will be necessary where a trench has been cut through the pavement. It is recommended that any HBM layer present in the construction is cut back to sound material (300mm beyond the edges of the trench is usually sufficient) and to a vertical face. The layer can then be reinstated with fresh HBM or similar and well compacted. Great care should be taken when back-filling so that satisfactory compaction is obtained.

With all rectification and reinstatement work, the fresh material should be sealed and traffic kept off for seven days, or until the engineer is satisfied that the material has attained sufficient strength or bearing capacity or has the requisite grading or IBI to withstand traffic and weathering.

7. Testing

The satisfactory performance of HBM depends on constructing a layer that is of adequate and uniform thickness and strength or stiffness.

Adequate and uniform thickness is necessary because under-dimensioned HBM layers are susceptible to over-stressing and premature failure. Thus careful control should be exercised over the surface level of both the HBM layer itself and the underlying layer.

The strength or stiffness should be uniform and adequate for the same reason and for purposes of durability. Strength/stiffness depends on binder content and on the density of the compacted layer. Careful control needs to be exercised over these aspects. Binder content is controlled in the mixing or batching process. However, the control and achievement of density is more involved since the state of compaction achieved in a HBM layer depends on the following:

- Mixture characteristics – grading, workability etc
- Compactive effort – type of roller, number of passes etc
- Degree of support provided by the underlying layer(s).

It is important to monitor all these aspects so that HBM layers can withstand the stresses that are generated by traffic and changes in temperature.

The intended application and importance of the HBM determines the amount of testing. As the project proceeds and experience grows, the frequency of testing may be reduced.

7.1 Types of test

There are two main types of test:

- **Production control tests.** As the description indicates, these are carried out at the production stage of the HBM. This testing involves monitoring the uniformity of the constituents of the mix and their correct metering.
- **Compliance or end-product tests.** These are carried out on the finished product. They include tests to determine the thickness, density and surface stiffness of the layer, as well as tests carried out on the production mixture to determine laboratory strength, compressive or tensile, CBR or modulus of elasticity.

There is one aspect of control that does not fit easily into either category of testing, but which can greatly affect the quality of the finished product. Whatever control is exercised over the monitoring of the constituents and the compaction of the layer, the dry density in the field is very dependent on the support of the underlying layer. Attention should be paid to the integrity and uniformity of the supporting layer, otherwise a layer of variable density and hence performance will result.

7.2 Production control testing

Production control tests are carried out on a continuous basis during the construction of the HBM layer.

Uniformity of constituents

The grading and/or plasticity of the material will have been established at the site investigation stage. During the course of construction, the uniformity of all the constituents should be checked regularly, so that any variation can be catered for. This could mean adjustments to the mixture and/or adjustments to the mixing times.

The moisture content required to achieve maximum compaction will also have been established at the outset. The moisture content of the material should be monitored continuously so that the amount of water to be added can be adjusted accordingly. Where the material is wetter than the optimum the usual solution is to wait until it has dried out naturally. For HBM made from cohesive materials, the MCV test is recommended for the monitoring of moisture content. For the same and other materials, the use of the moisture meter on a nuclear density meter is recommended. It is particularly useful when placed on the uncompacted mat just issued from the paver or after mixing with the rotovator in mix-in-place work.

Metering of binder in mix-in-place stabilisation

The rate of binder spread from mechanical spreaders should be checked over the full width of working. This is carried out by placing on the ground a sheet of canvas or tray of known mass and area in a position that the spreader can pass over it. The canvas/tray and binder contained are weighed and the rate of spread thus determined. If necessary, the rate of spread can be adjusted and the test repeated until the desired rate is achieved.

Figure 31
Checking 'rate-of-spread' of powder with mix-in-place work. The powder-spreader has passed over a tray of known area and weight

A sheet of canvas is preferred to a tray, as it can be used to check the rate in the wheel tracks of the spreader, which is not possible with a metal tray.

A useful double check can also be carried out. Knowing the capacity of the spreader and the rate of spread of binder, the theoretical coverage can be compared with the area covered by one load of the spreader. This check should be used throughout the duration of the project and is a very good indicator of any problem with the spreader.

Metering of components in mix-in-plant stabilisation

HBM are mainly produced in stationary plants that use weigh batching. Checks on the weigh-gear should be implemented regularly, as in a normal ready-mixed concrete plant.

Continuous volume batch mixers are also sometimes used and permitted for mix-in-plant stabilisation. In these cases, the rate of feed of the materials from the hoppers, especially the aggregate, sandy materials like gbs and ASS, and conditioned fly ash, needs to be accurate. The addition of water and dry constituents like lime, cement, ggbs and dry fly ash from silos should pose few problems, as they do not vary in consistency, but hopper materials can present problems because a change in grading or moisture content could alter the rate of feed. The plant should therefore be frequently monitored and calibrated to ensure uniformity of feed.

A useful double check for both weigh and volume batching is to compare the consumption of the materials at the plant with the quantity of material actually laid in the pavement. It should be apparent if something is amiss with the batching.

7.3 Compliance or end-product tests

Surface level and regularity

The surface level and regularity of a HBM layer should be checked in the same way as for normal pavement layers.

As discussed earlier, it is also necessary to check the surface level and regularity not only of the HBM layer but also of the supporting layer. This is straightforward in the case of *mix-in-plant stabilisation*.

For *mix-in-place stabilisation*, however, where in the majority of cases the underlying material is never exposed, it is important to check that the rotovator is processing to the correct depth. This is quick and easy to do and will not interrupt the work. The process is as follows:

- Alongside the area being treated there will be pins that control the working level of the operation.
- Somewhere on a line between opposite pins, dig a hole in the processed material. This will be easiest after mixing and before compaction.
- Dig into the layer until it is possible to discern the depth to which the material has been mixed. There will be an obvious transition point, usually distinguished by colour, grading or density.
- Draw a string line between the positions of known level on the pins and measure down from the string line the depth to which processing has taken place. This will establish the level of the top of the unprocessed material or put another way, the bottom of the stabilised layer.
- If the depth of processing is out-of-tolerance, it should be corrected before carrying out any further work.

Another method for checking the depth of layer in mix-in-place stabilisation is to measure the depth of processing from the top of the dug hole. However, it is important that this method is used only after final compaction and checking of the surface level adjacent to the hole.

It should be noted that rotovators use the surface level of the layer on which they are working to control the depth of processing. If this is high at the outset, the final thickness of correctly levelled and compacted stabilised material will be thinner than intended, by an amount equal to the difference between surface level at the outset and the theoretical level. If the level at the outset is 50mm high (not unusual), then the finished layer after trimming could be 50mm thinner than theoretical. This is significant on a theoretical depth of, say, 200mm. In this case, a layer subject to over-stressing and premature failure is the likely outcome.

It is easy to spot a layer where the surface level was high at commencement. The time for final grading and trimming to level will be extensive as will be the amount of material discarded in the windrows at the side or at either end of the piece of work.

Degree of compaction

The dry density of the compacted HBM layer is a measure of the effectiveness of the compaction and hence the strength or bearing capacity of the layer.

Compaction in the field is usually monitored in one of two ways:
- by specifying the compactive effort, i.e. method specification
- by specifying a target density, i.e. end-product specification.

Method specifications are well established and are simple to use. In essence the contractor chooses the type of roller and number of passes required from a table that equates compactive effort with the thickness of the layer concerned, the grading of the material and whether the material is crushed or uncrushed, or a combination of both. Provided the recommendations are followed, the compaction achieved in the field will be satisfactory. If vibrating rollers are used site personnel should ensure that they are working at the correct frequency and amplitude of vibration. Pneumatic-tyred rollers should be checked to ensure that they are working at the correct tyre pressures. Where ballast tanks are incorporated within the roller, they should be kept full.

End-product specifications are equally well established, but require site testing equipment and, above all, experienced testing personnel. The density of the layer in the field is established and compared with a specified target density. Provided the field density is greater than or equal to this figure, the compaction in the field is deemed satisfactory. A nuclear density meter normally determines the in-situ density.

Both types of specification are used widely in the construction industry, and both are appropriate for large schemes. If the project is being carried out to a national specification, the specification used is usually dependent on the type of HBM and its position in the pavement. In the case of small schemes, the method of specification is recommended as end-product density testing may be inappropriate.

Laboratory strength, California bearing ratio or modulus of elasticity

Representative samples from the full depth of the HBM layer should be taken from the site immediately before compaction. The frequency of the sampling should be related to the size of the treated area and its structural importance. The making, curing and testing of specimens will be stated in the specification and are normally carried out in accordance with BS 1924 and the relevant BS EN.

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Hydraulically-bound Mixtures for Pavements

Hydraulically-bound mixtures have been used in road, airport, port and other pavement construction for over 50 years. The performance of these mixtures are superior to that of unbound granular materials and often equivalent to those of bitumen bound materials. Use of hydraulically-bound mixtures is a sustainable form of construction, as extraction of primary aggregate is avoided through the reuse of site arisings, recycled material or artificial materials.
In addition industrial by products such as fly ash or granulated blastfurnace slag may be usefully incorporated as an active part of the binder.

This guide covers the stabilisation of naturally occurring soils or other materials to improve their mechanical properties and performance for use as capping layers, sub-bases and bases. To be in line with European standards and Highways Agency documents, the guide covers treatment with cement and the full range of hydraulic combinations based on fly ash, granulated blastfurnace slag, gypsum and lime. The resulting materials are known as hydraulically-bound mixtures (HBM).

The guide scope covers the performance, behaviour, materials, mixture design, construction and control testing of hydraulically bound pavements and as such will be of use to Civil Engineering designers, specifiers and contractors.

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