A guide to the use and specification of cold recycled materials for the maintenance of road pavements

Prepared for County Surveyors' Society, Highways Agency, Hanson Environmental Fund (Viridis), Scottish Executive, Tarmac, UKQAA, WS Atkins, Colas, RBA

D Merrill, M Nunn and I Carswell

TRL Report TRL611

First Published 2004
ISSN 0968-4107

This report has been produced by TRL Limited as part of a contract jointly sponsored by the Highways Agency, County Surveyors' Society, Hanson Environmental Fund (Viridis), Scottish Executive Development Department, Tarmac, United Kingdom Quality Ash Association (UKQAA), WS Atkins, Colas and the Refined Bitumen Association (RBA).

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Executive Summary

Recycling of existing pavement materials has become, and is, an increasingly important factor in the UK for maintenance of highways. Use of the 'linear quarry' concept of using the existing highway as a source of road-stone aggregates has gained considerable favour in recent years following the introduction of the first nationally consistent guidelines in TRL Report TRL386 (Milton and Earland, 1999). Since that time, sustainability and environmental issues have continued to receive more attention and this has resulted in the demand to consider recycling in the maintenance of a larger proportion of the primary and secondary road network. In construction and maintenance, the way in which materials are specified is changing to allow for innovation and alternatives to the use of primary aggregates newly extracted from a quarry. For instance, specifications can be based upon performance rather than on the use of standard materials made to strict recipes, design procedures can be introduced to permit many options to be considered rather than demanding combinations of strengths and layer thicknesses that limits the choice to new materials. A comprehensive sustainability strategy requires considering the use of all resources (including aggregates, binders and fuel) alongside engineering requirements in the selection of construction techniques.

Cold recycling is evolving into a major construction activity. *In situ* and *ex situ* variants of hot and cold techniques are now all feasible and many large and specialist contracting organisations can offer these services. Cold recycling can contribute to a reduction in energy, fuel and material consumption. The lower mixing temperatures reduce the energy required to produce these materials compared to conventional hot bituminous materials. Recycling technology has also improved with increasing use now being made of binder blends and cold recycling using the ex situ process which allows for screening and crushing of aggregates, prior to mixing with binder(s) in plant located nearby and laying of materials in one or more layers using a paver. In addition, the ex situ process allows the use of alternative aggregates from sources other than the existing pavement.

This guide to the use and specification of cold recycled materials for road maintenance is an extension of the earlier work described in TRL Report TRL386. The development of this guide was jointly sponsored by the Highways Agency, County Surveyors' Society, Hanson Environmental Fund (Viridis), Scottish Executive, Tarmac, United Kingdom Quality Ash Association (UKQAA), WS Atkins, Colas and the Refined Bitumen Association (RBA). It is aimed at 'end performance' and sets out design guidelines and specifications applicable to both in situ and ex situ recycling techniques. Materials have been divided into families based upon the binder or the binder blend being used in the construction.

The guidance is based upon a three year programme of work in which a detailed study was made at several sites during construction and for the first year following construction for a range of material families and construction methods so that the curing characteristics of each material family could be determined. Relationships between laboratory prepared samples, curing regimes and one year properties from site have also been assessed.

Aside from recycling existing pavement materials, there is now a wide range of alternative materials available for use in construction. These materials may have properties that are different from primary materials because of their mode of formation, and this difference affects their engineering behaviour. In many cases, these properties can be turned to advantage to create new materials that have no natural analogues. For example, pulverised fuel ash or blast furnace slag (granulated or ground granulated) can be used as hydraulic binders. In other cases, alternative materials may be used in place of primary materials to preserve scarce natural resources. Alternative materials that can now be readily used in highway construction include: recycled construction and demolition material, asphalt planings, pulverised fuel ash, china clay sand, slate aggregate, steel and blast furnace slag, colliery spoil, incinerator bottom ash, crushed glass, recycled tyres and recycled plastic.

The pavement design and material specification guide described in this report will help to facilitate the take-up of cold recycling. It is a comprehensive guide that covers material design, site evaluation, pavement design and end-product specification. The main features of this design guide are:

- It covers a wide range of cold-mix recycled materials involving a range of binders and binder blends. Materials are classified into families, which enables materials produced with new binders or combinations of binders to be introduced with relative ease.
- The advice covers a wide range of traffic conditions ranging from the lightly traffic roads to heavily trafficked trunk roads. However, some caution should be exercised in this extrapolation of current knowledge to heavier trafficked roads until more knowledge can be gained on the performance of cold mixed materials under these conditions.
- The pavement designs encompass the latest design methodology developed for the Highways Agency. This utilises 1-year material properties, which enables slow curing materials to be used in an equivalent manner to traditional materials.
- Material specification focuses on quality control of the material to ensure that proposals for end-performance made at the mix design stage are achieved in the permanent works. A quality plan, prepared by the contractor and agreed with the client, forms the core of the specification for cold recycled materials. It covers the entire production process of cold recycled material from the mix design stage through to *in situ* end-product testing.
- This extension of design guidance to cover a wider range of recycled materials and traffic conditions will allow more prudent use to be made of natural resources and assist in the protection of the environment in line with Government Policy.

1 Introduction

1.1 General

Recycling of existing pavement materials has become, and is, an increasingly important factor in the UK for maintenance of highways. Use of the 'linear quarry' concept of using the existing highway as a source of roadstone aggregates has gained considerable favour in recent years with the introduction of the first nationally consistent guidelines in the publication of TRL Report TRL386 (Milton and Earland, 1999), *Design guide and specification for structural maintenance of highway pavements by cold in situ recycling.* This report gave design guidance and specifications for in situ recycling using either foamed bitumen or cement for traffic levels up to 20 million standard axles (msa).

Since that time, increasing use has been made of binder blends and cold recycling using the ex situ process which allows for screening and crushing of aggregates, prior to mixing with binder(s) in plant located nearby and laying of materials in one or more layers using a paver. In addition, the ex situ process allows the use of alternative aggregates from sources other than the existing pavement.

This report is aimed at 'end performance' and sets out design guidelines and specifications applicable to both in situ and ex situ recycling techniques, although to ensure durability it has still been necessary to maintain some 'method' type elements in the specification clauses. Materials have been divided into families based upon the binder or the binder blend being used in the construction.

Proposals are included for pavement designs with heavy traffic, although it is stressed that this is an extrapolation of current knowledge of these materials and designs for heavier trafficked roads should be applied with caution until further knowledge can be gained on their performance. Use of designs for more heavily trafficked roads should provide for more prudent use of natural resources and protection of the environment in line with Government Policy.

The guidance is based upon a three year programme of work in which a detailed study was made at several sites during construction and for the first year following construction for a range of material families and construction methods so that the curing characteristics of each material family could be determined. Relationships between laboratory prepared samples and curing regimes and one year properties from site have also been assessed.

1.2 Design guide

The design guidance and advice contained in this report are based on a 3 year programme reviewing the performance during, and for the first year after, construction of pavements built using both in situ and ex situ techniques covering several material families. The type of binder or binders included within the mix describes each material family. Cores were extracted at various stages after construction using the air flush technique, to provide samples for studying the *in situ* curing behaviour of each family and to compare this behaviour with the curing behaviour of laboratory prepared samples subjected to different curing regimes. Design traffic levels of up to 80 msa are considered in this report although it is recognised that this is an extrapolation of current data for these types of materials and, therefore, these designs should be applied with caution until further knowledge can be gained on their performance.

2 Sustainable construction practices

The need and desire for change to the methods and materials used for construction and maintenance has accelerated in the last 10 years. The major instigator was the Rio Earth Summit in 1992 (Keaton, 1993) that elevated sustainable development to the forefront of government policy. The UK Government definition was developed as *'…a better quality of life for everyone, now and for generations to come'*; with a number of key elements including protection of the environment and prudent use of natural resources.

The UK Government objective for our transport system is that it should provide the choice, or freedom to travel, but minimise damage to the environment. In designing for construction projects, the way in which materials are specified is changing to allow for innovation and alternatives to the use of primary aggregates newly extracted from a quarry. For instance, specifications can be based upon performance rather than on the use of standard materials made to strict recipes and design procedures can be introduced to permit many options to be considered rather than demanding combinations of strengths and layer thicknesses that limits the choice to new materials. A comprehensive sustainability strategy requires considering the use of all resources (including aggregates, binders, and fuel) alongside engineering requirements in the selection of construction techniques.

Cold recycling should now be a major construction activity. *In situ* and *ex situ* variants of hot and cold techniques are now all feasible and many large and specialist contracting organisations can offer these services. Cold recycling can contribute to a reduction in energy, fuel and material consumption. The lower mixing temperatures reduce the energy required to produce these materials compared to conventional hot bituminous materials.

Aside from recycling existing pavement materials, there is now a wide range of alternative materials also available for use in construction. These materials may have properties that are different from primary materials because of their mode of formation, and this difference affects their engineering behaviour. In many cases, these properties can be turned to advantage to create new materials that have no natural analogues. For example, pulverised fuel ash or blast furnace slag (granulated or ground granulated) can be used as hydraulic binders. In other cases, alternative materials may be used in place of primary materials to preserve scarce natural resources. Alternative materials that can now be readily used in highway construction include: recycled construction and demolition material, asphalt planings, pulverised fuel ash, china clay sand, slate aggregate, steel and blast furnace slag, colliery spoil, incinerator bottom ash, crushed glass, recycled tyres and recycled plastic.

Specification clauses for the use of alternative materials have been developed by TRL and are included in the Highways Agency Specification and many local authorities also have their own guidance on the use of alternative materials.

3 Cold recycled materials in pavement construction

3.1 Current specifications for cold recycled materials

Current specifications for cold recycled materials are limited to in situ methods following the guidance given in TRL Report TRL386 (Milton and Earland, 1999) and the introduction in May 2001 of Clauses 948 for bitumen bound material and 1046 for cement bound material in the *Specification for Highway Works* (MCHW1).

3.2 Potential uses of cold recycled material

Provided that the cold recycled materials can achieve the desired performance, the potential use of cold recycling is not limited. However, there are general details that need consideration at each site.

The decision to use cold *in situ* recycling will depend mainly on the nature and consistency of the existing materials and the availability of appropriate specialised plant and skilled contractors.

Each site needs to be evaluated for the most appropriate maintenance in terms of:

- Location.
- Proximity of suitable location for setting up *ex situ* plant.
- Proximity of source(s) of alternative materials, if required.
- Type(s) and severity of deterioration.
- Extent of deterioration.
- Location of services within the pavement construction.
- Condition of drainage.
- Edge detail and verge condition.

3.3 Families of cold recycled material

This design guide covers all material types that could be considered as cold recycled materials and both *in situ* and *ex situ* construction processes. In order to adequately consider this wide range of materials, definitions of the material families are required.

Milton and Earland (1999) defined two families of *in situ* stabilised materials: one family where the primary binder was portland cement and the other family where the primary binder was foamed bitumen. Each family was treated separately with a design method and specification for each.

A versatile design methodology will permit a wide range of aggregate types to be used for both *in situ* and *ex situ* recycling; however, the stabilising agents are likely to be the dominant component in terms of the overall performance characteristics of a given mixture. Materials bound with portland cement are expected to cure more quickly than materials with other types of hydraulic binder, and visco-elastic materials are likely to be less prone to shrinkage cracking than hydraulically bound materials. It is, therefore, practical to define material families based upon the characteristics of the stabilising agents.

A ternary diagram, based on three distinct material types, can be used to classify materials into families, as shown in Figure 3.1. The apexes of this diagram correspond to fully hydraulic bound, fully visco-elastic bound and unbound material. Recycled materials using combinations of binder and curing behaviour can be characterised by areas within this chart. Four material types that fall into three material families are illustrated on this chart. These are classified according to the primary binder type and their rate of curing. The four materials are defined as:

- Quick hydraulic (QH) with hydraulic only binder(s) including cement.
- Slow hydraulic (SH) with hydraulic only binder(s) excluding cement.
- Quick visco-elastic (QVE) with bituminous and hydraulic binder(s) including cement.
- Slow visco-elastic (SVE) with bituminous only or bituminous and hydraulic binder(s) excluding cement.

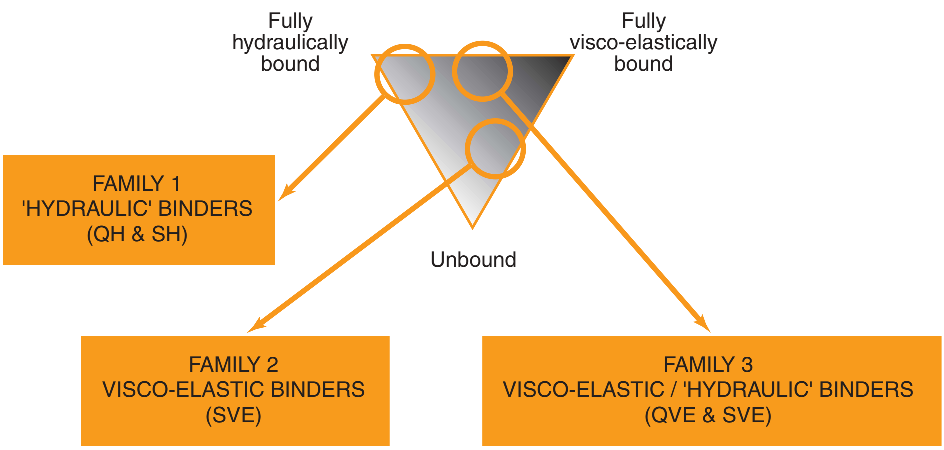

Figure 3.1 Identification of material families

4 Use of this guide

The following flow diagram (Figure 4.1) is an example of how this document can be used. In this example, the first task is to assess a site's suitability for recycling in terms of traffic and overall risk; such factors could negate the use of recycling at an early stage. Once the details of the scheme are finalised, an economic assessment should be carried out to see if the proposed solution is economically viable; there is the possibility that even if cold recycling is not the most economical solution, it could still be the preferred solution due to other issues such as sustainability.

5 Site evaluation

5.1 Assessment of pavement deterioration

A site may be identified for maintenance following an assessment of the pavement condition. The maintenance needs of the pavement can range from a remedy for substandard functional characteristics of the pavement such as ride quality to structural maintenance. A pavement assessment procedure is defined in the *Design Manual for Roads and Bridges* (DMRB 7.3.3); this assessment procedure is aimed at the principal road network although the underlying principles can apply to other parts of the road network.

Where pavement deterioration is identified as being a failure in the road haunch, the site assessment should be carried out in accordance with the advice contained in the following documents.

- Road Haunches: A Guide to Maintenance Practice. (TRL, 1994).
- Practical Guide to Haunching. (County Surveyors' Society, 1991).
- Road Haunches: A Guide to Re-useable Materials. (Potter, 1996).

If the deterioration in the pavement can be remedied by the replacement of the surfacing, refer to the *Design Manual for Roads and Bridges* (DMRB 7.4.1) for advice on possible maintenance treatments.

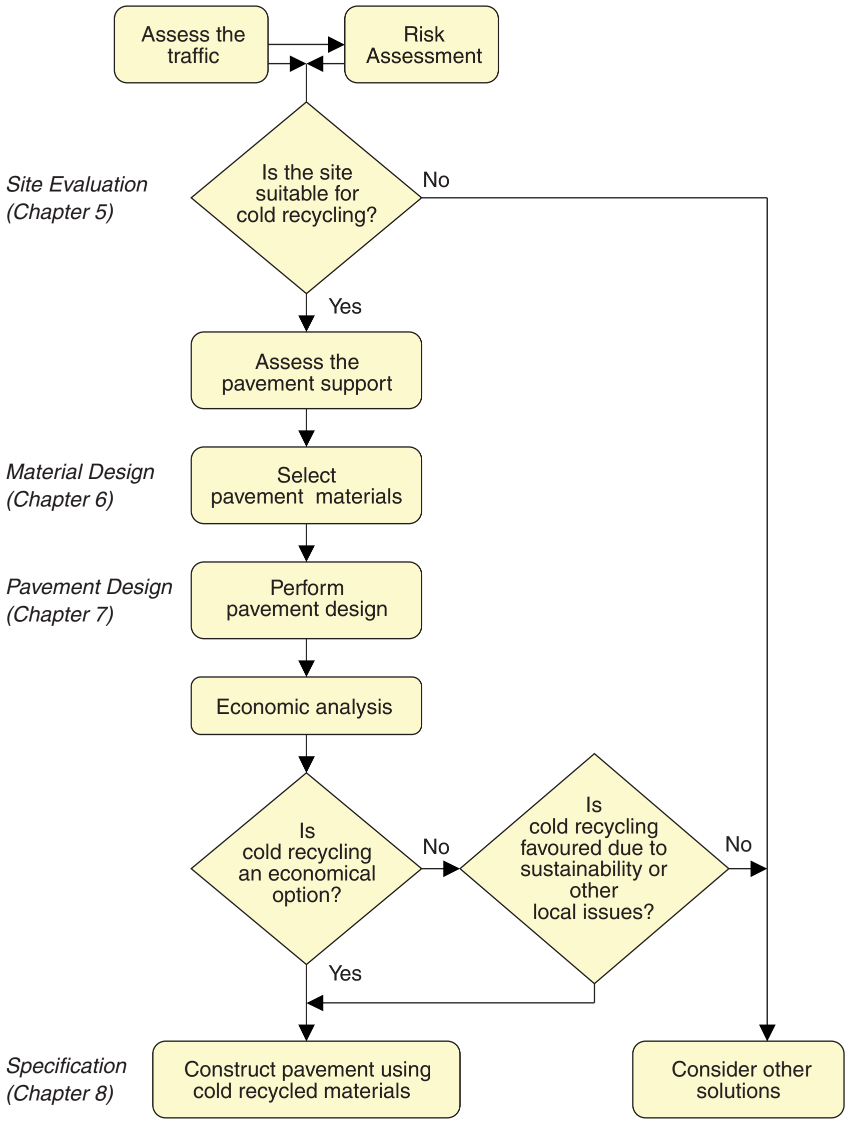

Figure 4.1 An example of the use of this guide

Where structural maintenance is required, or replacement of the binder course layer, a rehabilitation treatment of the pavement using cold recycled pavement materials can be considered.

5.2 Traffic assessment

A pavement containing recycled materials must be designed so that it can carry the traffic over the whole of the design period. Traffic can be described in terms of a cumulative number of equivalent 80 kN standard axles. A method of calculating design traffic for maintenance purposes is described in the *Design Manual for Roads and Bridges* (DMRB 7.2.1).

The HAUC specification for re-instatement of openings in highways (HAUC, 2002) includes five road categories. These road categories are defined in terms of million standard axles (msa) in Table 5.1 and will be maintained to describe the pavement design options for pavements comprising cold recycled materials.

Table 5.1 Road type categories

Road type category	*Traffic design standard (msa)*
0	Roads carrying over 30 to 80* msa
1	Roads carrying over 10 to 30 msa
2	Roads carrying over 2.5 to 10 msa
3	Roads carrying over 0.5 to 2.5 msa
4	Roads carrying up to 0.5 msa

** Road type category 0 has been restricted to 80 msa in this guide.*

For each road type category, different levels of risk can be assigned. For the road categories carrying the heaviest traffic, the risk of failure should be minimised due to a high risk for traffic delays if emergency intervention is required. However for the lighter road type categories, an increased risk of failure could be accommodated to increase the economy of pavement recycling methods for low volume roads. The pavement designs for Type 0, 1 and 2 roads have been produced according to a design methodology analogous to that which is implemented in the *Design Manual for Roads and Bridges* (DMRB 7.2.3). For Type 3 and 4 roads, there are permitted variations in the core design methodology that balance an increased risk of failure with more economic pavements incorporating cold recycled materials.

The road type category initially directs the designer to use the appropriate design methodology and later to select the appropriate design thicknesses; an exception is for full depth cold recycling on roads carrying traffic greater than 5 msa, where the pavement is designed for the actual design traffic level not the road type category.

5.3 Evaluating the suitability of cold recycling treatments

The suitability of cold recycling treatments depends on a large number of factors. The chief criterion for the selection of rehabilitation treatments will be an economic one. However, if cold recycling treatments are uneconomic compared to treatments using conventional hot mix materials, the case for cold recycling may still be viable provided that there is an appropriate policy for cold recycling treatments as part of a wider sustainability campaign.

The economic analysis of treatments comprising cold recycled material should be based on a whole life cost approach. This whole life cost approach should include the present cost of performing the treatment as well as all other discounted future maintenance costs associated with this treatment within a specified analysis period. In order to compare with conventional treatments, a default analysis period should be 30 years although longer periods could be selected dependent on the local policy or the nature of the treatment. For example, a full-depth reconstruction may need to be assessed over 40 years to be compared with long-life fully-flexible pavements. Advice on the economic assessment of road maintenance is available in the *Design Manual for Roads and Bridges* Volume 14.

As part of the economic assessment, the determination of initial costs of the treatments is required. For a maintenance scheme where cold recycling is a consideration, the initial costs are likely to be highly scheme specific. The method of estimating initial costs will include:

- The size of the maintenance scheme and the amount of recycled material that is expected to be required. It is likely that the economic recycling of a road pavement will be highly influenced by economies of scale. Some methods of cold recycling will involve the mobilisation of a substantial amount of plant. As a rough guide, a minimum programme of work in the order of 3,000 m^2 is estimated to be an economic threshold.
- The availability of raw recycled aggregates, both from within the maintenance scheme and also from other locally won materials. The cost of cold recycling can increase if there is insufficient raw materials from within the scheme or if raw aggregates are required to be transported over long distances.
- Where a treatment comprising recycled materials cannot be accommodated within the existing pavement thickness, adjustment of the drainage and other street furniture will need to be considered. If the finished level cannot be raised to accommodate the new pavement design, it may be possible to process some of the existing foundation material into the recycled material; such a procedure could introduce cohesive material that will require modification prior to stabilisation.

The suitability of cold recycling for maintenance is closely tied in with the likely performance of the recycled material and the consequential pavement design. Thus the economic assessment of a cold recycling scheme must be allied to a robust pavement and material design.

Most cold recycled materials are suitable for use in heavily trafficked pavements. This guide contains pavement designs for sites with traffic carrying up to 80 msa, although these designs are an extrapolation of the current knowledge which exists for pavements up to 30 msa. Also, heavily trafficked sites may require that the road is reopened immediately after construction to prevent excessive user delays. A high demand may also be required of the performance of recycled materials at an early stage. For these reasons, special care should taken to ensure that the mix design has adequate mechanical stability in early life. One test that could be used to show the mechanical stability of cold recycled material is the Immediate Bearing Index as described in BS EN 13286-47 (BSI, 2004).

The requirements for maintenance assessment when using cold recycling techniques can require that different procedures are employed to those described in the *Design Manual for Roads and Bridges* (DMRB 7.3.3). The location, condition and construction of the existing pavement will have a significant bearing on the methods of assessment as well as the contract details such as job size and job risk. An assessment of the pavement support as well as the suitability of materials from the existing pavement may be required.

5.4 Assessment of pavement support for full depth recycling treatments

The design of a pavement containing recycled materials is affected by the quality of support provided by the layer below the recycling treatment. Weak support may necessitate a high quality or thicker material to be placed. The intrinsic support offered to the pavement is one factor of the design that should be provided to the pavement designer and is, in most cases, an aspect of the design that is fixed.

The pavement design procedure for road types two, or superior roads, requires that the foundation is classified into one of four classes labelled 1 to 4. Foundation classes are an integral part of a versatile design methodology that is being developed on behalf of the Highways Agency concurrently with the development of this guide; the definitions of foundation classes in that methodology has been transferred to this guide for consistency.

- In most cases, a road foundation will be formed of a substantial thickness of well-graded, sound granular material and the thickness will be suitable for the subgrade strength; such a foundation is considered a Class 2 foundation.
- If the foundation is formed of poor quality granular material or the granular layer is thin for the strength of subgrade, it could be considered as a Class 1 foundation.
- Class 3 foundations represent stabilised foundations in good condition.
- Class 4 foundations represent stabilised foundations in good condition; however these foundations should be formed of coarse granular material, suitably thick and strong.

This advice applies only to full depth recycling. While the support plays an important role in all pavements, a partial depth recycling treatment implies that the lower layers of the pavement (and the foundations) are in a satisfactory condition. By implication of the maintenance assessment procedure, the support provided to the pavement is adequate for the conditions at the site and further assessment of the lower layers will be of little value.

Advice on the assessment of the support conditions for a pavement is catered for in the *Design Manual for Roads and Bridges*. For new constructions, the support conditions are easily available for assessment using standard procedures (DMRB 7.2.2). For maintenance assessments, other procedures are available (DMRB 7.3.3) for the detailed assessment of the condition of the existing pavement and a detailed assessment of the lower layers.

Three main avenues for the assessment of the support under a proposed recycling scheme are available to the designer; these are a desk-based records study, invasive assessment and non-destructive assessment.

The desk-based records study is likely to be the most economic method of determining the support. It does, however, attract a certain degree of risk. The quality of the information provided to the records, the maintenance of those records and the methods of retrieval could influence the result of the desk study. It may be advisable to augment this study with some limited investigation to confirm the quality of the construction records.

Invasive assessment requires that the supporting layers in the existing structure be exposed in some manner for assessment. Milton and Earland (1999) advised that the assessment be based around the excavation of trial pits at a maximum frequency of one trial pit per 500 m^2 or roughly one trial pit every 135 lane metres. These trials pits should be of sufficient size to extract a sufficient quantity of pavement materials to determine factors such as for:

Subgrade:	Atterberg limits, natural moisture content and CBR of the subgrade.
Foundation:	Thickness and nature of the foundation layers.
Pulverised aggregate:	Grading.
Lean concrete bases:	Compressive strength if suspected that the base is too strong for planning or pulverisation.

This advice is applicable for medium to heavily trafficked sites. Milton and Earland acknowledged that the allowable risk is different at different sites and advised that the frequency of excavations can be reduced for investigations of sites where there are lower traffic levels.

Non-destructive test methods are described in the *Design Manual for Roads and Bridges (DMRB 7.3.2)* for the assessment of the lower layers of an existing pavement. Primarily using a Falling Weight Deflectometer (FWD), the results can be analysed to give a stiffness for the foundation layers. At the present time, the precision of this result is such that only two performance classifications of foundation are advised; above 100 MPa is said to be associated with foundations providing good performance.

Although these non-destructive test methods provide an indication of stiffness, which is a key factor in the determination of foundation support, the current permitted methods of classification suggest that it is not sufficiently precise in order to classify the support of the layers below a recycled layer into one of up to four classifications.

The preferred methodology for the assessment of the supporting layers remains invasive assessments. The advice provided by Milton and Earland for cold *in situ* recycling procedures is still valid although some modification is required to reflect the need to classify the support if full depth recycling is required.

The proposed methodology for assessing the foundation support requires a combination of *in situ* and laboratory tests to classify the supporting layers. The *in situ* test method is principally the Dynamic Cone Penetrometer (DCP) that provides an estimate of the strength of the pavement layers and also the thickness of each layer. Foundation materials can be extracted from the trial pit after testing using the DCP; these materials can be tested according to the type of material. The extracted materials should be visually classified as unbound, weakly bound or strongly bound materials and the aggregate type noted, including whether fine or coarse aggregates have been used; this process will enable a crude comparison of the excavated material with that required for standard materials for new foundations. The following advice is provided on the assessment of different materials.

- Unbound aggregate samples can be tested for grading and soundness.
- Strongly bound materials can be extracted by coring to determine compressive strength.
- The strength of weakly bound materials can be gained from DCP tests although laboratory compressive strength tests are of value.
- The nature of the grading of the aggregates can be used to assess risk. Cracked materials containing fine aggregates are at increased risk of poor load transfer around cracks. Foundations containing rounded gravel aggregates may provide additional risks at the time of construction or may require treatment if the design traffic is above 5 msa; this is in accordance with the design requirements for new pavements described in *Design Manual for Roads and Bridges* (DMRB 7.2.3).

The foundation classes (or support classes) in the design method reflect a conservative condition taking into account long-term *in situ* properties of the materials. Consequently a series of tests performed on materials extracted from a trial pit are unlikely to replicate the conditions which the foundation classes describe. Therefore, the information collected at the time of the assessment should be allied with information from laboratory tests and more subjective information such as time of year.

A crude method of indicating the assignment of foundation class based on the DCP test is proposed in this guide. The outcome of this method does not supersede the advice of foundation classes provided earlier in this section. The method is based upon integrating the area under a Penetration versus Depth chart down to a depth of 600mm; integration in this fashion incorporates the contribution of supporting layers at different depths but the classification is biased towards those supports which have stiff layers close to the recycled layer. The integrated value has been called 'penetration area' and can be considered to reflect a weighted amount of energy required to drive the DCP cone through the supporting layers; an example of penetration area is shown in the shaded region of Figure 5.1.

Where P = Penetration (blows)
PA = Penetration area (mm blows)
D = Depth (mm)

The following classifications are suggested:

Table 5.2 Proposed assignments for foundation classes

Foundation class	*Penetration area (mm blows)*
1	>6500
2	>10000
3 or 4	>18000*

** May be impractical to measure with a DCP.*

Where the penetration area value is less than 6500 mm blows, the foundation could be considered as inadequate; in such cases the foundation can be improved using methods such as described in the *Design Manual for Roads and Bridges* (DMRB 7.2.2). For foundation classes 3 and above, assessment of support using a DCP may be impractical due to high strength materials being present. In these cases, alternative assessment techniques, including extraction of material for laboratory strength measurements, are preferred.

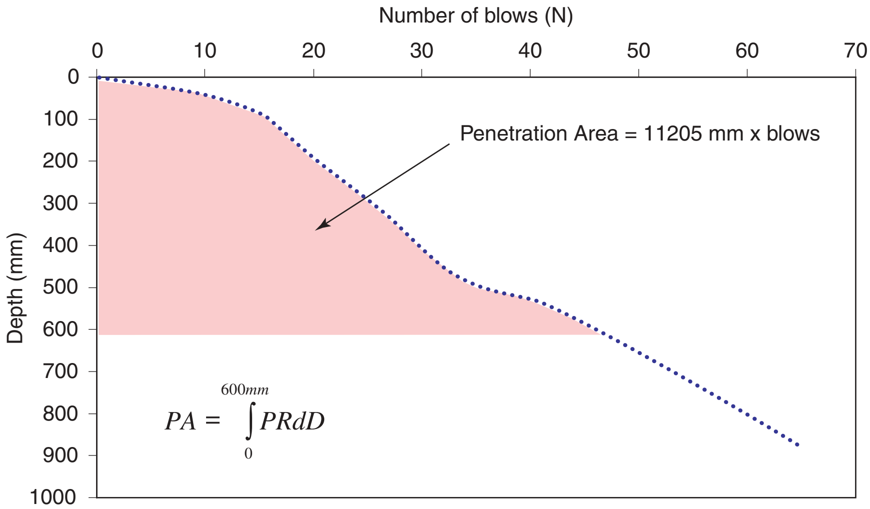

Figure 5.1 Illustration of penetration area

5.5 Assessment of the suitability of materials from an existing pavement

The assessment of the suitability of materials in existing pavement structures will only be required if it is anticipated that the cold recycled materials will contain aggregate from the existing structures. Where required, the assessment is likely to be carried out at the same time as the assessment of pavement support using invasive procedures. If this is not possible, an alternative method of obtaining material for the assessment should be investigated such as a limited coring survey.

For any assessment related to the design of recycling works, it is particularly important that any sample of aggregate obtained is fully representative of the aggregate to be used in the recycled pavement. The sample can be obtained as a mixed sample or in separate components, for recombining later in appropriate proportions. Furthermore, test specimens should ideally be representative of the aggregate obtained by pulverisation or planing, for both grading and particle shape.

Pulverised aggregate is normally obtained from the existing pavement. The design process may rely on test specimens derived from samples crushed in the laboratory. A variety of laboratory crushing methods are currently available, although none are believed to be specifically designed to recreate the pulverised aggregate produced by a recycler or planer. Guidance should be sought from the plant manufacturer on the most appropriate method of crushing material in the laboratory to simulate the performance of their plant.

The method of sampling material from the existing pavement should consider the condition of that pavement. Milton and Earland (1999) gave advice based on sampling from trial pits and cores, and defined three basic conditions of existing pavements with each condition associated with a level of uncertainty. As uncertainty increases, the operations proposed for sampling material increase; the proposals are reproduced in Table 5.3.

5.6 Risk assessment

5.6.1 General

The use of cold recycling techniques for pavement maintenance involves particular risks that may not be encountered with other types of maintenance. This section gives guidance on the likely risks associated with cold recycling so that consideration can be given to either mitigating or accommodating these risks. The types of risk covered in this document cannot be considered comprehensive. Site specific and material specific risks will be encountered which will need to be considered prior to commencement of the works. These risks are often difficult to quantify in terms of any standard measure, but their consideration and equitable allocation will be vital if the cold recycling operations are to be completed to the satisfaction of both contractor and client. Ignorance of these risks could lead to economic losses and/or a poor product and it is recommended that both the client as well as the contractor should be aware of the risks associated with cold recycling at a particular site to prevent unnecessary negative outcomes on maintenance schemes. Cold recycling is a developing industry that will have an important role in road construction and maintenance; early negative relationships between clients and contractors due to an insufficient comprehension of risk could seriously affect the future of this industry.

In all types of construction work, even where comprehensive site evaluation has been carried out, there will always remain those sites where unsuspected situations arise. However, for certain types of recycling works, such situations are more likely to play a part in the final outcome. Furthermore, for cold *in situ* recycling, there is an increased risk due to the variability of existing materials to be included in the finished works.

To offset this risk, greater understanding through a shared risk approach should be accepted for cold recycling operations. When existing pavement materials are being used, both parties in the contract are given the opportunity to satisfy themselves and agree that these materials in the sections of the works defined by the contract, are capable of being recycled to form the main aggregate component of the cold recycled mixture. For sites where *ex situ* materials are to be laid, the contractor will usually supply the main aggregate; for *ex situ* processes the risk is similar to other conventional material supplies. In general, the client is responsible for ensuring that the contracting partner has sufficient capability to obtain the main aggregate and material components of sufficient quantity and quality so that the recycled mixture is capable of being designed and produced to meet the specified end-product performance requirements.

For sites where the existing pavement materials are to be used in the cold recycled material, the client is normally expected to organise and implement the site investigation works separately, as part of the general design process for the purposes of competitive tender arrangements. In these circumstances, if risk is to be shared, the investigation must be comprehensive, and offer all potential contractors suitable data for designing and programming their individual method of working, appropriate to the particular site conditions.

The risks associated with any particular pavement recycling scheme will need to be included in any whole-life cost analysis. Milton and Earland (1999) reported that 'experience to date has indicated that even where quite pessimistic projections for the service life of cold *in situ* recycled pavements are used, significant whole life cost savings are possible'.

Risks can be broadly classified into design risks and construction risks. The design risks are associated with the pavement design in terms of the expected performance on the structure and mix design risks in terms of the expected performance on the recycled material. Construction risks are encountered during the preparation of the site for laying recycled materials as well as the production, transporting and laying of recycled material.

5.6.2 Pavement design risks

Pavement design is the process of selecting materials and construction thicknesses in order to ensure that the pavement

Table 5.3 Guidance on site investigation requirements for cold recycling projects on medium to heavy trafficked sites where material in the existing pavement is to be used

Pavement type	*Fieldwork proposals*	*Sampling and testing*
Designed pavement structure comprising standard materials of known thickness and consistency.	Excavate trial pits at a target frequency of 1 per 200 m in each of the lanes to be recycled, with a minimum of three pits for any scheme. Record details of each construction layer, including any unbound foundation. Obtain separate representative samples of each distinct material. Determine the nature and condition of the subgrade and obtain a measure of bearing strength.	Collect sufficient representative material from each construction layer to produce a 100 kg bulk sample comprising proportionally recombined mixture of materials from all trial pits. Use bulk sample for design and trial mix tests.
Designed pavement structure comprising standard materials of known thickness and consistency - but with reinstatement of openings or pavement repairs that could locally affect the consistency of the pulverised aggregate.	As above. Plus one trial pit or full-depth 200 mm diameter core from each distinct reinstatement/repair that has an area greater than 25 m^2 or extends full width for more than 5 m in any lane. Plus minimum of one full-depth 200 mm diameter core from smaller, closely spaced and recurrent areas of reinstatements, where their combined area locally, accounts for more than 20 per cent of the paved area in any lane.	As above, with additional representative bulk samples from each distinct area of reinstatement/ repair, used to produce additional recombined bulk samples to assess any mixture design changes that may be needed in these areas.
Undesigned pavement structure comprising a variety of standard and/or non-standard materials built over time by maintenance processes, in layers/zones of unknown thickness or continuity.	Carry out an initial evaluation by extracting full-depth 200 mm diameter cores at target frequency of 1 per 100 m in each lane to be recycled. If materials are consistent proceed with design using the material from the cores as the test samples. If pavement structure is inconsistent, carry out further investigations to try to determine the extent and/or thickness changes of the different materials. As an alternative to widespread coverage of further cores, traverses of ground penetrating radar may be found useful to reveal thickness and profile changes, to help divide the site into reasonably consistent sections and target the position of trial pits and/or further cores. Investigate each section using a minimum of three trial pits or three sets of three full-depth 200 mm diameter cores, dispersing evenly throughout the section, with at least one trial pit or core in each lane to be recycled. Obtain representative samples from each layer from each section.	Visually assess the material retrieved from the initial cores to decide on the consistency of materials. For a consistent material profile use the materials from the cores to produce a proportionally representative 100 kg bulk sample for overall design and trial mix tests. For inconsistent material profiles, collect sufficient representative material from each construction layer in each of the defined sections to produce 100 kg bulk samples comprising proportionally recombined mixtures of materials from each section. Use bulk sample from each section for separate design and trial mix tests.

structure will carry the expected traffic for a given period of time. It relies upon the assumption that the construction process will provide expected long-term properties of the material in layers that are of sufficient thickness.

A comprehensive site investigation needs to be carried out to minimise the risks in the calculation of the design of the pavement structure, including a detailed subgrade study looking at such aspects as moisture, density and strength of the subgrade where these properties need to be taken into account in the design process. The properties of subgrade may be variable and, therefore, the investigation should be detailed enough to detect significant changes; a pavement design based upon an insufficient site investigation that did not detect weak areas in the subgrade could adversely affect the performance of the recycled pavement structure.

The fatigue life of strongly cemented pavements is highly sensitive to thickness and stiffness. It is imperative that the expected long-term properties of the material and the pavement thickness design are monitored at construction in a reliable fashion otherwise substantial reductions in performance may occur. Also, the type of binders used in the recycled mixture will affect the workability and setting time. Such considerations are important in being able to achieve the specified layer density; density is the key factor in ensuring that the long-term performance that is assumed in the design is achieved.

The binder content will also influence the stiffness and strength of the recycled mixture. An inadequate quantity of binder may lead to the material being susceptible to moisture. Increasing the quantity of bituminous binders could lead to premature deformation problems while increasing the quantity of quick setting cementitious binders increases likelihood of thermal cracking.

This guide contains pavement designs for sites with traffic carrying up to 80 msa although the road trials on which the design guidance contained in this report was formed carried a maximum of 25 msa; therefore designs for heavily traffic roads are based upon extrapolations of existing knowledge and they should therefore be used with caution.

5.6.3 Mix design risks

The mix design is principally performed as an essential input to the pavement design process. As such the risks for mix design will have a significant impact on the risks associated with pavement design.

The principle feedstock of aggregate for the mix design process should be the same feedstock of aggregate for the permanent works. In some cases, sufficient aggregate from the same source as for the permanent works may be unavailable. Where aggregate is unavailable, the mix design should be performed on an aggregate as close as is reasonably possible to the aggregate in the permanent works. A degree of caution should be applied to the results of this mix design process because these can be highly influenced by the nature of the aggregate involved.

The recycled aggregates from existing roads containing multiple layers may be more variable in quality and type than those from a single layer because there is effectively more than one source. Where possible, the mix design stage should take into account this variability by varying the proportions of recycled aggregate from each layer.

5.6.4 Construction risks

Construction of a pavement comprising cold recycled materials is dependent on a large number of linked processes.

During the *in situ* recycling process, the time between pulverisation of the existing pavement and compaction of the recycled material is generally much quicker than conventional reconstruction techniques; therefore there is a corresponding reduced risk as a result of exposure of the lower pavement layers to inclement weather and traffic during construction.

The compaction of cold recycled material is one of the most critical parts of the construction procedure; it can be influenced by the duration between mixing and laying of the material and the selection and use of compaction plant. The contractor should be aware of the workability of the material and manage the construction processes so that delays are minimised; some slow curing cold recycled materials are more workable and tolerant of delays than quick curing materials. Delay after mixing the material or poor selection or use of compaction equipment may lead to a substantial loss of serviceability of the finished pavement due to reduced levels of compaction and consequential loss of durability in the material.

For sites on heavily trafficked routes, there will be an urgency to re-open the pavement to traffic. In their early life, cold recycled materials rely upon internal mechanical stability or strength in order to resist damage under traffic. While the speed of opening to traffic is a consideration for the mix design process, construction issues and the local environment can affect the time required for the material to gain sufficient mechanical stability or strength.

In urban situations, the risk of causing nuisance and possible risk to health by dust must be assessed when a pulverisation process forms part of the maintenance scheme. In addition, the effects from the use of pulverisation plant and large compaction plant need to be considered and monitored if works are adjacent to underground services and buildings or other structures likely to be damaged by high amplitude vibrations.

In situ recycling is particularly useful in areas where the existing road geometry must be maintained. For example, an urban situation where the maintaining of the position of road furniture, such as kerbing, will have a beneficial economic effect, and situations where there is restrictive headroom at over bridges. Where recycling has been justified on the basis of maintaining existing road geometry, there is an increased economic risk from failure to meet the specification requirements at either mix design or, worse, at construction stage; in other circumstances, poor material properties could be mitigated by increasing the thickness of the pavement layers.

5.6.5 Underground services and other hazards

It is vital to accurately locate and record the depth of all underground services because of their disruptive potential within recycling works, particularly if disturbed or damaged. If a pipe or cable lies within 150 mm of formation level, it should be deemed at risk, particularly if the services are old. It is prudent, therefore, to consult with the statutory undertakers at an early stage of the design process. Additional enquiries and investigation will probably be needed to establish the location and depth of service connections to adjacent properties, because these connections are often unrecorded and are at a shallow depth in relation to the depth of the mains supply. If premature deterioration of the existing road has been caused by damaged or defective services, any such problem should be remedied before or as part of the pavement renovation contract.

Care must be taken to locate and avoid existing road furniture, such as man-hole covers, because collision with these items during pulverisation may cause serious damage to the plant and delay the works.

6 Mix design of cold recycled materials

6.1 Aggregate

6.1.1 General requirements for aggregate

The aggregate for cold recycled material can come from the pulverised material from existing roads; alternatively, other approved aggregate types may be used from other sources.

The source and stock of the aggregate for recycling is a key factor in the decision about material composition and the construction process. A fine grained aggregate may be more suitable to hydraulic binders whilst certain types of aggregate may prove incompatible with certain bituminous binders. If it is possible to obtain an adequate volume of aggregate from the road to be maintained by pulverisation of the existing material, then an *in situ* stabilisation process could be favoured to an *ex situ* process.

6.1.2 Grading

Many of the materials that could be considered to be cold recycled materials are described under the umbrella of European (CEN) standards. It is, therefore, prudent to ensure that the grading used for the specification to cover cold recycled materials is consistent with all the materials in the European standards that are likely to be required to be covered by this guide. In particular, the sieve sizes shall be consistent with European standards (which have replaced previous BS sieve sizes in the UK).

Milton and Earland (1999) defined two grading zones for *in situ* stabilisation: Zone A and Zone B. Zone A is a well graded aggregate of nominal size 50 mm. Zone B is a finer grading than Zone A; materials graded to within Zone B were only permitted to be used if mix design testing proved that this aggregate could be used to produce a consistent cold recycled material.

The development of the grading curves in this guide has attempted to maintain the curves defined by Milton and Earland whilst incorporating the CEN approach to grading. Three grading envelopes are shown in Figure 6.1: Zone A (suitable for all cold recycled materials), Zone B (finely graded aggregate only suitable in certain circumstances) and Zone C (a coarse grading that is only suitable for *in situ* stabilisation). The detail of the grading requirements for these zones is given in Appendix A.

Materials that are in Zone C are reported to have a greater risk of segregation (BSI, 2002) but were covered by Milton and Earland for *in situ* stabilisation; therefore their use is recommended only for materials constructed using an *in situ* stabilisation process.

Milton and Earland suggest that bitumen bound material is highly sensitive to the fines component of the material. For cold recycled materials, bitumen has a tendency to be attracted to the fine aggregate particles before coating the coarser fractions of aggregate. They recommended that the amount of fine material passing the 75 micron sieve should be restricted to between 5 and 20%, while coarse material that cannot be modified to meet the desired grading should be augmented by pit sand or PFA as filler. Such advice has been maintained in the production of the grading curves for cold recycled mixtures (although using a 63 micron CEN sieve); Zone B is unlikely to be used with bitumen bound mixtures.

6.2 Moisture content

The moisture content of a cold recycled material has a large influence on the workability of the material, in particular, it can control the degree of compaction that may be achieved. Whilst the optimum moisture content would be the natural selection as a target moisture content, for recycled materials the target moisture content depends, to a certain extent, on the moisture content of the recycled aggregate.

Due to the effect of variable moisture content in the road, the moisture content of the mix can be difficult to control; this is an important issue for *in situ* processing. Experience with producing and compacting *in situ* foamed bitumen treated materials in South Africa has recommended 'working slightly dry of optimum' (Asphalt Academy, 2002).

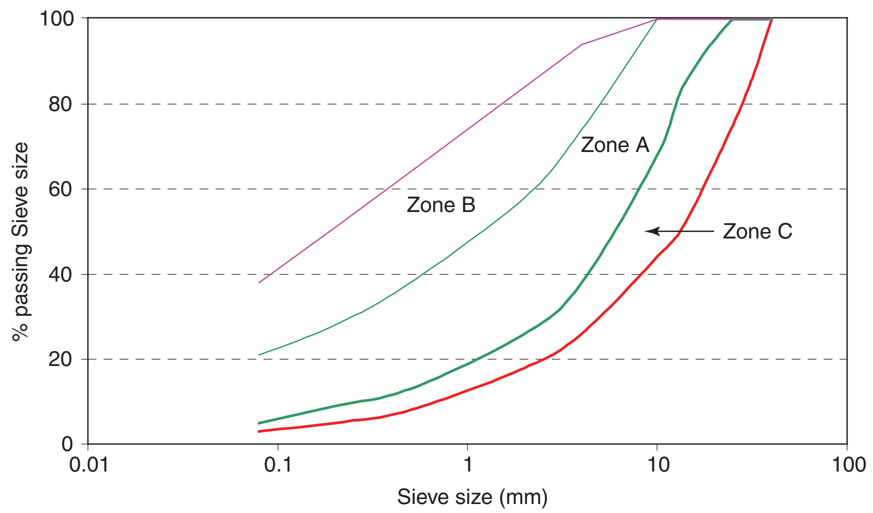

Figure 6.1 Grading curves for cold recycled mixtures

6.3 Binding agents

6.3.1 Portland cement

Portland cement is used to a lesser or greater degree in quick hydraulic (QH) materials and quick visco-elastic (QVE) materials; it is the key component that ensures the materials are classified as quick curing.

The primary reason for the use of portland cement is to provide a material that gains strength quickly at reasonable cost. Portland cement is a widely used road construction binding agent that can be used with a wide range of aggregate types (including pulverised aggregates). It is relatively tolerant of poor weather conditions because it cures quickly. It is also tolerant of some plastic or organic material in the mixture.

Care should be taken in the design of materials comprising portland cement. Whilst its use has clear advantageous effects, mixtures with a high proportion of cement will have a risk of thermal cracking.

Highways Agency and CEN specifications cover the use of cement bound aggregates; therefore, the use of mixtures comprising cement only may also be covered by other specifications providing the recycled aggregate also meets the particular requirements.

6.3.2 Other hydraulic binders

Granulated blast furnace slag (GBS) and ground granulated blast furnace slag (GGBS) are by-products of the steel industry. These materials are formed by rapid cooling of molten slag in water. GGBS is a fine material that can be used to substitute for a proportion of portland cement. GBS is a coarse material that could be used to form more of the aggregate skeleton of the mix; GBS can also be used as a binder if crushed in the presence of lime or sulphate.

Pulverised fuel ash (PFA) is a by-product from the burning of fuels in power stations and has been used in road construction for many years. Its use in road construction is currently covered by BS EN 14227-3 (BSI, 2001) for fly ash bound material (FABM). It is possible to use lime with PFA and generate a strong binder through pozzolanic reaction. It is a very fine grained material and can be used to modify the amount of fine materials in the mix. The use of PFA in preference to portland cement creates a slower curing material in which diffuse cracking rather than large cracks develop. The long-term properties of a mixture containing PFA are likely to be similar to the equivalent mixture containing portland cement.

Unweathered 0/4 mm basic oxygen slag (BOS) is covered by the specification; BOS is referred to as air-cooled steel slag (ASS) in CEN standards. These fines have a high free lime content and can perform many of the functions of traditional lime. The proportion of BOS in the mix should be restricted due to its expansion characteristics as the material hydrates to form a binder.

6.3.3 Foamed bitumen

Foamed bitumen can be used with a variety of combinations of other binders to produce fully-flexible pavement structures. When used with other hydraulic binders, it could be viewed as a hybrid material: neither bituminous nor hydraulic. Foamed bitumen binders are used to produce both QVE and SVE material families; QVE material also includes a proportion of portland cement.

Foamed bitumen is produced by the injection of 1 to 2% cold water with air into hot penetration grade bitumen. This process produces a high-volume, low viscosity fluid with low surface tension; these properties enable the foamed bitumen to coat a wide range of moist, cold recycled aggregates.

The foaming temperature or water content has an influence on the expansion ratio (volumetric fluid expansion after foaming) and bubble life; high temperatures and water content increases the expansion ratio but reduces bubble life. The choice of bitumen grade is a compromise between foaming ability and stiffness; higher grade bitumen foams easily but has lower stiffness.

Materials bound with foamed bitumen, on its own or with lime and PFA, are highly workable; they can be stock-piled or reworked if necessary up to 48 hours after production. This feature indicates that the material is slow curing; indeed, the long-term performance of these materials is reliant on the slow curing properties. Provided that the material is sufficiently compacted, it can normally be opened to a moderate degree of traffic after one day.

For an increased rate of curing, foamed bitumen can be combined with portland cement or other hydraulic binder. Increased curing may be required when the chosen binder/aggregate combination does not generate early-life stiffness or when more demanding traffic conditions are encountered. The balance between foamed bitumen and some hydraulic binders can be a compromise between early life performance and the risk of thermal cracking.

6.3.4 Bitumen emulsions

Bitumen emulsions are widely used in highway engineering in a range of applications from tack coats to surface dressings. They are also used as a bituminous binder for cold mixed materials including those in cold-mix recycling.

An emulsion is a system comprised of two immiscible liquids, the one dispersed in the other, in the form of fine globules or droplets. Bitumen emulsion is generally an oil-in-water type of emulsion in which the bitumen (the oil) is dispersed in water and held in suspension by means of one or more emulsifying agents. This produces a low viscosity fluid at low temperatures that is suitable for coating cold recycled aggregates. Compaction of the mixture accelerates the rate of development of cohesion by laminating the bitumen globules and squeezing out the water. Bitumen emulsion is readily combined with hydraulic binders but care should be taken to prevent stripping problems by selecting an emulsion that it is compatible with the aggregate.

The early life and long term properties of mixtures with bitumen emulsion are similar to those with foamed bitumen.

6.3.5 Other components

Other components that are covered in this guide and specification are principally lime, although the guide does not exclude any particular material components provided that their value in road construction can be demonstrated.

Lime (quick lime or hydrated lime) is used as both a modifier and an activator of certain hydraulic components. Lime can create weak bonds between the recycled aggregate particles and can be used to reduce the plasticity of aggregate containing plastic or organic elements. Lime can improve the adhesion properties of the aggregate with bituminous binder. For some slow curing hydraulic binders, lime is an activator for the other binding agents.

6.4 Guidance on the selection of materials

The scope of the design guide covers a range of material types using a wide range of components. It is not the role of the guide to advise on material composition; such decisions should be made based on the results of the mix design process and directed by local economic factors. However some general advice on cold recycled materials is given, and advice on the applicability of different components is given in Section 6.3.

Guidance is, provided on the main features of the four principal material families.

Quick curing materials achieve their optimal properties fairly early in their life. Such materials are suited to locations where there are demands to open the pavement quickly and/or the traffic intensity will be high.

Slow curing materials offer increased workability and a reduced risk of material performance being adversely affected by delays during construction. Hydraulically bound, slow curing materials are thought to have a lower risk of reflection cracking than their quick curing counterparts; naturally forming shrinkage cracks form in a more dispersed manner for slow curing materials than for quick curing materials. Slow curing materials can be suitable for locations where there is a traffic demand in early life provided that the material has adequate mechanical stability.

Cold recycled materials can perform well under early-life trafficking provided that the materials are not damaged through permanent deformation or cracking. Permanent deformation occurs where the traffic stresses exceed the internal friction or strength of the material, when the material is said to be unstable. For some materials, cracks that have occurred in early-life can be healed if significant curing occurs after the cracks were initially formed. Quick curing materials are at risk of damage during early-life trafficking due to cracking; deformation should be prevented by adequate stability. Slow curing materials are at risk of damage during early-life trafficking due to deformation; cracks that occur in early-life are likely to be healed during the slow curing process.

In the scope of this guide, the selection of either hydraulic or visco-elastic materials remains largely an economic decision. However, aggregates whose grading contains a high proportion of fine material may be unsuitable for the production of bitumen bound cold recycled material.

6.5 Mix appraisal and design

6.5.1 General

Milton and Earland (1999) developed a mix design process based upon an accelerated curing regime for *in situ* stabilised material containing either cement or foamed bitumen. The approach proposed for cold recycled materials in this document allows the contractor more freedom in which to conduct the mix design; it is, however, a requirement of the specification that the mix design stage is documented and used as part of the compliance procedure in the permanent works.

Advice is supplied on the mix design process on the treatment of the different families in the Notes for Guidance section of the specification. Therefore, it does not form part of the contract requirements but the end product requirements (which state that the work carried out in the mix design stage must be followed) will form part of the contract. The contractor has some freedom to choose the method and detail of the mix design stage as agreed with the client. The method of acquiring the results of the mix design will need to be recorded for insertion into the Material Quality Plan (see Section 8.2).

The mix design stage should be as detailed as is economically feasible. The greater investment in the mix design stage, the less the risk at construction stage. It should be remembered that the law of diminishing returns applies, and the investment in the mix design stage must be balanced with the risk of failure in the construction stage. For example, contracts on high profile routes for which delays in opening to traffic or repeat works are critical would justify a large investment in the mix design stage.

6.5.2 Material conditioning in the laboratory

The design and specification of cold recycled material is based upon the one year or long-term performance of the materials. In order to obtain these estimates of performance in the laboratory, some form of sample conditioning is required. When a material is described as quick-curing, it can develop stiffness or strength rapidly and assurance of its long-term characteristics can be obtained in a relatively short time. In the UK, such behaviour has been traditionally exploited for specification of portland cement bound materials.

Many materials cure at a slower rate and it is not possible to provide assurance of the long-term properties of the materials in the traditional manner. In order to obtain a reliable estimate of the long-term properties, there should either be a defined progression of performance from short to long-term or an accelerated curing regime implemented that reliably predicts the long term properties of the material. The wide spectrum of materials that are covered in this guide does not allow for a defined progression of performance to be assumed; there is, therefore, a requirement to cure the material in some accelerated manner to provide a more reliable assurance of its long-term properties.

Accelerated curing is achieved by raising the temperature of the environment surrounding the material to increase the rate of chemical reaction in the sample. Curing at elevated temperatures can affect the type of chemical reaction in the sample and it is, therefore, preferable to use a temperature for curing that is as close as possible to the temperature that would be encountered in the pavement. Milton and Earland advocated a curing regime of 60 °C for 72 hours. This curing regime was undertaken at a far higher temperature than average *in situ* pavement temperatures and may be considered unrealistic.

For this design guide, a low temperature regime for sample conditioning has been sought wherever possible. The specification does not prescribe the method to use but simply advises on the most applicable regime in the Notes for Guidance. A summary of the advised conditioning regimes is shown in Table 6.1. A curing regime for SVE material is provided only when it contains a pozzolanic component; otherwise a high curing temperature is required to generate some form of curing in early life. Curing at such temperatures is not encouraged for prediction of long-term performance, but may be suitable only for establishing a provisional mix design.

Table 6.1 Laboratory conditioning regimes and factors to relate to long-term performance

Family	*Temperature (°C)*	*Duration (days)*	*Long-term factor*
QH	20	28	1.2
SH	40	28	1.0
QVE	20	28	1.2
QVE*	40	28	1.0
SVE	–	–	–
SVE*	40	28	1.0

** For materials containing a pozzolanic binder.*

The long-term factors shown in Table 6.1 are used to provide an estimate of the performance of cold recycled materials after approximately one year. The pavement designs given in Section 7 of this guide are based upon the properties of cold recycled material at one year. Therefore, the conditioning regimes described in Table 6.1 can be used with an appropriate laboratory test procedure to give confidence, at an early stage, that the properties assumed to design the pavement are likely to be achieved. The long-term factors are conservative but other factors may be used with appropriate supporting evidence.

7 Pavement design using cold recycled materials

7.1 Full depth or partial depth pavement design

Cold recycled materials can be utilised in a pavement structure in two ways:

- The cold recycled material forms the layer immediately above the foundation and is covered by a bituminous surfacing.
- Bitumen bound cold recycled material can be used as a substitute for conventional hot mix material for inlay treatments where a significant proportion of the existing pavement remains to form part of the rehabilitated pavement.

This design guide includes mutually exclusive methods to perform pavement design for both situations.

7.2 Pavement design for full depth cold recycling

7.2.1 Background

Milton and Earland (1999) produced design curves for *in situ* cold recycled material based upon a limited set of trial data. These curves were developed in isolation due to the small number of possible constructions considered. This design guide extends these curves to cover a wide range of recycled pavement materials using both *in situ* and *ex situ* construction techniques.

The design of pavements comprising Cold Recycled Material follows the Versatile Pavement Design methodology that is currently under development by the Highways Agency (Nunn, 2004). This method uses a single pool of input data from which separate design criteria are applied depending on whether the base comprises a hydraulically bound or bituminous bound material. Figure 7.1 gives an illustrative view of the pavement design process for cold recycled materials.

7.2.2 Definitions

In the context of structural maintenance of highway pavements using cold recycling, whilst carrying out the same function, a standard pavement layer may be constructed significantly different to that of the same layer in a new pavement. Therefore, the broader definitions applicable to this design guide are:

Subgrade: Underlying natural soil or rock. However, in the situations where the subgrade is weak or there is insufficient depth to the existing pavement, the upper layer of the subgrade may be stabilised using the *in situ* recycling technique and incorporated as part the foundation platform.

Formation level: Immediately below the sub-base layer and at the top of the subgrade or capping layer.

Foundation: The support to the overlying pavement layers that serves as a platform to construct the structural course. It includes the sub-base, subgrade and the capping layer if required. For maintenance purposes, this layer will normally comprise the undisturbed lower sections of the existing pavement. In situations where there is insufficient depth of existing pavement to satisfy the current design or where other circumstances dictate, this platform may be constructed, in part or whole, using cold recycled material.

Structural course: The main stress distribution layer within the pavement whose thickness is dependent on stiffness of the material itself, stiffness of the underlying structure and the anticipated traffic loading. This layer will normally comprise cold recycled material, but where there is insufficient depth of existing pavement and the *in situ* recycled material is used to form the foundation platform, it may comprise in part or whole, new plant mixed material. This layer is often called the base.

Surfacing: The upper layer or layers of the road, designed to provide an even surface with a high resistance to deformation and an adequate resistance to skidding.

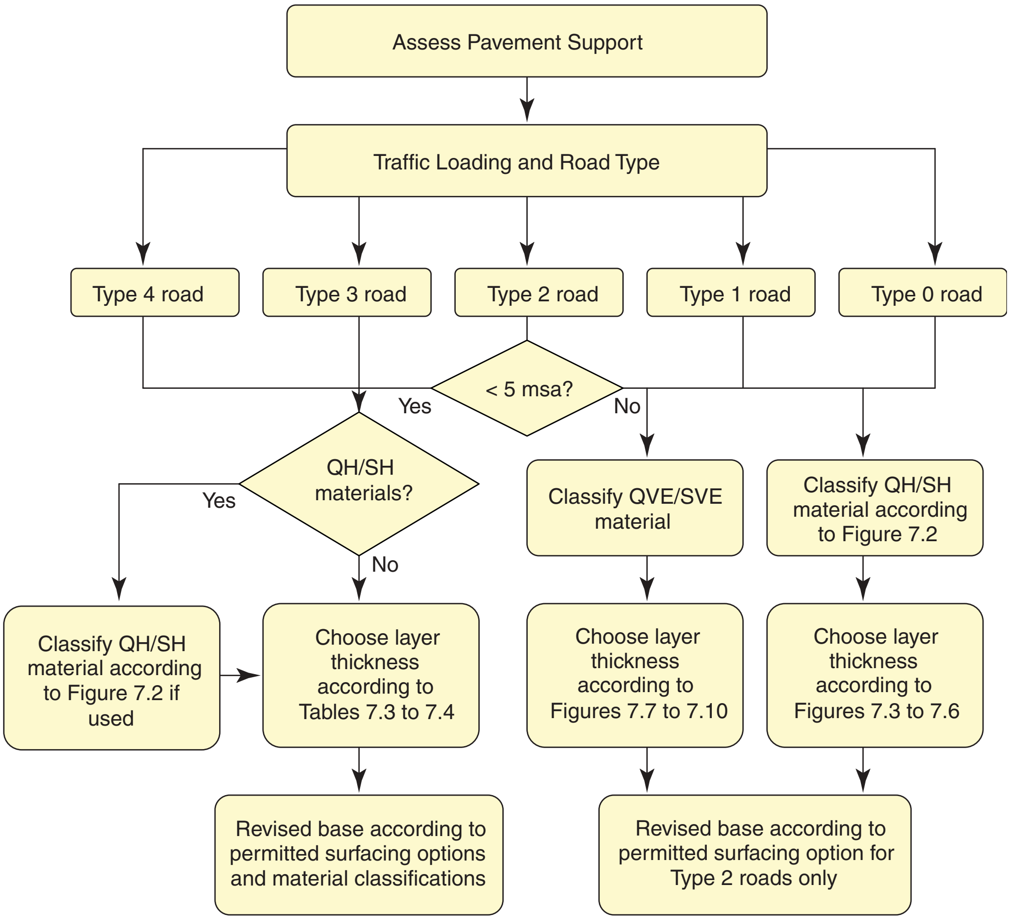

Figure 7.1 Full depth pavement design process for cold recycled materials

7.2.3 Pavement support

The foundation layer of a pavement performs two main functions: to allow the construction of the overlying pavement and to provide support to the pavement throughout the life of the pavement. The scope of this design guide is not to design the foundation but to characterise the foundation in order to design the overlying pavement. As such, it is assumed that the foundation design is sufficient to carry the construction traffic to build the pavement layers.

The pavement design requires the foundation to be characterised into four levels of support, called foundation classes. These foundation classes are defined according to a long-term support provided to the pavement by the foundation called the design support value. For superior foundation classes, adjustments are permitted in the overlying pavement design to enable potential economies to be realised.

The four foundations classes are given in Table 7.1.

These assumed design values can be compared to measurements made whilst the foundation is exposed. It should be remembered that such measurements are short-term values and consideration should be given to the long-term changes in the foundation; such changes include:

- Changes in equilibrium moisture.
- Confinement of unbound or weakly bound material.
- Curing of hydraulically bound and bituminous bound materials.
- The development of naturally occurring cracks in hydraulically bound material.
- Long-term durability issues

Table 7.1 Permitted foundation classes

Foundation class	*Assumed design support*
1	50 MPa
2	100 MPa
3	200 MPa
4	400 MPa

7.2.4 Pavements with hydraulically bound cold recycled structural course

The design method for pavements comprising hydraulically bound structural courses has two stages: material classification and thickness design. Hydraulically bound materials are classified into one of nine zones labelled H1 to H9. Once classified, the designer selects the thickness design chart for the appropriate foundation class; the thickness for the design traffic can be determined for the curve associated with the material zone.

The combination of stiffness and strength is imperative for the design of a hydraulically bound structural course. Two different hydraulically bound materials can have the same base thickness for a given level of traffic, provided their flexural strengths compensate for any differences in their levels of stiffness. If stiffness is increased, the traffic induced tensile stresses in the structural course, which influence performance, also increase. Therefore, the strength would need to be higher to achieve the same performance. Relationships between elastic stiffness modulus and flexural strength have been developed for equivalent performance and grouped into nine zones. These are shown for materials of stiffness between 5 GPa and 60 GPa in Figure 7.2.

The triangle illustrates that a material with elastic modulus of 20 GPa and a flexural strength of 0.9 MPa falls into material zone H3. Classification of materials according to Figure 7.2 requires that the dynamic modulus and flexural strength are known. Where these values are not directly measurable, suitable alternative apparatus and transfer functions may be utilised as described below.

Using compressive strength tests in accordance with BS EN13286-41 (BSI, 2003a) and using relationships from Croney *et al.* (1997):

$$E_{dyn} = \frac{\log R_f + 0.773}{0.0301} \qquad (7.1)$$

$$R_f = 0.11 R_c \qquad (7.2)$$

Using the indirect tensile strength and static stiffness in accordance with BS EN13286-42 (BSI, 2003b).

$$E_{dyn} = 8.4 + 0.93 E_s \qquad (7.3)$$

$$R_f = 1.33 R_{it} \qquad (7.4)$$

Where E_{dyn} is dynamic stiffness in GPa, E_s is the static stiffness in GPa, R_f is the flexural strength in MPa, R_c is the compressive strength in MPa, R_{it} is the indirect tensile strength in MPa.

These hydraulic classification zones shown in Figure 7.2 are used to fix the thickness of the structural course in Figures 7.3 to 7.6. For road categories 3 and 4, permitted alternatives to these designs have been defined.

Figure 7.4 illustrates the use of the chart for a 20 msa design with a QH or SH type material in zone H3; this gives a 150 mm asphalt layer on a 300 mm thick layer of the QH or SH type material.

The asphalt thickness shown in Figures 7.3 to 7.6 has been defined so that there is a minimal risk of reflection cracking. It is possible to reduce the thickness of asphalt cover with a corresponding increase in the thickness of hydraulically bound layer without compromising the bearing capacity of the structure; however, such action could increase the risk of reflection cracking occurring in the asphalt layer.

Many slow-curing materials are thought to give a low risk of reflection cracking due to the diffuse nature in which naturally forming shrinkage cracks occur; for such materials, substituting asphalt for hydraulically bound material will result in a minor change in the risk of reflection cracking. Materials that cure quickly are most likely to produce wide, naturally formed shrinkage cracks; for such materials, the substitution of asphalt for hydraulically bound material should be avoided.

7.2.5 Pavements with bitumen bound cold recycled structural course

The design method for pavements comprising bitumen bound structural courses has two stages: material classification and thickness design. Bitumen bound materials are classified into one of three zones labelled B1, B2 and B3. Once classified, the designer selects the appropriate thickness design chart for the foundation class; the thickness for the design traffic can be determined for the curve associated with the material zone.

Bituminous bound recycled structural courses cover a wide range of material compositions. They may contain cement in the case of QVE type materials or other binders. In a study by Nunn and Thom (2002), *ex situ* foamix material was found to be not unduly susceptible to fatigue and could therefore be treated in a similar fashion to

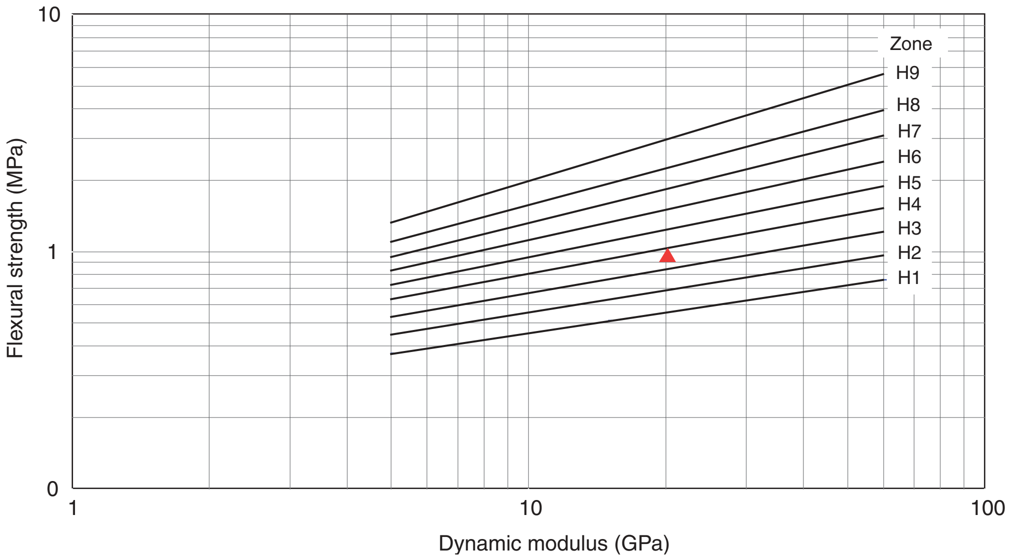

Figure 7.2 Performance classifications for hydraulically bound recycled materials

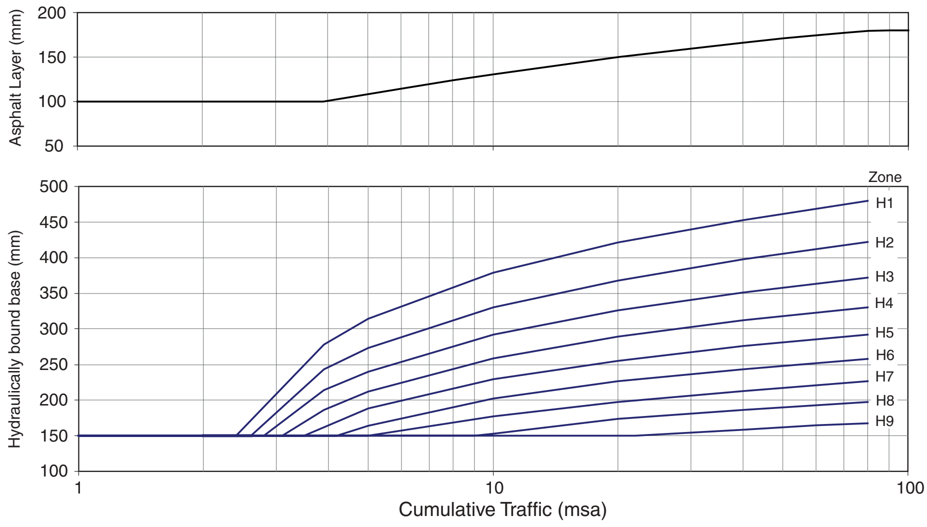

Figure 7.3 Design thicknesses for road Type 2 and superior roads with a Class 1 foundation

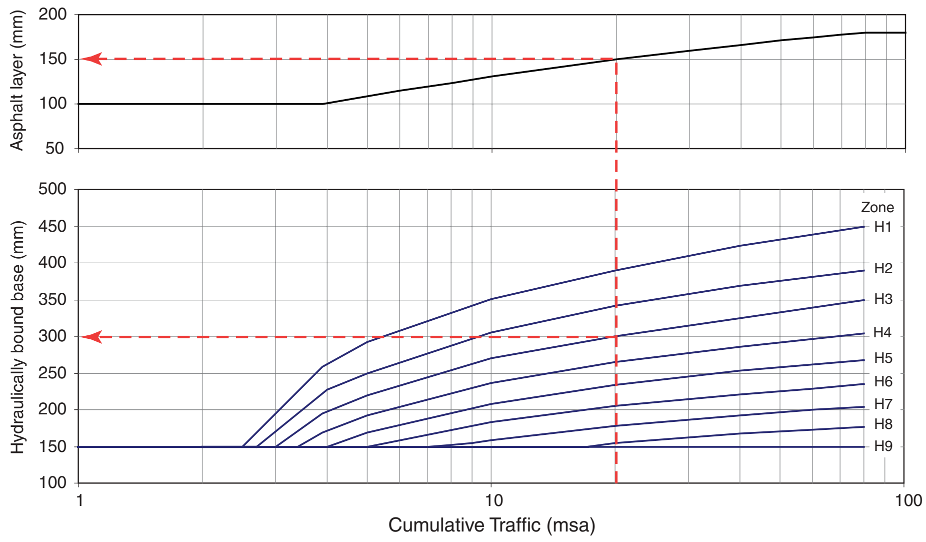

Figure 7.4 Design thicknesses for road Type 2 and superior roads with a Class 2 foundation

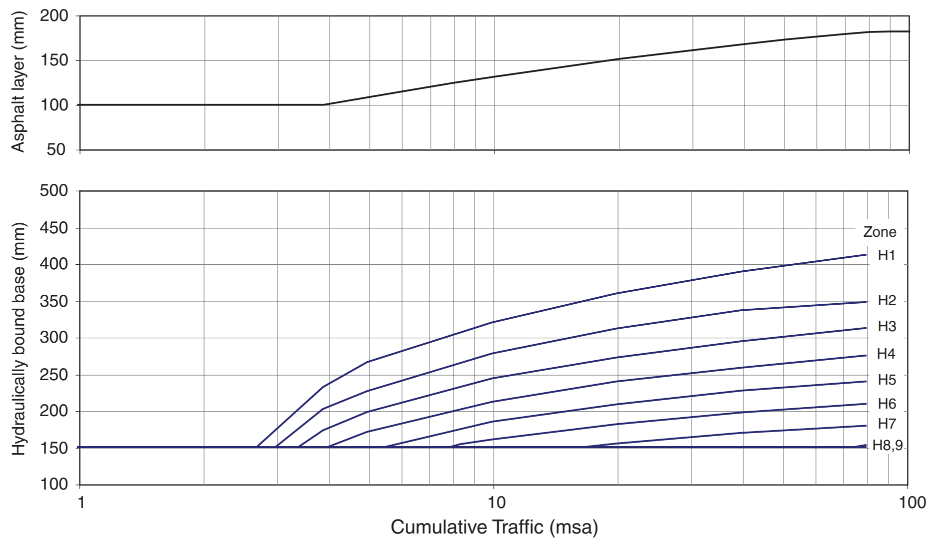

Figure 7.5 Design thicknesses for road Type 2 and superior roads with a Class 3 foundation

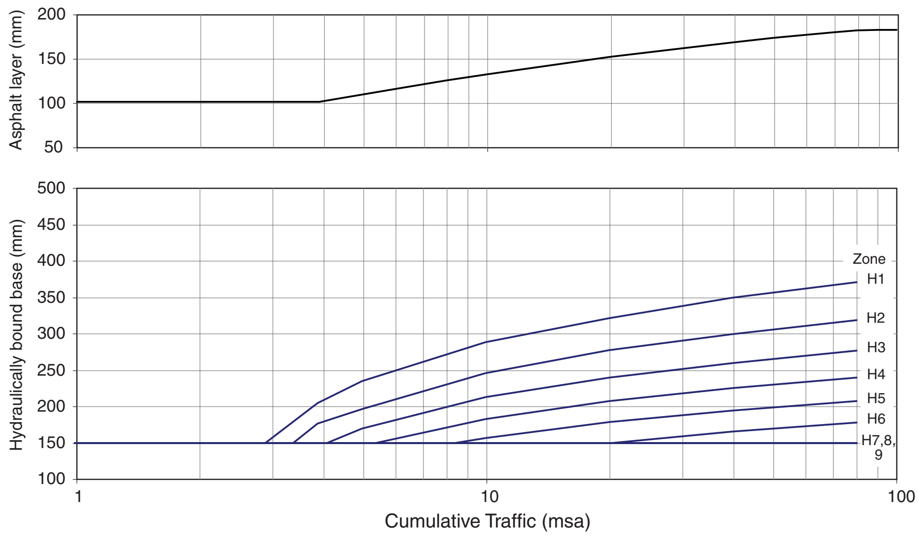

Figure 7.6 Design thicknesses for road Type 2 and superior roads with a Class 4 foundation

conventional hot mixed bituminous material. In the absence of any evidence to suggest otherwise, the entire family of bituminous bound structural courses is treated in a similar fashion to conventional bituminous materials.

Table 7.2 specifies a minimum long-term stiffness for each class which should be demonstrated in the specification using the laboratory conditioning regimes defined in Table 6.1. The pavement structural courses can be designed according to Figures 7.7 to 7.10 depending on the material and foundation classification. It is unlikely that *in situ* stabilised cold recycled materials will satisfy the premium category in Table 7.2, Zone B3, due to inherent variations in the production process. For road categories Type 2 and below, the bitumen bound structural course is supported by an adequate foundation and is generally surfaced with 100 mm of hot mixed bituminous material comprising binder course and surfacing. For road categories Type 3 and 4, permitted alternatives to these designs have been defined.

Table 7.2 Bitumen bound cold recycled material classification

Bitumen bound cold recycled zone	*Minimum long-term stiffness*
B1	1900 MPa
B2	2500 MPa
B3	3100 MPa

Figures 7.7 to 7.10 show the total thickness including up to 100 mm of asphalt surfacing. The minimum thickness of surfacing is dependant on the traffic category as given in Table 7.3.

Permitted adjustments for Type 1 and 2 roads using bitumen bound cold recycled materials

For Type 1 and 2 roads, the thickness of the surfacing placed on top of the bitumen bound cold recycled material

Table 7.3 Requirements for surfacing thickness

Road type category	*Minimum thickness of surfacing (mm)*
0	100
1	70
2	50

described in Figures 7.7 to 7.10 can be reduced to a minimum of 50 mm with a compensating increase in the thickness of the cold recycled structural course. For Class B1 and B2 materials the compensation of the structural course can be determined using the equivalence relationship given in equation 7.5.

$$\Delta H_{RBase} = -1.3 \times \Delta H_{Surfacing} \qquad (7.5)$$

where $\Delta H_{Surfacing}$ = change in the thickness of bituminous surfacing.

ΔH_{RBase} = change in the thickness of bitumen bound cold recycled base.

For example, a bitumen bound pavement design with a 100 mm surfacing could be reduced to a 50 mm surfacing with a corresponding increase of 65 mm in the thickness of the cold recycled layer. The nominal thickness of bituminous surfacing provides a degree of deformation resistance under trafficking in early life. For slow curing materials that are initially weak, reducing the thickness of bituminous cover to the cold recycled material may increase the risk of problems in early life due to traffic.

7.2.6 Alternative designs for Type 2, 3 and 4 roads up to 5 msa traffic

The standard pavement designs shown in Figures 7.3 to 7.10 have a minimum recycled structural course layer thickness of 150 mm and a 100 mm thick bituminous surfacing. For low volume roads, these minimum thickness requirements may give excess structural capacity and overly low risk of failure. Therefore, an alternative design

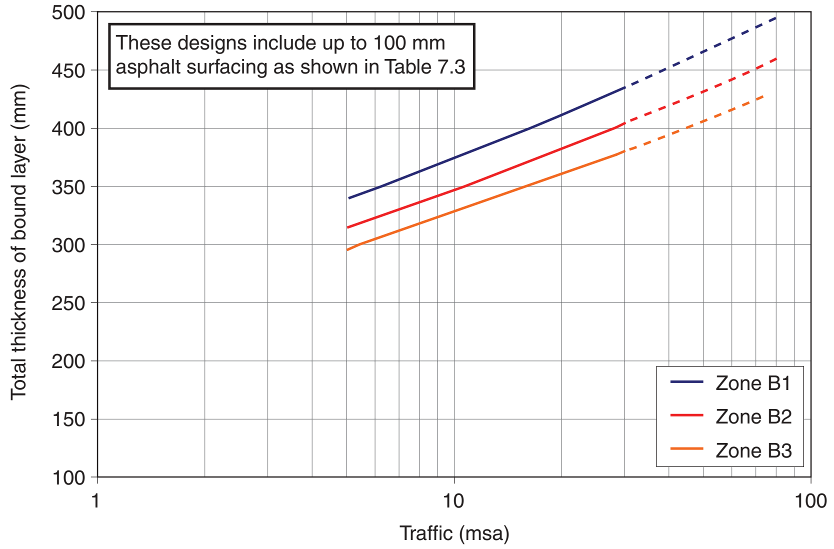

Figure 7.7 Design curves for bitumen bound cold recycled material (Foundation Class 1)

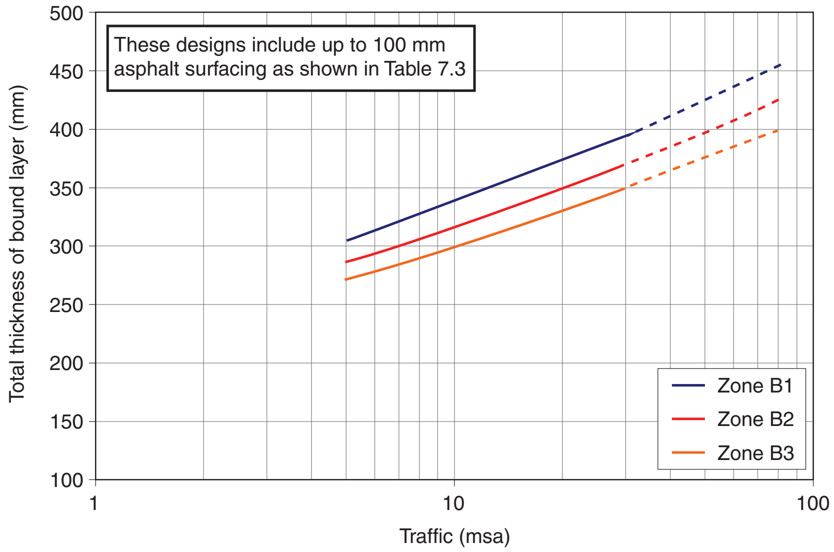

Figure 7.8 Design curves for bitumen bound cold recycled material (Foundation Class 2)

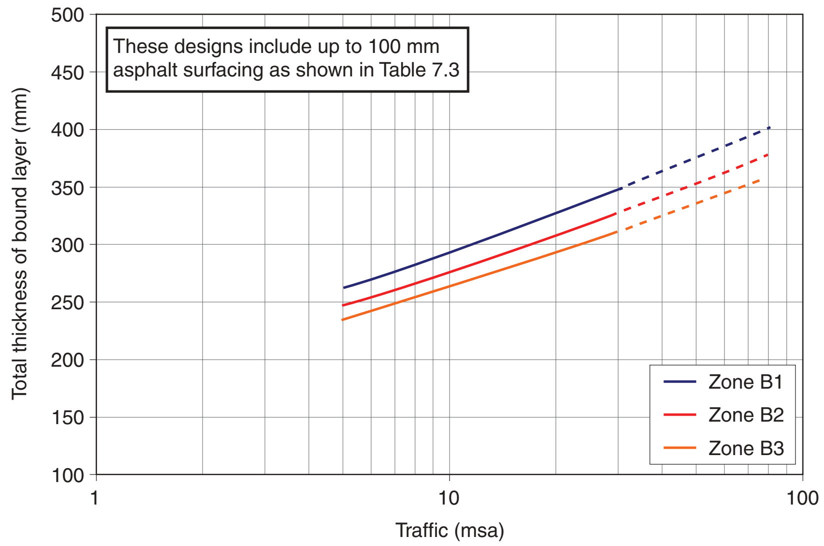

Figure 7.9 Design curves for bitumen bound cold recycled material (Foundation Class 3)

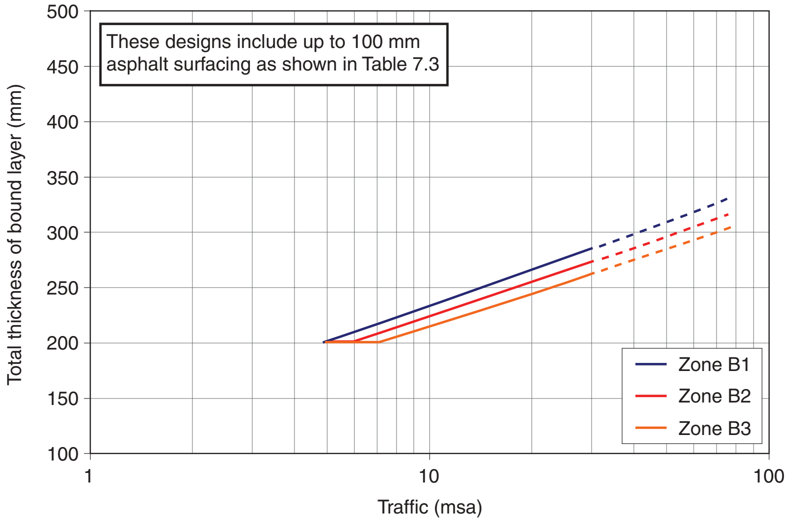

Figure 7.10 Design curves for bitumen bound cold recycled material (Foundation Class 4)

approach for these roads is provided for roads with traffic less than 5 msa that will take advantage of a reduced requirement for structural capacity and improve the economic viability of cold recycling.

Potter (1996) proposed designs for pavements containing cold *in situ* recycled materials for Type 2, 3 and 4 roads. These low volume roads can be designed from the formation level with the structural contribution of the sub-base layer incorporated into an increased thickness of recycled structural course. There is no evidence to suggest that these designs have not performed well and, therefore, they have been maintained for all cold recycled materials covered within this guide. These designs cover a range of surfacing options from surface dressing up to a cover of 100 mm of asphalt surfacing.

Table 7.4 shows the thickness design of cold recycled structural courses (incorporating the foundation platform). Alternative surfacing options allow for a reduction in the thickness of the cold recycled layer for a compensating increase in surfacing thickness.

These designs incorporating structural and foundation layers were proposed assuming minimum performance

Table 7.4 Thickness of pavements using cold recycled materials as the combined structural course and foundation platform in roads up to 5 msa

	Thickness of cold recycled material (mm)								
Binder type	*Hydraulically bound material*								
	Type 2 road			*Type 3 road*			*Type 4 road*		
Surfacing thickness (mm)	*Surface dressing*	*40*	*100*	*Surface dressing*	*40*	*100*	*Surface dressing*	*40*	*100*
Subgrade CBR (%)									
<2	n/r	n/r	n/r	n/r	n/r	n/r	n/r	n/r	n/r
2-4	n/r	300	240	280	240	180	240	200	150
5-7	n/r	280	220	260	220	160	220	180	150
8-14	n/r	270	200	240	200	150	200	160	150
>15	n/r	250	200	220	180	150	190	150	150
Binder type	*Bitumen bound material*								
	Type 2 road			*Type 3 road*			*Type 4 road*		
Surfacing thickness (mm)	*Surface dressing*	*40*	*100*	*Surface dressing*	*40*	*100*	*Surface dressing*	*40*	*100*
Subgrade CBR (%)									
<2	n/r	n/r	n/r	n/r	n/r	n/r	n/r	n/r	n/r
2-4	n/r	n/r	n/r	n/r	310(n/r)	250	320(n/r)	280	195
5-7	n/r	n/r	n/r	330	290	230	300	260	185
8-14	n/r	n/r	300	315	275	215	285	245	160
>15	n/r	n/r	270	285	245	185	255	215	150

n/r: not recommended

requirements for strength and stiffness; the equivalent minimum requirements are:

- Hydraulically bound material should be Type H5 or superior (Figure 7.2).
- Bitumen bound material should be Type B1 or superior (Table 7.2).

For hydraulically bound materials classed as H1, H2, H3 or H4 the following adjustments in Table 7.5 can be applied to the thickness of the materials in Table 7.4. For example, for a Type 3 road with subgrade CBR of between 5 and 7%, a hydraulically bound material of class H4 with a layer thickness of 250 mm (220 × 1.13) with a 40 mm surfacing can be used. Some combinations of material quality and subgrade strength will produce thick layers; for these combinations, the standard approach given in Section 7.2.2 can be used.

Table 7.5 Adjustments for hydraulically bound materials H1 to H4

Material	*Thickness adjustment*
H1	1.66
H2	1.45
H3	1.28
H4	1.13
H5 or superior	1.0

All permitted alternatives are subject to a 150 mm minimum layer thickness of cold recycled material; a maximum thickness of 300 mm is also recommended.

Designs are not provided for weak subgrade conditions that may give inadequate resistance to damage by construction traffic or may not provide the necessary support for adequate compaction of the cold recycled layer. Methods for dealing with weak subgrade conditions can be found in the *Design Manual for Roads and Bridges* (DMRB 7.2.2).

7.3 Treatment design for partial depth cold recycling

7.3.1 Design methodology

Section 7.2 covered pavement designs comprising cold *in situ* recycled materials for the pavement layers from the foundation upwards. Such designs were applicable to new construction and full-depth reconstruction. Some maintenance treatments for fully-flexible roads do not require the complete replacement of the pavement layers particularly for thick bituminous roads and, therefore, an alternative treatment design procedure is proposed that could still utilise significant amounts of cold recycled materials.

A conservative approach would be to design the pavement using the approach described in Section 7.2. The approach would ensure that the total thickness of the pavement is maintained as shown in Figures 7.7 to 7.10 and any bituminous material remaining in good condition would then add assurance. Such an approach would be applicable when the remaining mature bituminous layer forms the minority of the rehabilitated pavement.

When the thickness of remaining mature bituminous material is significant, the method described in Section 7.2 is likely to produce overly thick pavement layers. The following methodology attempts to account for the structural value of the existing 'good quality' bituminous material together with the cold recycled layers.

The design methodology described is based upon long-term design stiffness for *in situ* and *ex situ* cold recycled materials. The method of equivalent thickness (Ullidtz, 1987) can be used to compare the adequacy of a rehabilitated layer using cold recycled material compared with that of a conventional hot mix material, such as a dense bitumen macadam, using a structural equivalence number (SEN). The structural equivalence number is calculated using Equation 7.6 using the parameters given in Table 7.6.

$$SEN = \sum_i h_i E_i^{1/3} \tag{7.6}$$

Where i = Layer identifier.
h = Thickness of the layer (m).
E = Design stiffness of the layer (MPa).

Table 7.6 Long-term design stiffness for bitumen bound material

Material description	*Design stiffness (MPa)*
Surface course	2000
Cold recycled material Class B1	1900
Cold recycled material Class B2	2500
Cold recycled material Class B3	3100
New hot-mixed asphalt	3100
Existing asphalt base material*	3100

* *The design stiffness may be augmented by values obtained from laboratory testing.*

Using standard designs for full depth constructions using conventional hot mix material, the criterion for the minimum SEN for designing a partial depth treatment comprising cold recycled materials is given in Table 7.7. A minimum thickness of asphalt surfacing is required to concur with the requirements for full depth recycling options shown in Figures 7.7 to 7.10. For cases where a CBM base layer exists, alternative SEN are given; for these cases, the structural contribution of the CBM layer is not accounted for in the SEN calculations.

The minimum requirements for the SEN shown in Table 7.7 have been deduced from the curves given by Powell *et al.* (1984); these curves were constructed using an 85% probability of survival. Powell *et al.* (1984)

Table 7.7 Minimum required SEN for partial depth recycling

Road type category	*Minimum SEN*	*Minimum SEN (CBM base)*	*Minimum surfacing thickness (mm)*
0	5.7	2.6	100
1	4.8	2.4	70
2	4.0	1.9	50
3	3.2	1.2	Surface dressing
4	2.5	0.2	Surface dressing

acknowledge that for less important roads, a lower probability appropriate to the performance of the road should be used. Table 7.8 gives factors that can be applied to the SEN for different probabilities of survival. For a 70% probability of survival, the minimum SEN requirement for a Road Type Category 2 will be 4.0 × 0.9 = 3.6.

Table 7.8 Factors to be applied to SEN requirements

Probability of survival	*Factor*
85%	1.0
70%	0.9
60%	0.8

7.3.2 Examples of treatment design using partial depth cold recycling

The following examples of partial depth recycling are presented. Example 1 is a pavement that is maintained to remedy deterioration and to provide the same structural capacity at the existing pavement. Example 2 is a pavement whose structural capacity is to be upgraded by partial depth recycling.

Example 1:

An existing asphalt pavement of 270 mm comprising a DBM type material and hot rolled asphalt surfacing is to be maintained by partial depth recycling to carry a design traffic of 5 msa. The existing pavement contained some deterioration in the asphalt layers and the lower most 100 mm of the existing pavement is in a good condition.

A derivation of the necessary calculation using Class B2 materials is as follows:

Layer	*Thickness (m)*	*Design stiffness (MPa)*	$h_i E_i^{1/3}$
Surface course	0.050	2000	0.6
Cold recycled material Class B2	0.140	2500	2.1
Existing asphalt base material	0.1	3100	1.5
SEN = 0.44 + 2.1 + 1.46 = 4.0			

Figure 7.11 shows three partial depth recycling solutions using each of the bitumen bound cold recycled material classes: B1, B2 and B3. For the solution using Class B1 material, the uppermost 170 mm of the existing pavement could be *in situ* stabilised and a thin surfacing is laid on top of the recycled material; alternatively the existing pavement material could be removed and *ex situ* cold recycled materials used. Using class B2 and B3 materials will result in reductions in the overall pavement thickness.

Example 2:

In this example the existing asphalt pavement is 320 mm thick and the pavement is to be upgraded by partial depth cold recycled material to carry design traffic of 30 msa. The deterioration in the existing structure requires that only the lower most 150 mm of the existing pavement structure be retained after maintenance.

Figure 7.12 shows three partial depth recycling solutions using each of the bitumen bound cold recycled material classes: B1, B2 and B3. For the solution using Class B1 material, the upper most 170 mm of the existing pavement could be *in situ* stabilised and a bituminous surfacing of thickness 100 mm (50 mm surface course and 50 mm asphalt binder course) is laid on top of the recycled material; alternatively, the existing pavement material could be removed and *ex situ* cold recycled materials used. Using class B2 and B3 materials will result in reductions in the overall pavement thickness.

8 Specification of cold recycled materials

8.1 General

Specifications for the production of cold recycled materials has been covered in the *Specification for Highway Works* (MCHW1) Series 900 and 1000 for a number of years. These specifications have covered the production of cement bound and foamed bitumen bound recycled material using an *in situ* stabilisation process. In recent years, *ex situ* or plant mixed cold recycled material

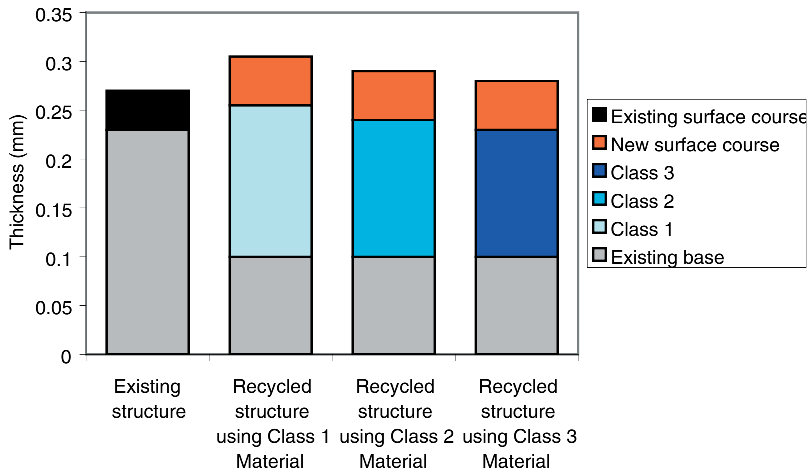

Figure 7.11 Example of an existing structure maintained by partial depth recycling

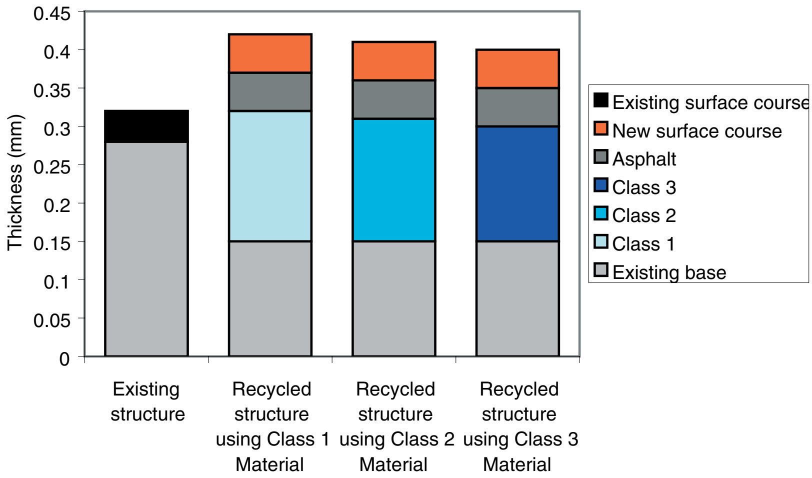

Figure 7.12 Example of an existing structure upgraded by partial depth recycling

technology has evolved and there is increasing demand for a wider range of materials to be covered by a publicly available material specification.

The over-arching concept of this specification is to have a specification document that covers the whole range of cold recycled materials. This document will improve the procurement of these materials, especially when such a diverse range of cold recycled materials are available. The components of cold recycled materials covered by this specification include:

- Bitumen emulsion.
- Foamed bitumen.
- Cement.
- Granulated blast furnace slag (GBS).
- Ground granulated blast furnace slag (GGBS).
- Lime.
- Pulverised fly ash (PFA).
- Unweathered 0/4 mm basic oxygen slag (BOS).

The specification has been designed to focus on the quality control of the material and to ensure that proposals for end-performance made at the mix design stage are achieved in the permanent works.

Two specifications have been developed: one for the *ex situ* process and one for the *in situ* process. The division of the specifications has been done for means of clarity only. The structure and performance requirements for the materials in each specification are identical. The procurement of cold recycled materials should not be biased towards either specification instead the choice of process should primarily be an economic one.

The specifications include end-product performance tests of the material where rationally possible. The notes for guidance gives more advice on end-product tests and other best-practice approaches to quality control.

8.2 Quality plan

8.2.1 General

The quality plan forms the core of the specification for cold recycled materials. It is a document that is prepared by the contractor and agreed with the client and covers the entire life cycle for the production of the cold recycled materials from the mix design stage through to the end-product testing stage.

The specification does not prescribe the entire content of the quality plan although there are some mandatory minimum requirements. Instead, the contractor is provided with significant freedom to produce a material quality plan that satisfies the client whilst ensuring economic efficiency.

8.2.2 Mix design

The aim of the mix design process is to provide assurance that a cold recycled mixture will have the appropriate properties one year after construction. The selection of one year properties is to encompass slow curing materials as prescribed by the pavement design method described in this guide.

In the absence of an appropriate test, durability is handled in the mix design stage of the production life-cycle by the specification of minimum binder contents.

8.2.3 Method statement

The method statement shall comprehensively describe the process of producing and laying the material. It shall include:

The sources of recycled components

The method statement shall include as full a description as possible of the composition of the components to be used in the cold recycled material. It shall also cover the size of the available stock of the components and an indication of the security of the stock, in other words how reliable is the source of material. For *in situ* stabilisation, the method of pulverisation to extract the aggregate to the required grading shall be stated.

Production

The method of production of the cold recycled materials shall be described in detail. The storage of the component materials may be important to maintain the quality of the product material. The plant used for mixing the components shall be detailed including the method of addition of the components and the methods for controlling the addition of the components.

Transportation to site for ex situ process

The location of the mixing plant shall be declared. A preferred route and an alternative route for the transportation of material to the site shall be declared with a statement on the time of the day when transportation will occur and the anticipated duration between the mixing process and compaction. A risk assessment shall be performed for the travelling time to site on the preferred and the alternative route including likely delays due to congestion or accidents.

Laying and compaction

The plant used for placement and compaction of the cold recycled mixture shall be described in the method statement. Although some compaction controls are indeed specified, any additional quality control measures that will be undertaken at the site should be highlighted.

Although the process control for compaction of thick layers is the same as for thinner layers, requiring the same level of compaction for the full depth, the compactive effort needs to be considerably greater, using either heavy vibratory compaction or possibly, a tamping roller. In some situations, the use of a heavy pneumatic tyred roller (PTR) may also be considered.

The procedure for laying the material should also cover early life trafficking issues. For all types of material, curing will occur that will increase the strength and stiffness of the material with time. In early life there maybe a risk of over-stressing the material and forming cracks, and unduly damaging the recycled material. Damage to the material through early life trafficking may be mitigated by ensuring that adequate compaction has been achieved (as indicated by the density of the material). Regular visual monitoring of the condition of the recycled material is advised to detect any degradation at an early stage and to enable the progression of damage to be halted if visually occurring. For certain slow-curing materials, damage due to early-life trafficking may be mitigated by the long-term curing behaviour of the material. In justifying the performance under heavy traffic in early life, previous case studies can be utilised to illustrate the risks to the material.

8.2.4 Process control and end-product criteria

The specified process control procedures have been designed to be generally consistent for all types of cold recycled material covered under the specification although there are permitted variances for certain tests. Overall, the specified process controls cover:

- Moisture content.
- Batching checks.
- Degree of compaction.
- Structural performance.
- Thickness.

The moisture content is monitored so that the material immediately prior to compaction is within 2% of the optimum moisture content for compaction. The proportions of the binding fractions are also monitored by the batching checks; more stringent compliance targets have been placed on bituminous fractions than other hydraulic fractions. The degree of compaction is monitored using relative *in situ* density as measured using a Nuclear Density Gauge operated in direct transmission mode with an average limit of 95% of refusal density being specified.

The *in situ* structural performance of the material is not monitored in the specification. It is often the case that the early life performance of cold recycled materials is ruled by factors outside of the control of the contractor; in particular, the climatic conditions at the site after construction. Longer term performance is less likely to be affected by climatic conditions due to the fact that the material will experience a full year's variation in environment. It is, therefore, unreasonable to set minimum requirements on structural performance in early life, but long term compliance is not a practical alternative. The specification focuses on the adherence to stated performance characteristics in the quality plan (QP), as defined in the mix design process. Material sampled from the mat prior to compaction is then subjected to an identical sample preparation, laboratory curing and testing regime as was declared for the job site mix in the QP; the values of stiffness and strength obtained from the process need to satisfy the same criteria as defined in the mix design stage. Where superior performance has been used as a basis for adjusting the pavement design, the results of the process control tests shall also be compared to the design values.

Thickness is an important determinant of durability of the structure. Therefore, the thickness of the recycled layer is monitored so that its performance is not compromised by variation of thickness. This requirement does not negate the need for global pavement level tolerances. Efficient operation of this process control requires consideration of the variability of the level immediately below the recycled layer, the consistency of the recycled material and the effective control of compaction operations.

All the specified process control criteria are minimum permissible values. There is an opportunity for the contractor to demonstrate adherence to superior process control procedures using the appropriate sections of the quality plan.

9 Acknowledgements

The work described in this report was carried out in the Infrastructure Division of TRL Limited (Director: Mike Head). The authors are grateful to Dr Cliff Nicholls who carried out the quality review and auditing of this report.

The authors are grateful for the assistance and contribution of the project steering group whose members include:

Dave Adams	Atkins.
Steve Biczysko	Atkins (Chairman).
Robert Dudgeon	Highways Agency.
Brian Hicks	Colas.
Jim Hill	Total Bitumen (Representing RBA).
John Kennedy	Consultant (representing UKQAA).
Terry Lomas	Hants CC (representing CSS).
Colin Loveday	Tarmac.
Forbes Macgregor	Scottish Executive Development Department.

Particular thanks are due to Tarmac for constructing a pilot scale trial specifically for the project and undertaking extensive laboratory testing under various curing regimes (Nizar Ghazireh is acknowledged for his contribution and assistance); and to Colas for the modification to one of their schemes to include additional material families specifically for the project.

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Appendix A: Specification of cold recycled material with notes for guidance

A1 *Ex situ* cold recycled bound material – specification

A1.1 General

Ex situ cold recycled bound material (CRBM) comprises base and binder courses produced in a fixed or mobile mixing plant from graded aggregate processed from arisings from the excavation of roads and similar sources, blended if necessary with other aggregate and bound with hydraulic or bituminous binders, separately or in combination. This clause covers four generic material families: quick hydraulic (QH), slow hydraulic (SH), quick visco-elastic (QVE) and slow visco-elastic (SVE). The primary binder of these families of materials shall be as follows:

QH: Portland cement as the main hydraulic component and excluding bituminous binders.

SH: Hydraulic binders (e.g. PFA/lime and GBS/lime) excluding bituminous binders and portland cement.

QVE: Bituminous binder as the main component but also including portland cement.

SVE: Bituminous binder as main component but excluding portland cement.

Ex situ CRBM shall be designed to achieve the specified level of the appropriate end performance property.

A1.2 Quality plan

Ex situ CRBM shall be produced to a quality plan (QP) with the following elements:

- Sourcing of aggregate components.
- Processing of aggregate components.
- Declaration of constituents.
- Declaration of Job Standard Mixture.
- Process control of mixing.
- Inspection and test schedules.
- Demonstration of performance properties.

A1.3 Sourcing of aggregate

The quality plan shall contain details of all aggregates to be used in the CRBM. Aggregate may include:

- Asphalt, concrete or granular material planed or excavated from a road or other paved area.
- Primary, secondary or recycled aggregate from other sources.
- Fillers from primary or secondary sources (e.g. PFA).

The processed aggregate, including added filler, shall not contain deleterious material that adversely affects the performance of the mixture.

A1.4 Processing of aggregate

The quality plan shall describe how, in particular, highway arisings are to be processed, crushed, screened and stocked to enable consistent production of the CRBM in line with the job standard mixture.

A1.5 Binders and other constituents

- Bitumen emulsion shall conform with BS 434-1 and be used in accordance with BS 434-2.
- Cement shall conform to EN 197-1.
- Bitumen used for foaming shall conform with EN12591 and shall be grade 160/220 or harder.
- Granulated blast furnace slag (GBS) shall comply with EN 14227-2.
- Ground granulated blast furnace slag (GGBS) shall comply with EN 14227-2.
- Lime shall comply with EN 14227-11.
- Fly ash (PFA) used as either filler or pozzolan, shall comply with EN 14227-4.
- Un-weathered 0/4 mm basic oxygen slag (BOS) used in SH material as activator/accelerator to the GBS shall comply with BS 6463 Part 102.
- Other constituents, including setting and hardening agents, may be used to enhance the performance of the mixture, subject to the approval of the overseeing organisation.
- Water shall not contain material that adversely affects the performance of the mixture.

A1.6 Job standard mixture

The composition of the job standard mixture shall be declared as follows:

- Source, origin and proportion of all aggregate constituents.
- Combined target grading, including mineral binders and tolerances.
- Source, origin and proportion of all binders.
- Target moisture content.

The grading of the job standard mixture (the aggregate together with the other constituents including binders) shall comply with one of the zones in Table A1.1.

Table A1.1 Particle size distribution of mixture for cold recycling

	Percentage by mass passing		
Sieve (mm)	*Zone A*	*Zone B*	*Zone C*
40	100	100	100
31,5	100	100	86-100
20	100	100	75-100
14	85-100	85-100	52-100
10	68-100	68-100	44-100
4	38-74	38-94	26-74
2	26-58	26-84	18-58
0,5	13-38	13-64	8-38
0,250	9-28	9-51	5-28
0,063	5-21	5-38	3-21

Use of Zone B or C graded material shall be permitted only when the results of a full mixture design showing compliance with the required 28 day performance properties are available or when evidence can be provided of satisfactory achievement of the performance requirements on an earlier contract with a similar composition.

The binder addition shall comply with Table A1.2.

A1.7 Mixture design validation

When a mixture design validation is required, it shall be carried out on aggregates and binders representative of those to be used in the works. The validation shall be carried out on CRBM mixed either in the laboratory or on a pilot basis using full scale plant.

The target mixture shall comply with sub clauses A1.5 and A1.6.

A preliminary exercise shall be undertaken to establish a target grading and suitable moisture content.

Representative samples of the mixture shall be taken; from which 150 mm diameter cylindrical specimens shall be produced in accordance with sub clause A1.14. The height of these specimens shall be appropriate to the mechanical performance test declared in the quality plan. The time between mixing and specimen production shall be kept to a minimum but within the setting times given in Table A1.4.

The density of each specimen shall be measured and, using the respective moisture content values, the dry density values shall be determined.

The cylindrical specimens shall be conditioned and tested in accordance with sub clauses A1.15 and A1.16.

The performance properties of the conditioned specimens shall be declared. The results shall be considered as indicative only; the end product compliance criteria, as stated in sub-clause A1.16, shall apply only to the specimens prepared during the execution of the works.

A1.8 Trafficking trial

A trafficking trial shall be undertaken when required in the QP to demonstrate that the CRBM is not prone to excessive rutting in its early life.

A trial area shall be laid using the materials and plant to be used for the main works and on a foundation typical of that in the main works. The trial area shall be left to cure for 24 hours, or other declared time, and shall then be subjected to controlled trafficking. The trafficking shall be performed by a heavy goods vehicle with an axle configuration and loading typical of that to be encountered in the construction phase. The number of passes shall equate to the total expected amount of traffic to be carried during construction, with a default value equivalent to 100 standard axles.

The measured rutting in the trafficking trial shall be less than 10 mm or that stated in the job specific appendix.

A1.9 Process control

Production of the *ex situ* CRBM shall be subject to process control detailed in the quality plan and meeting the following requirements:

- There shall be a description of the plant and the production process, preferably including a flow diagram, detailing how material is to be produced in accordance with this specification.
- Calibration schedules for all parts of the plant involved in determining mix consistency shall be provided. These shall be accompanied by calibration records.
- Details of transportation shall be provided. These shall include the location of the mixing plant and the expected average time between mixing and laying. The contractor shall record the duration between mixing and the completion of compaction at the site during the execution of the works.
- The measures to maintain quality of construction at joints shall be described; in addition, measures to deal with hard edges and obstructions shall be included.
- Measures to avoid problems caused by extreme weather. In particular, production shall not proceed if the feedstock is frozen or excessively wet.

Table A1.2 Minimum binder contents for *ex situ* construction by family and binder type

Family	*OPC*	*Lime*	*BOS*	*PFA*	*GBS*	*GGBS*	*Bitumen*[1]
QH	3%	–	–	–	–	–	–
	2%	–	–	4%	–	–	–
	2%	–	–	–	4%	–	–
	2%	–	–	–	–	2%	–
SH	–	2%	–	8%	–	–	–
	–	2%	–	–	8%	–	–
	–	2%	–	–	–	4%	–
	–	1.5%	–	–	10%	–	–
	–	–	2.5%	–	10%	–	–
QVE	1%	–	–	[2]	–	–	3%
SVE	–	1.5%[3]	–	[2]	–	–	3%

[1] Foamed or emulsion (residual).

[2] PFA may be added as filler.

[3] Lime may be added for 'breaking' and adhesion purposes, and, if PFA included as filler, will contribute to strength.

A1.10 Inspection and test

There shall be a schedule of inspection and test frequencies to be made during production of CRBM. This shall comply with the minimum frequencies in Table A1.3.

A1.11 Laying

A written procedure for the laying of the *ex situ* CRBM shall be provided.

The plant used for placing *ex situ* processed material shall be capable of laying the material without significant segregation, evenly and to the required thickness across at least one lane width.

A method for the making of longitudinal and transverse joints, appropriate to the type of CRBM being laid shall be provided.

A1.12 Compaction

The compaction of each layer shall be carried out to a defined rolling pattern until both the required *in situ* density is achieved and the recycled layer provides a stable and dense tight surface. The stability of the layer after compaction shall be deemed adequate if the finished surface does not shove, rut or exhibit transverse cracking under the load of subsequent traffic. Open edges shall be protected from traffic.

After trimming and final compaction of the recycled layer, the *in situ* bulk density shall be measured using a nuclear density gauge in direct transmission mode, to a depth within 25 mm of the layer thickness. The meter readings shall be verified periodically in accordance with Clause 1041 of the Specification for Highway Works, with the gauge calibrated in accordance with BS 1377: Part 9.

The *in situ* bulk density values obtained shall be compared with the refusal density value of the job standard mixture or of the refusal density of a specimen representative of the day's production. The average *in situ* bulk density of each set of five values shall be at least 95% of the refusal density, with no individual *in situ* density value being less than 93% of the respective refusal density.

A1.13 Sealing

Unless surfaced immediately or kept moist by light water spraying, the surface shall be sealed using a sprayed membrane of Class K1 - 40 bitumen emulsion complying with Clause 920 in the Specification for Highway Works when required in the QP. The bitumen emulsion shall be sprayed at a rate not less than 0.5 l/m^2 to achieve a uniform and continuous seal to the surface of the layer. Where the surface is opened to traffic, the bitumen emulsion shall be blinded with fine aggregate or sand applied at a rate of 5.5 to 7.0 kg/m^2.

A1.14 End product testing

The end product testing of the *ex situ* CRBM shall be assessed on the basis of representative specimens made up in accordance with the schedule in the quality plan.

Representative samples of the *ex situ* CRBM shall be taken either at the mixing plant or from site prior to compaction. 150 mm diameter cylindrical test specimens shall be manufactured in sets of six by compacting to refusal in accordance with BS 598 Part 104. The time period after mixing during which compaction must be completed shall be in accordance with Table A1.4.

Table A1.4 Setting times of cold recycled families

Family	*Setting time under normal temperature conditions*
QH	2 hours
SH	24 hours*
QVE	2 hours
SVE	24 hours*

* *Can be longer depending on material composition.*

A1.15 Conditioning and testing of samples

Immediately after compaction, the cylindrical specimens (either in their moulds or after extracting from their moulds if applicable) shall be double wrapped in cling-film plastic using two separate sheets; each of which shall be sufficient to cover the entire circumference of the cylinder and the two ends of the specimen. Once wrapped in cling-film the sample shall be placed in a sealed plastic bag. Care shall be taken when handling the specimens not to damage the plastic bag or the underlying cling-film layer. The specimens shall be stored in air or water at a temperature within 2 °C of the nominal conditioning temperature.

QH and QVE[1] specimens shall be conditioned for a period of 28 days at a temperature of (20$\pm$2) °C.

SH, QVE[2], SVE[2] specimens shall be conditioned for a period of 28 days at a temperature of (40$\pm$2) °C.

SVE[1] specimens shall be conditioned according to a procedure declared in the quality plan.

[1] *Not containing a pozzolanic binder.*
[2] *Containing a pozzolanic binder.*

Table A1.3 Minimum frequencies for inspection and test

Item	*Inspection*	*Test*
Aggregate stockpiles	Daily	Grading and moisture content before production and weekly
Binders	On receipt	Supplier data
Combined grading of mixture	Continual	Daily
Moisture content of mixture	Continual	Daily

A1.16 End product criteria

The minimum specification compliance criteria for the process control tests shall be as described in Table A1.5.

In the event of test specimens failing to achieve the required mechanical performance, compliance shall be determined by the testing of cores extracted by dry coring after one year.

Table A1.5 End product criteria

Material property or characteristic	*Individual results*	*Mean from test set of six measurements*
Particle size distribution	Zone	–
Moisture content	±2%	–
Relative *in situ* density	93% minimum	95% minimum
Layer thickness	±25 mm of specified	±15 mm of specified
Mechanical performance	n/a	As stated in the QP

A2 *Ex situ* cold recycled material – notes for guidance

A2.1

Examples of the types of materials that satisfy the material classifications QH, SH, QVE and SVE are provided in Table A2.1. It is realised that the combinations listed for each family are not exhaustive and alternatives to those shown can be considered (as indicated by 'other' in the table).

A2.2

Appendix 7/1 contained in Series 700 of the Notes for Guidance to the *Specification for Highways Works* (MCHW2) is a widely used method for specifying pavement constructions, and it is advised that the format of this Appendix should be used in the quality plan unless otherwise requested. The contractor should also justify the construction with appropriate references to design charts or, if requested by the overseeing organisation, by carrying out analytical pavement design.

A2.3

The aggregate component should be of a quality generally suitable for use in cement bound material or asphalt. However, given the nature of the operation, which involves processing arisings from existing road pavements, some discretion should be applied. The emphasis should be on ensuring that deleterious materials, such as clay lumps and badly weathered aggregate, are excluded from the recycled material.

A2.6

When determining the grading of materials containing asphalt planings, samples should be dried to constant mass at 40 ºC and care should be taken not to break down the aggregated particles of asphalt unnecessarily.

A2.7

It is good practice to undertake mix design evaluation in advance of works on site, but it must be recognised that this is not always practicable, particularly for small projects. Additionally, there will not always be time for the full design procedure and, in particular, the curing stage to be carried out in advance of the works. Where this is the case, information from earlier works with similar material and the same process or accelerated curing regimes should be taken into consideration.

The components used in the mix design stage should represent the materials available in the permanent works. Where a representative component is unavailable, the contractor should use a replacement component of similar properties in the mix design stage.

The laboratory prepared aggregate should be thoroughly mixed with the measured proportions of the binder and other constituents. The constituents should be the same as those used in the finished works.

For QVE materials, as well as SVE materials that contain pozzolanic binders, the contractor should declare the indirect tensile stiffness modulus in accordance with BS DD 213 after conditioning.

For SVE materials that do not contain pozzolanic binders, it is recommended that an accelerated curing regime is used involving curing at 60 ºC for 72 hours and then determining indirect tensile stiffness modulus. This test cannot be related to 360 day performance as the values obtained in this way may not reflect *in situ* performance in the same way as for the other material types.

For QH and SH materials the contractor should declare the minimum performance class achieved according to the direct measurement of Dynamic Modulus and Flexural Strength after conditioning; where these values are not directly measurable, suitable alternative apparatus and transfer functions may be utilised as described below.

Table A2.1 Examples of material families

Quick hydraulic (QH)	*Slow hydraulic (SH)*	*Quick visco-elastic/ hydraulic (QVE)*	*Slow visco-elastic/ hydraulic (SVE)*
● PC/PFA	● Lime/PFA	● Foam/PC	● Foam/Lime/PFA
● PC/GGBS	● Lime/GGBS	● Foam/PC/PFA	● Foam/Lime/GGBS
● PC/PFA/GGBS	● Lime/PFA/GGBS	● Foam/PC/GGBS	● Foam/Lime
● PC/'other'	● Lime/GBS	● Foam/PC/'other'	● Foam/GBS
	● Lime/PFA/GBS	● Emulsion/PC	● Foam/'other'
	● Lime/'other'	● Emulsion/PC/PFA	● Emulsion/GBS
	● BOS/GBS	● Emulsion/PC/GGBS	● Emulsion/Lime/PFA
		● Emulsion/PC/GBS	● Emulsion/Lime/'other'
		● Emulsion/PC/'other'	● Emulsion/'other'

If information is required on the moisture sensitivity of the mixtures, additional sets of specimens can be made for testing after 7 days soaking in water at (20±2) °C after the 28 day conditioning period. The soaked specimen should not show any signs of cracking or swelling and the modulus or strength values should be at least 80% of the un-soaked values determined at the same age.

Declaration using alternative test methods for hydraulic mixtures should be dealt with as follows:

Using compressive strength tests in accordance with BS EN13286-41 and using relationships from Croney *et al.* (1997):

$$E_{dyn} = \frac{\log R_f + 0.773}{0.0301} \quad \text{(A2.1)}$$

$$R_f = 0.11 R_c \quad \text{(A2.2)}$$

Using the indirect tensile strength and static stiffness in accordance with BS EN13286-42.

$$E_{dyn} = 8.4 + 0.93 E_s \quad \text{(A2.3)}$$

$$R_f = 1.33 R_{it} \quad \text{(A2.4)}$$

Where E_{dyn} is dynamic stiffness in GPa, E_S is the static stiffness in GPa, R_f is the flexural strength in MPa, R_c is the compressive strength in MPa, R_{it} is the indirect tensile strength in MPa.

This declaration shall include the direct values from laboratory tests, the converted values using the above transfer functions and also predicted 360 day values. Based on current knowledge, the factors in Table A2.2 are suggested; other factors may be used with supporting evidence. These factors should be applied to the test results prior to any transfer functions. Although the mix design values are indicative, these values should meet the end product criteria given in sub-clause A1.16 to provide assurance that the material will comply when tested in the permanent works. No factor is recommended to link the laboratory test values for SVE material without pozzolanic binder.

Table A2.2 Factors to link 28 day laboratory test values and 360 day values

Material type	*Factor*
QH	1.2
QVE	1.2
QVE*	1.0
SH	1.0
SVE*	1.0

** Indicates materials with pozzolanic binder.*

A2.8

Where a PTR is used to compact the cold recycled layer, it can be also be used to assess the stability of the layer. Rutting can be measured after 8 passes of a PTR with a minimum wheel load of 3 tonnes.

Alternatively, it is recommended that a trafficking trial be performed as part of the mixture approval trial and is a best-practice approach to ensure that excessive deformation will not occur in the Permanent Works. It should be noted that a trafficking trial cannot guarantee deformation resistance in the Permanent Works and it can be a time-consuming method of approving the mechanical stability of the material. An alternative method such as the IBI test (BS EN 13286-47) could be considered; this test can be used to provide an indication of the mechanical stability of the mixture but it does not reflect the actual loading conditions to be experienced by the CRBM.

As a general rule, the 'quick' mixtures, which include cement, are less likely to be susceptible to rutting, as are other materials with a stable, angular, granular aggregate content. Particular care should be taken if there is a high proportion of rounded gravel in the mixture.

A trafficking trial may not be necessary if:

- evidence is available to show that the proposed construction (materials, construction and thicknesses) has performed well at other sites under the same moisture conditions; or
- the type of construction is of a type that is unlikely to be susceptible to deformation.

The experience of the contractor with this type of work and evidence of satisfactory application of the same techniques on similar sites in the past should be taken into consideration.

Deformation may also result from weak underlying foundations which may be exposed during recycling operations. This should be taken into account by those responsible for the design of the works. Whether a trafficking trial is performed or not, it is important to ensure that the foundation meets the specified requirements in the Permanent Works.

If the construction is to be trafficked by special, very heavy vehicles, additional consideration should be given to the proven performance of the material approval trial under trafficking in relation to these vehicles.

A2.9

The plant used for *ex situ* stabilisation should be capable of achieving controlled batching by weight or volume. The plant should have hoppers and tanks appropriate for the component materials to be mixed.

The mixing plant should be located close enough to the site to enable placing of the material within the appropriate setting time.

A2.13

A tack coat or bond coat may be required by the overseeing organisation to improve the bond between layers and the overall durability of the structure.

A2.14

It is important to establish a testing regime for end performance properties (stiffness, tensile strength) appropriate to the nature of the works. It is recommended, given the precision of the testing, that the results are assessed for conformity in sets of six. This recommendation does not, however, mean that a full set of six specimens needs to be made up at one time.

For works of a reasonable size, it is recommended that specimens are prepared at an overall frequency of three per 1000 tonnes with a minimum of three per working day. Conformity should be assessed on a rolling basis.

It may be possible to relax this requirement for small and intermittent jobs with the prior agreement of the overseeing organisation.

40kg of material is required for each sample to have sufficient material for the three test samples (PRD, Cylindrical and Moisture Content) to be produced. PRD samples require a minimum of 5kg of material; Cylindrical samples, 4kg; Moisture Content samples, 3kg; as well as three partical size distribution tests from a bulk sample of six individual samples.

A2.15

Prior to testing, specimens shall be conditioned in a controlled environment, sealed to keep the moisture in, as described in this clause. The purpose of this conditioning is to simulate the likely curing over the first year in the road. A PRD or other suitable mould may be used. Where long-term storage of materials is required, the use of an inexpensive mould such as a plastic soil pipe is advised.

No curing regime is been specified for SVE material without pozzolanic binders; it is anticipated that a laboratory test of material in early life will not be a suitable method to demonstrate the 360 day performance of this material. For these materials, early life determination of performance using accelerated curing is recommended for quality control purposes but not for prediction of 360 day performance.

A2.16

The material performance requirements for QVE and SVE type CRBM are given in terms of indirect tensile stiffness modulus as shown in Table A2.3. The material performance requirements for QH and SH materials are given in terms of flexural strength and dynamic stiffness as shown in Figure A2.1.

Table A2.3 End product requirements for QVE and SVE CRBM at 360 days*

Material class	*Mean from test set*
Class B1	1900 MPa
Class B2	2500 MPa
Class B3	3100 MPa

** 360 days in situ or cured in accordance with sub clause A1.15.*

The criteria in this sub-clause represent the minimum permitted end product compliance criteria; however, they can be supplemented by other laboratory and non-destructive *in situ* test methods as agreed with the overseeing organisation. For visco-elastic materials, particularly those containing asphalt planings, testing for bitumen content is unlikely to be of value. This aspect of process control is better controlled through tank reconciliation. A description of the supplementary test methods and expected outcomes of the testing can be included in the quality plan declaration. Supplementary testing can be of value to both the contractor and the overseeing organisation and should be viewed as good practice. For example, a non-destructive falling weight test device can, in certain circumstances, be used to show the *in situ* performance of the layer and also show that curing is occurring. It is advised that any agreed supplementary testing is used as a tool for 'acceptance' (as opposed to 'rejection') so that, along with practical evidence at other sites, these may be used to resolve non-compliance issues should they occur.

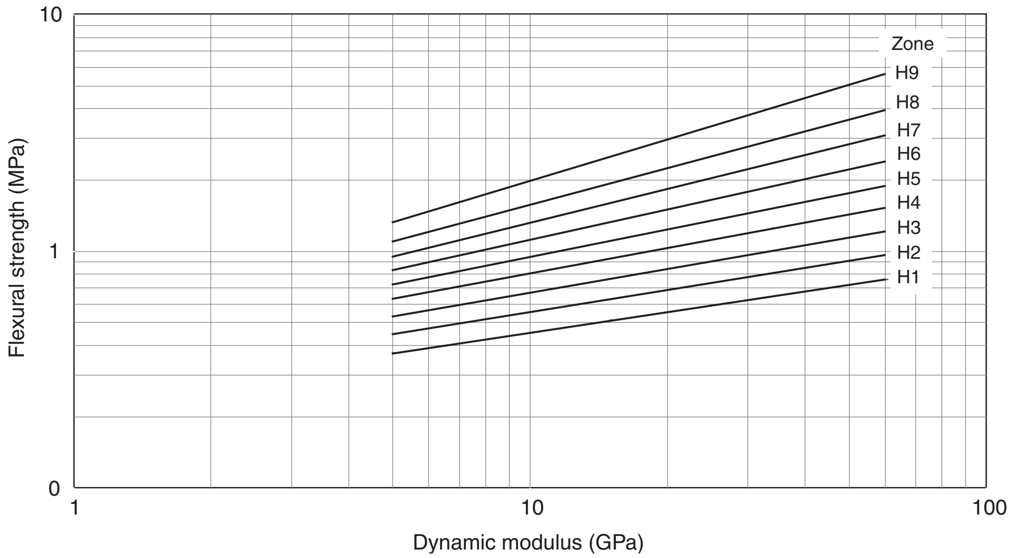

Figure A2.1 End product requirements of QH and SH CRBM at 360 days*

** 360 days in situ or cured in accordance with sub clause A1.15*

A3 *In situ* cold recycled bound material – specification

A3.1 General

In situ cold recycled bound material (CRBM) comprises base and binder courses produced by the pulverisation and stabilisation of all, or part, of the existing road structure. *In situ* CRBM is bound with hydraulic or bituminous binders, separately or in combination. This clause covers four generic material families: quick hydraulic (QH), slow hydraulic (SH), quick visco-elastic (QVE) and slow visco-elastic (SVE). The primary binder of these families of materials shall be as follows:

QH: Portland cement as the main hydraulic component and excluding bituminous binders.

SH: Hydraulic binders (e.g. PFA/lime and GBS/lime) excluding bituminous binders and portland cement.

QVE: Bituminous binder as the main component but also including portland cement.

SVE: Bituminous binder as main component but excluding portland cement.

In situ CRBM shall be designed to achieve the specified level of the appropriate end performance property

A3.2 Quality plan

In situ CRBM shall be produced to a quality plan (QP) with the following elements:

- Sourcing of additional aggregate and other constituents.
- Declaration of constituents and the job standard mixture.
- Process control of pulverisation and mixing.
- Inspection and test schedules.
- Demonstration of performance properties.

A3.3 Sourcing of aggregate

The quality plan shall contain details of all aggregates, including the pulverised road, to be used in the CRBM. Aggregate may include:

- Asphalt, concrete or granular material pulverised, planed or excavated from a road or other paved area.
- Fillers from primary or secondary sources (e.g. PFA).

The pulverised aggregate, including added filler, shall not contain deleterious material that adversely affects the performance of the mixture.

A3.4. Processing of aggregate

Not used

A3.5 Binders and other constituents

- Bitumen emulsion shall conform with BS 434-1 and be used in accordance with BS 434-2.
- Cement shall conform to EN 197-1.
- Bitumen used for foaming shall conform with EN12591 and shall be grade 160/220 or harder.
- Granulated blast furnace slag (GBS) shall comply with EN 14227-2.
- Ground granulated blast furnace slag (GGBS) shall comply with EN 14227-2.
- Lime shall comply with EN 14227-11.
- Fly ash (PFA) used as either as filler or pozzolan, shall comply with EN 14227-4.
- Un-weathered 0/4 mm basic oxygen slag (BOS) slag fines used in SH material as activator/accelerator to the GBS shall comply with BS 6463 Part 102
- Other constituents, including setting and hardening agents, may be used to enhance the performance of the mixture, subject to the approval of the overseeing organisation.
- Water shall not contain material that adversely affects the performance of the mixture.

A3.6 Job standard mixture

The composition of the job standard mixture shall be declared as follows:

- Source, origin and proportion of all aggregate constituents.
- Combined target grading, including mineral binders and tolerances.
- Source, origin and proportion of all binders.
- Target moisture content.

The grading of the job standard mixture (the aggregate together with the other constituents including hydraulic binders) shall comply with one of the zones in Table A3.1.

Table A3.1 Particle size distribution of mixture for cold recycling

	Percentage by mass passing		
Sieve (mm)	*Zone A*	*Zone B*	*Zone C*
40	100	100	100
31,5	100	100	86-100
20	100	100	75-100
14	85-100	85-100	52-100
10	68-100	68-100	44-100
4	38-74	38-94	26-74
2	26-58	26-84	18-58
0,5	13-38	13-64	8-38
0,250	9-28	9-51	5-28
0,063	5-21	5-38	3-21

Use of Zone B or C graded material shall be permitted only when the results of a full mix design showing compliance with the required 28 day performance properties are available or when evidence can be provided of satisfactory achievement of the performance requirements on an earlier contract with a similar composition.

The addition of binder shall comply with Table A3.2.

A3.7 Mixture design validation

When a mixture design validation is required it shall be carried out on aggregates and binders representative of those to be used in the works. The validation may be carried out on CRBM mixed in the laboratory.

Table A3.2 Minimum binder contents for *in situ* construction by family and binder type

Family	*OPC*	*Lime*	*BOS*	*PFA*	*GBS*	*GGBS*	*Bitumen*[1]
QH	4%	–	–	–	–	–	–
	3%	–	–	5%	–	–	–
	3%	–	–	–	5%	–	–
	3%	–	–	–	–	3%	–
SH	–	3%	–	10%	–	–	–
	–	3%	–	–	10%	–	–
	–	3%	–	–	–	6%	–
	–	2%	–	–	10%	–	–
	–	–	2.5%	–	10%	–	–
QVE	1%	–	–	[2]	–	–	4%
SVE	–	2.5%[3]	–	[2]	–	–	4%

[1] *foamed or emulsion (residual).*
[2] *PFA may be added as filler.*
[3] *lime may be added for 'breaking' and adhesion purposes, and, if PFA included as filler, will contribute to strength.*

The target mixture shall comply with sub-clause A3.5.

A preliminary exercise shall be undertaken to establish a target grading and suitable moisture content.

Representative samples of the mixture shall be taken, from which 150 mm diameter cylindrical specimens shall be produced in accordance with sub clause A3.14. The height of these specimens shall be appropriate to the mechanical performance test declared in the quality plan. The time between mixing and specimen production shall be kept to a minimum but within the setting times given in Table A3.4.

The density of each specimen shall be measured and, using the respective moisture content values, the dry density values shall be determined.

The cylindrical specimens shall be conditioned and tested in accordance with sub clauses A3.15 and A3.16.

The performance properties of the conditioned specimens shall be declared. The results shall be considered as indicative only; the end product compliance criteria, as stated in sub-clause A3.16, shall apply only to the specimens prepared during the execution of the works.

A3.8 Trafficking trial

A trafficking trial shall be undertaken when required in the QP to demonstrate that the CRBM is not prone to excessive rutting in its early life.

A trial area shall be laid using the materials and plant to be used for the main works and on a foundation typical of that in the main works. The trial area shall be left to cure for 24 hours, or other declared time, and shall then be subjected to controlled trafficking. The trafficking shall be performed by a heavy goods vehicle with an axle configuration and loading typical of that to be encountered in the construction phase. The number of passes shall equate to the total expected amount of traffic to be carried during construction, with a default value equivalent to 100 standard axles.

The measured rutting in the trafficking trial shall be less than 10 mm or that stated in the job specific appendix.

A3.9 Process control

Production of the *in situ* CRBM shall be subject to process control detailed in the quality plan and meeting the following requirements:

- There shall be a description of the plant and the production process, preferably including a flow diagram, detailing how material is to be produced in accordance with this specification. A description of the systematic pattern of the pulverisation and stabilisation process shall be included.
- Measures to deal with hard edges and obstructions shall be included.
- Calibration schedules for all parts of the plant involved in determining mix consistency shall be provided. Calibration records shall accompany these schedules.
- Measures to avoid problems caused by extreme weather. In particular, construction shall not proceed if road and/or other materials are frozen or excessively wet.

A3.10 Inspection and test

There shall be a schedule of inspection and test frequencies to be made during production of CRBM. This shall comply with the minimum frequencies in Table A3.3.

Table A3.3 Minimum frequencies for inspection and test

Item	*Inspection*	*Test*
Aggregate stockpiles*	Daily	Grading and moisture content before production and weekly
Binders	On receipt	Supplier data
Combined grading of mixture	Continual	Daily
Moisture content of mixture	Continual	Daily

* *If applicable.*

A3.11 Laying

A written procedure for the levelling of the *in situ* CRBM shall be provided.

The plant used for levelling the *in situ* processed material shall be capable of levelling without significant segregation, evenly and to the required thickness across the full width.

A method for the forming of longitudinal and transverse joints shall be provided that is appropriate to the type of CRBM being laid.

A3.12 Compaction

The compaction of each layer shall be carried out to a defined rolling pattern until both the required *in situ* density is achieved and the recycled layer provides a stable and dense tight surface. The stability of the layer after compaction shall be deemed adequate if the finished surface does not shove, rut or exhibit transverse cracking under the load of subsequent traffic. Open edges shall be protected from traffic.

After trimming and final compaction of the recycled layer, the *in situ* bulk density shall be measured using a nuclear density gauge in direct transmission mode, to a depth within 25 mm of the layer thickness. The meter readings shall be verified periodically in accordance with Clause 1041 of the Specification for Highway Works, with the gauge calibrated in accordance with BS 1377: Part 9.

The *in situ* bulk density values obtained shall be compared with the refusal density value of the job standard mixture or of the refusal density of a specimen representative of the day's production. The average *in situ* bulk density of each set of five values shall be at least 95% of the refusal density, with no individual *in situ* density value being less than 93% of the respective refusal density.

A3.13 Sealing

Unless surfaced immediately or kept moist by light water spraying, the surface shall be sealed using a sprayed membrane of Class K1 - 40 bitumen emulsion complying with Clause 920 in the Specification for Highway Works when required in the quality plan. The bitumen emulsion shall be sprayed at a rate not less than 0.5 l/m^2 to achieve a uniform and continuous seal to the surface of the layer. Where the surface is opened to traffic, the bitumen emulsion shall be blinded with fine aggregate or sand applied at a rate of 5.5 to 7.0 kg/m^2.

A3.14 End product testing

The end product testing of the *in situ* CRBM shall be assessed on the basis of representative specimens made up in accordance with the schedule in the quality plan.

Representative samples of the *in situ* CRBM shall be taken at the stabilisation plant prior to compaction. 150 mm diameter cylindrical test specimens shall be manufactured in sets of six by compacting to refusal in accordance with BS 598: Part 104. The time period after mixing during which compaction must be completed shall be in accordance with Table A3.4.

Table A3.4 Setting times of cold recycled families

Family	*Setting time under normal temperature conditions*
QH	2 hours
SH	24 hours*
QVE	2 hours
SVE	24 hours*

* *Can be longer depending on material composition.*

A3.15 Conditioning and testing of samples

Immediately after compaction, the cylindrical specimens (either in their moulds or after extraction from the moulds if applicable), shall be double wrapped in cling-film plastic using two separate sheets, each of which shall be sufficient to cover the entire circumference of the cylinder and the two ends of the specimen. Once wrapped in cling-film, the sample shall be placed in a sealed plastic bag. Care shall be taken when handling the specimens not to damage the plastic bag or the underlying cling-film layer. The specimens shall be stored in air or water at a temperature within 2 ^{o}C of the nominal conditioning temperature.

QH and QVE[1] specimens shall be conditioned for a period of 28 days at a temperature of (20$\pm$2) ^{o}C.

SH, QVE[2], SVE[2] specimens shall be conditioned for a period of 28 days at a temperature of (40$\pm$2) ^{o}C.

SVE[1] specimens shall be conditioned according to a procedure declared in the quality plan.

A3.16. End product criteria

The minimum specification compliance criteria for the process control tests shall be as described in Table A3.5.

Table A3.5 End product criteria

Material property or characteristic	*Individual results*	*Mean from test set of six measurements*
Particle size distribution	Zone	–
Moisture content	±2%	–
Relative *in situ* density	93% minimum	95% minimum
Layer thickness	±25 mm of specified	±15 mm of specified
Mechanical performance	n/a	As stated in the QP

In the event of test specimens failing to achieve the required mechanical performance, compliance shall be determined by the testing of cores extracted by dry coring after one year. The results shall be compared with the material performance requirements in the QP.

A4 *In situ* cold recycled material – Notes for guidance

A4. 1 General

Examples of the types of materials that satisfy the material classifications QH, SH, QVE and SVE are provided below. It is realised that the combinations listed in Table A4.1 for each family are not exhaustive and alternatives to those shown can be considered (as indicated by 'other' in the table).

A4.2 Quality plan

Appendix 7/1 contained in Series 700 of the Notes for Guidance to the *Specification for Highways Works* (MCHW2) is a widely used method for specifying pavement construction, and it is advised that the format of this Appendix should be used in the quality plan unless otherwise requested. The contractor should also justify the

[1] *Not containing a pozzolanic binder.*
[2] *Containing a pozzolanic binder.*

Table A4.1 Examples of material families

Quick hydraulic (QH)	*Slow hydraulic (SH)*	*Quick visco-elastic/ hydraulic (QVE)*	*Slow visco-elastic/ hydraulic (SVE)*
• PC/PFA	• Lime/PFA	• Foam/PC	• Foam/Lime/PFA
• PC/GGBS	• Lime/GGBS	• Foam/PC/PFA	• Foam/Lime/GGBS
• PC/PFA/GGBS	• Lime/PFA/GGBS	• Foam/PC/GGBS	• Foam/Lime
• PC/'other'	• Lime/GBS	• Foam/PC/'other'	• Foam/GBS
	• Lime/PFA/GBS	• Emulsion/PC	• Foam/'other'
	• Lime/'other'	• Emulsion/PC/PFA	• Emulsion/GBS
	• BOS/GBS	• Emulsion/PC/GGBS	• Emulsion/Lime/PFA
		• Emulsion/PC/GBS	• Emulsion/Lime/'other'
		• Emulsion/PC/'other'	• Emulsion/'other'

construction with appropriate references to design charts or, if requested, by the overseeing organisation, carrying out analytical pavement design.

A4.3 Sourcing of aggregate

The aggregate component should be of a quality generally suitable for use in cement bound material or asphalt. However, given the nature of the operation, which involves processing arisings from existing road pavements, some discretion should be applied. The emphasis should be on ensuring that deleterious materials, such as clay lumps and badly weathered aggregate are excluded from the recycled material.

A4.6 Job standard mixture

When determining the grading of materials containing asphalt planings, samples should be dried to constant mass at 40 °C and care should be taken not to break down the aggregated particles of asphalt unnecessarily.

A4.7 Mixture design validation

It is good practice to undertake mix design evaluation in advance of works on site, but it must be recognised that this is not always practicable, particularly for small projects. Additionally, there will not always be time for the full design procedure and, in particular, the curing stage to be carried out in advance of the works. Where this is the case, information from earlier works with the same process or accelerated curing regimes should be taken into consideration.

The components used in the mix design stage should represent the materials available in the permanent works. Where a representative component is unavailable, the contractor should use a replacement component of similar properties in the mix design stage.

The laboratory prepared aggregate should be thoroughly mixed with the measured proportions of the binder and other constituents. The constituents shall be the same as those used in the finished works.

For QVE materials, as well as SVE materials that contain pozzolanic binders, the contractor should declare the indirect tensile stiffness modulus in accordance with BS DD 213 after conditioning.

For SVE materials that do not contain pozzolanic binders, it is recommended that an accelerated curing regime is used involving curing at 60 °C for 72 hours and then determining indirect tensile stiffness modulus. This test cannot be related to 360 day performance as the values obtained in this way may not reflect *in situ* performance in the same way as for the other material types.

For QH and SH materials the contractor should declare the minimum performance class achieved according to the direct measurement of dynamic modulus and flexural strength after conditioning; where these values are not directly measurable, suitable alternative apparatus and transfer functions may be utilised as described below.

If information is required on the moisture sensitivity of the mixtures, additional sets of specimens can be made for testing after 7 days soaking in water at (20±2) °C after the 28 day conditioning period. The soaked specimens should not show any signs of cracking or swelling and the modulus or strength values should be at least 80% of the un-soaked values determined at the same age.

Declaration using alternative test methods for hydraulic mixtures should be dealt with as follows:

Using compressive strength tests in accordance with BS EN13286-41 and using relationships from Croney *et al.* (1997):

$$E_{dyn} = \frac{\log R_f + 0.773}{0.0301} \qquad (4.1)$$

$$R_f = 0.11R_c \qquad (4.2)$$

Using the indirect tensile strength and static stiffness in accordance with BS EN13286-42:

$$E_{dyn} = 8.4 + 0.93E_s \qquad (4.3)$$

$$R_f = 1.33R_{it} \qquad (4.4)$$

Where E_{dyn} is dynamic stiffness in GPa, E_S is the static stiffness in GPa, R_f is the flexural strength in MPa, R_c is the compressive strength in MPa, R_{it} is the indirect tensile strength in MPa.

This declaration shall include the direct values from laboratory tests, the converted values using the above transfer functions and also predicted 360 day values. Based on current knowledge, the factors in Table A4.2 are suggested; other factors may be used with supporting evidence. These factors should be applied to the test results prior to any transfer functions. Although the mix

Table A4.2 Factors to link laboratory test values and 360 day values

Material type	*Factor*
QH	1.2
QVE	1.2
QVE*	1.0
SH	1.0
SVE*	1.0

** Indicates materials with pozzolanic binder.*

design values are indicative, these values should meet the end product criteria given in sub-clause A3.16 to provide assurance that the material will comply when tested in the permanent works. No factor is recommended to link the laboratory test values for SVE material without pozzolanic binder.

A4.8 Trafficking trial

Where a PTR is used to compact the cold recycled layer, it can be also be used to assess the stability of the layer. Rutting can be measured after 8 passes of a PTR with a minimum wheel load of 3 tonnes.

Alternatively, it is recommended that a trafficking trial be performed as part of the mixture approval trial and is a best-practice approach to ensure that excessive deformation will not occur in the permanent works. It should be noted that a trafficking trial cannot guarantee deformation resistance in the Permanent Works and it can be a time-consuming method of approving the mechanical stability of the material. An alternative method such as the IBI test (BS EN 13286-47) could be considered; this test can be used to provide an indication of the mechanical stability of the mixture but it does not reflect the actual loading conditions to be experienced by the CRBM.

As a general rule, the 'quick' mixtures, which include cement, are less likely to be susceptible to rutting, as are other materials with a stable, angular, granular aggregate content. Particular care should be taken if there is a high proportion of rounded gravel.

A trafficking trial may not be necessary if:

- evidence is available to show that the proposed construction (materials, construction and thicknesses) has performed well at other sites under the same moisture conditions; or
- the type of construction is of a type that is unlikely to be susceptible to deformation.

The experience of the contractor with this type of work and evidence of satisfactory application of the same techniques on similar sites in the past should be taken into consideration.

Deformation may also result from weak underlying foundations which may be exposed during recycling operations. This should be taken into account by those responsible for the design of the works. Whether a trafficking trial is performed or not, it is important to ensure that the foundation meets the specified requirements in the Permanent Works.

If the construction is to be trafficked by special, very heavy vehicles, additional consideration should be given to the proven performance of the material approval trial under trafficking in relation to these vehicles.

A4.9 Process control

Pulverisation of the existing road structure should be carried out in a systematic pattern, to the required depth, to ensure that it covers all parts of the existing road; a description of the pattern should be given in the QP. An overlap of at least 150 mm should be made between adjacent passes of the machine. Any material missed along hard edges or around obstructions should be excavated and placed in the path of subsequent passes of the machine until a uniform fully pulverised aggregate is obtained. The surface of the pulverised layer should be graded to the required level profile and nominally compacted.

Where work continues adjacent to previously recycled material, transverse joints should be reformed a minimum 0.5 m into the previously treated construction. Where a layer of material for recycling is placed over a layer previously recycled, the depth of pulverisation/stabilisation of the upper layer should be set to cut into the underlying recycled layer by at least 20 mm.

Excess pulverised material should be removed by grader and/or excavator for use elsewhere on site or transported to stockpile at locations given in the QP. The surface of the layer should be graded to the required level profile and nominally compacted.

The moisture content of the pulverised aggregate immediately prior to stabilisation should be measured in accordance with BS 812: Part 109 using a method suitable for subsequent process control testing. The moisture content should be uniform throughout the layer within the range ±2% of optimum moisture content for the pulverised aggregate including any designed proportion of filler, determined in accordance with BS 1924: Part 2 (1990).

If the moisture content of the pulverised aggregate fails to meet the specified moisture content range, corrective action should be taken either by aeration to reduce the moisture content or controlled addition of water to increase the moisture content.

Prior to stabilisation, pulverised materials within 100 mm of restricted hard edges such as kerbs and channels, or around obstructions such as gullies, should be removed and spread uniformly over the remaining full width of the pulverised material.

The stabilisation should be carried out to the required depth in a systematic pattern similar to that used for the pulverisation process, with an overlap of at least 150 mm between adjacent passes of the machine using a method approved by the overseeing organisation.

The layer of recycled material should be graded to level and compacted within two hours of the final pass of the stabilising plant, unless a curing or 'maturing' period of aeration is required. Any furrow formed by prior excavation of edge material should be re-filled by grading the adjacent recycled material into the space using a minimum amount of re-working.

A4.13

A tack coat or bond coat may be required by the overseeing organisation to improve the bond between layers and the overall durability of the structure.

A4.14 End product testing

It is important to establish a testing regime for end performance properties (stiffness, tensile strength) appropriate to the nature of the works. It is recommended, given the precision of the testing, that the results are assessed for conformity in sets of six. This recommendation does not, however, mean that a full set of six specimens needs to be made up at one time.

For works of a reasonable size, it is recommended that specimens are prepared at an overall frequency of three per 1000 tonnes along a diagonal bisecting, with a minimum of three per working day. Conformity should be assessed on a rolling basis.

It may be possible to relax this requirement for small and intermittent jobs with the prior agreement of the overseeing organisation.

40 kg of material is required for each sample to have sufficient material for the three test samples (PRD, cylindrical and moisture content) to be produced. PRD samples require a minimum of 5 kg of material; cylindrical samples, 4 kg; moisture content samples, 3 kg; as well as three particle size distribution tests from a bulk sample of six individual samples.

A4.15 Conditioning and testing of samples

Prior to testing, specimens shall be conditioned in a controlled environment, sealed to keep the moisture in, as described in this clause. The purpose of this conditioning is to simulate the likely curing over the first year in the road. A PRD or other suitable mould may be used. Where long-term storage of materials is required, the use of an inexpensive mould such as plastic soil pipe is advised.

No curing regime has been defined for SVE material without pozzolanic binders; it is anticipated that a laboratory test of material in early life will not be a suitable method to demonstrate the 360 day performance of this material. For these materials early life determination of performance using accelerated curing is recommended for quality control purposes but not for the prediction of 360 day performance.

A4.16 End product criteria

The material performance requirements for QVE and SVE type CRBM are given in terms of indirect tensile stiffness modulus as shown in Table A4.3. The material performance requirements for QH and SH materials are given in terms of flexural strength and dynamic stiffness as shown in Figure A4.1.

Table A4.3 End product requirements for QVE and SVE CRBM at 360 days*

Material class	*Mean from test set*
Class B1	1900 MPa
Class B2	2500 MPa
Class B3	3100 MPa

**360 days in situ or cured in accordance with sub clause A3.15.*

The criteria in this sub-clause represent the minimum permitted end product compliance criteria; however, they can be supplemented by other laboratory and non-destructive *in situ* test methods as agreed with the overseeing organisation. For visco-elastic materials, particularly those containing asphalt planings, analysing for bitumen content is unlikely to be of value. This aspect of process control is better controlled through tank reconciliation. A description of the supplementary test methods and expected outcomes of the testing can be

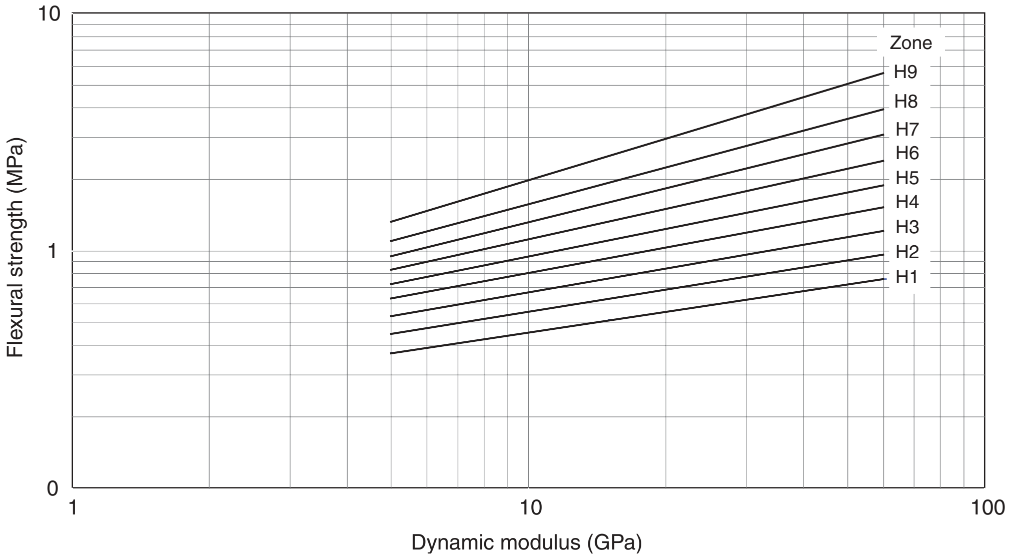

Figure A4.1 End product requirements of QH and SH CRBM at 360 days*

**360 days in situ or cured in accordance with sub clause A3.15.*

included in the quality plan declaration. Supplementary testing can be of value to both the contractor and the overseeing organisation and should be viewed as good practice. For example, a non-destructive falling weight test device can in certain circumstances be used to show the *in situ* performance of the layer and also show that curing is occurring. It is advised that any agreed supplementary testing is used as a tool for 'acceptance' (as opposed to 'rejection') so that, along with practical evidence at other sites, these may be used to resolve non-compliance issues should they occur.

A5 References

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Appendix B: Validation of design concepts at active sites

Fourteen active sites were identified as potential sites for the confirmation of the design concepts presented in Section 7; there were nine sites containing bitumen bound cold recycled material (QVE family) and five sites containing hydraulically bound cold recycled materials (SH and QH families). Tables B2.1 and B2.2 provide design comparisons of the pavements using bitumen and/ or hydraulic binders with the new design guide approach.

Table B2.3 gives longer term test data from cores extracted using air flush techniques from several sites using visco-elastic binders, and these results show the effect of age, moisture content and density on the indirect tensile stiffness modulus (ITSM). In particular, the results show the effect of cement and cement/PFA content on the stiffness results for the QVE materials. As expected, by increasing the cement and cement/PFA content, the stiffness increases. When no cement or pozzolanic component is added to the visco-elastic binder, low stiffness is achieved (A3088, Yeovil). As the cement and cement/PFA binder content increases, the *in situ* stiffness increases to much higher levels and transforms the material from SVE (with no pozzolanic component) into zones B2 and B3. The addition of 2 % or more of cement with or without PFA leads to very high stiffness values, which are equivalent to cement bound materials. For example the A40 Pwll Trap in Wales has very high stiffness values although the visco-elastic element in this material will still provide a degree of material flexibility. A limit of 1 % to 1.5 % of cement (with or without PFA) should be sufficient to provide high level performance.

Tables B2.4 to B2.6 give additional long-term test data from a number of sites using slow hydraulic binders. These tables show that these materials can develop good material performance. The classification of the hydraulic materials according to Figure 7.2 is also given.

Table B2.1 Comparison of pavement design using bitumen bound cold recycled material and the proposed design

	Site information						*Proposed design*	
Site	*Design traffic (msa)*	*Road category*	*Foundation class*	*Material class*	*Recycled layer thickness (mm)*	*Surfacing (mm)*	*Cold recycled base thickness (mm)*	*Surfacing (mm)*
A349 Cabot Lane	10	2	2	B2	300	50	220	100
A21 Sevenoaks	25.6	1	3	B3	200	100	210	60
A38 Tarnock	5.5	2	1	B1	250	80	250	100
Cleveland	2	3	2	B2	160	100	150	100
A40 Pwll Trap	20	1	1	B3	250	100	260	60
Bordesley Green	1	3	1	B2	170	60	150	100
A477 Llanteg	15	1	1	B3	250	100	240	50
A358 Taunton	20	1	1	B3	260	100	260	60

Table B2.2 Comparison of pavement design using hydraulically bound cold recycled material and the proposed design

	Site information						*Proposed design*	
Site	*Design traffic (msa)*	*Road category*	*Foundation class*	*Material class*	*Recycled layer thickness (mm)*	*Surfacing (mm)*	*Cold recycled base thickness (mm)*	*Surfacing (mm)*
Lichfield	14.5	1	1	H4	360	100	280	140
Flanchford Road	<0.5	4	1	H6	200	40	180-240	40
Deanoak Lane S1	<0.5	4	1	H6	200	40	180-240	40
Deanoak Lane S2	<0.5	4	1	H6	200	40	180-240	40
Deanoak Lane S3	<0.5	4	1	H4	200	40	200-270	40

Table B2.3 Summary of test results obtained on *in situ* Foamix cores extracted from selected sites

Condition	*As received*						*Dry at 20°C*						
Layer	*Upper*			*Lower*			*Upper*			*Lower*			
Age to date	*Stiffness (MPa)*	*MC (%)*	*Bulk density Mg/m³*	*Stiffness (MPa)*	*MC (%)*	*Bulk density Mg/m³*	*Stiffness (MPa)*	*MC (%)*	*Bulk density Mg/m³*	*Stiffness (MPa)*	*MC (%)*	*Bulk density Mg/m³*	*Mixture details*
Incinerator plant Haverton Hill, Billingham, Cleveland													
4 years and	3475	9.4	2.178	2496	9.4	2.09	4681	3.6	2.669	1951	3	2.713	100% crushed concrete aggregates (28/0)
3 months	3958	8.4	2.21	1809	9.6	2.073	5945	3.2	2.979	2498	2.6	2.805	1% cement
	4124	8.5	2.164	1158	8.8	1.769	4967	3.6	2.766	1100	2.2	2.449	2.8% FB (150 pen)
	1347	7.7	2.096	3256	9.2	2.16	1794	3	2.61	3688	3	2.748	1% water
	3226			**2180**			**4347**			**2309**			
A40 Pwll Trap, St Clears, Wales													
1 year and	11832	11.6	1.98	9249	4.1	2.159	12286	11.9	1.975	8828	4.4	2.154	95% wet mix macadam (28/0)
9 months	7179	6.9	2.251	14008	4.7	2.242	7495	7.1	2.245	12053	5	2.236	5% PFA
	9509	7.8	2.29	13381	7.3	2.319	9465	8.1	2.283	13600	7.5	2.313	2.0% cement
	14072	5	2.304	14518	4.6	2.349	13963	4.8	2.298	13932	4.3	2.342	3% FB (150 pen)
	11867	4.6	2.312	8158	12.2	2.244	10670	4.1	2.301	8223	11.9	2.237	0.5%-1.5% water
	13867	4.7	2.344	14135	6.2	2.34	14779	4.4	2.336	13563	5.9	2.334	
	10767	4.7	2.326	11030	4.4	2.221	10559	4.5	2.321	11332	4.2	2.216	
	15324	8.5	2.243	11461	4.4	2.271	16622	8.5	2.244	10525	4.1	2.264	
	17984	6.9	2.29	16188	3.8	2.291	17709	6.7	2.286	16021	3.5	2.286	
	12489			**12459**			**12616**			**12008**			
Bordesley Green, Birmingham													
4 years	Cracked	9.4	2.014	2403	11	1.966	Cracked	2.8	1.909	3305	3.1	1.853	60% recycled aggregates predominantly
	2504	11	2.032	3759	11	2.022	4116	3.1	1.905	5766	2.9	1.909	crushed concrete
	2902	11	2.009	3324	11	2.035	4565	3	1.9	4986	2.9	1.929	40% RAP
	3331	11	1.992	3270	11	2.018	4403	2.8	1.887	4693	2.8	1.906	1.5% cement
	3469	12	1.997	3981	11	2.029	4282	3.1	1.872	4844	2.8	1.926	2.8% FB (150pen)
	1315	12	1.973	3353	12	2.022	1356	2.9	1.846	4286	3	1.904	1% water
	3527	13	2.053	1911	11	2.022	4389	2.9	1.865	2717	2.7	1.901	
	1469	11	2.043	1975	11	2.012	2580	2.7	1.921	3064	3.1	1.887	
	2450	12	1.996	2047	11	2.032	3911	2.8	1.881	3535	2.2	1.912	
	2621			**2891**			**3700**			**4133**			

Table B2.3 (Continued) Summary of test results obtained on *in situ* Foamix cores extracted from selected sites

Condition	*As received*						*Dry at 20°C*						
Layer	*Upper*			*Lower*			*Upper*			*Lower*			
Age to date	*Stiffness (MPa)*	*MC (%)*	*Bulk density Mg/m³*	*Stiffness (MPa)*	*MC (%)*	*Bulk density Mg/m³*	*Stiffness (MPa)*	*MC (%)*	*Bulk density Mg/m³*	*Stiffness (MPa)*	*MC (%)*	*Bulk density Mg/m³*	*Mixture details*
A477, Llanteg													
6 months	4436	5.6	2.26	7763	4.8	2.331	6165	3.2	2.236	8306	3.3	2.316	95% RAP
	4526	5.5	2.254	6380	5.1	2.24	5801	3.2	2.231	7710	3.2	2.22	5% PFA
	4542	5.2	2.347	8567	4.5	2.277	4987	3	2.324	9060	3	2.262	1.5% cement
	2323	5.5	2.243	8569	5.3	2.257	3267	2.8	2.214	7891	3.6	2.24	3% FB (150 pen)
	3445	5	2.255	8252	4.7	2.287	3769	2.6	2.229	7983	3.2	2.273	0.5%-1.5% water
	3784	5.3	2.236	6611	4.9	2.293	4576	2.7	2.207	7102	3.2	2.276	
	6022	5.9	2.197	7624	5.2	2.348	7081	3.5	2.174	7956	3.1	2.327	
	5523	5.8	2.28	4981	5.2	2.266	7106	3.3	2.255	6774	2.9	2.24	
	4325			**7343**			**5344**			**7848**			
A358 Hatch Beauchamp Taunton, Somerset													
12 months	3128	5.2	2.054	5505	5.2	2.171	3281	3.5	2.021	5914	3.5	2.135	95% RAP and sub-base aggregates
	6238	5.9	2.133	6770	6.5	2.143	5665	4.1	2.096	8511	4.7	2.106	5% PFA
	4179	5.6	2.123	8183	6	2.167	3909	3.5	2.082	7984	4.3	2.131	1.5% cement
	4547	6.4	2.115	5307	6	2.175	5972	4.7	2.082	6016	3.7	2.128	3% FB (150 pen)
	6534	5.3	2.114	*	*	*	5861	3.7	2.081	*	*	*	2.0-2.5% water
	6732	5.1	2.174	3767	6.3	2.127	7150	3.4	2.138	4827	4.1	2.083	
	4947	6.1	2.168	6474	6.3	2.106	5955	3.1	2.106	7416	3.8	2.056	
	5186			**6001**			**5399**			**6778**			
A3088, Yeovil													
5 years	888	2	2.391	Too weak	2.3	2.259	3106	0.4	2.353	2222	0.3	2.216	60% lean mix recycled aggregates
	496	2	2.294	222	3.1	2.115	2.723	0.4	2.258	2137	0.3	2.058	40% RAP
	379	2.6	2.2	691	2.3	2.413	1743	0.4	2.154	1819	0.4	2.366	3% FB (150 pen)
	361	2	2.344	276	2.2	2.262	2717	0.4	2.306	2033	0.3	2.22	2.5% water
	531			**396**			**2572**			**2053**			

Table B2.4 A52 Reconstruction at Froghall, Staffordshire, 1997

Mixture: 85% planings 12% PFA 3% lime	*Age and curing*	*E_d in GPa derived from NAT stiffness E_s using $E_d = 8.4 + 0.93E_s$*	*R_f in MPa, derived from NAT indirect tensile strength R_{it} using $R_f = 1.33R_{it}$*	*1:1 cylinder compressive strength, R_c, in Mpa*	*E_dR_f classification in accordance with Figure 7.2*
Mixture design	20degC / 1 year	20	1.7	15	H6
Production results	20degC / 1 year	19	1.0	8.5	H4
Cores	1 year	23	1.2	6	H4
Falling weight deflectometer	1 year	13 (FWD stiffness)	–	–	–
Ditto	3 years	20+ (FWD stiffness)	–	–	–

Table B2.5 Ramsgate Harbour Approach Road, Kent, 1999/2000

Mixture: 85% planings 12% PFA 3% lime	*Age and curing*	*E_d in GPa derived from NAT stiffness E_s using $E_d = 8.4 + 0.93E_s$*	*R_f in MPa, derived from NAT indirect tensile strength R_{it} using $R_f = 1.33R_{it}$*	*1:1 cylinder compressive strength, R_c, in Mpa*	*E_dR_f classification in accordance with Figure 7.2*
Mixture design	14 days / 40degC	–	–	12.5	–
Production results	14 days / 40degC	–	–	10.5	–
Production results	2 years / 20degC	34	2.0	15	H6
Falling weight deflectometer	2 years	27 (FWD stiffness)	–	–	–

Table B2.6. Burntwood Bypass, Staffordshire, 2000/2001

Mixture: 85% planings 12% PFA 3% lime	*Age and curing*	*E_d in GPa derived from NAT stiffness E_s using $E_d = 8.4 + 0.93E_s$*	*R_f in MPa, derived from NAT indirect tensile strength R_{it} using $R_f = 1.33R_{it}$*	*1:1 cylinder compressive strength, R_c, in Mpa*	*E_dR_f classification in accordance with Figure 7.2*
Mixture design	28 days / 40degC	-	-	15	–
Production results	14 days / 40degC	21	1.5	9	H5
Cores	2 years	21	2.2	11.5	H7
Falling weight deflectometer	2 years	20+ (FWD stiffness)	–	–	–

Appendix C: Static stiffness and direct tensile strength

C1 Introduction

The UK has traditionally characterised cement bound materials in terms of dynamic elastic modulus and flexural strength for the purposes of pavement design. The dynamic elastic modulus is measured at a loading frequency of several kilohertz and at low stress amplitude. This differs from the conditions induced by a rolling wheel load, which has an effective loading frequency of a few hertz and generally induces a much higher stress. The proposed new European Standard for fly ash bound material, BS EN 14227-3 (BSI, 2001) uses static elastic modulus and direct tensile strength to characterise hydraulically bound materials and this characterisation will eventually be adopted in the UK.

In this appendix, the implications of harmonising with the material characteristics used to classify materials in the proposed new European Standards are examined. There are few measurements available for the static modulus and direct tensile strength for the standard cement bound materials used in the UK, and there is even less information on other hydraulically bound materials. It is also recognised that the relationship between these parameters and those that have been used traditionally in the UK is material specific. A programme of material testing would be required to establish authoritative relationships. Uncertainty is compounded by the fact that many of the values available were determined after 7, 28, 60 or 90 days of curing rather than after 360 days as required for design purposes. Therefore, the calculations and values contained in this appendix should be regarded with caution and their purpose is to explore the design implications of moving to the European method of characterisation.

C2 Relationship between material characteristics

C2.1 General

Existing data was reviewed to obtain provisional relationships between the dynamic and static elastic modulus and the flexural and direct tensile strength. A test programme would need to be devised to establish more robust static modulus and direct tensile strength values for cement bound and other hydraulically bound materials.

C2.2 Elastic modulus

The static elastic modulus is defined as the secant modulus at 30% of the load to failure whereas the dynamic elastic modulus is measured at the resonant frequency of a prismatic specimen (BS 1881, 1990). This frequency is typically between 2 and 5 kHz. During the vibration, negligible stress is applied. Therefore, the dynamic modulus refers to an almost purely elastic effect and is unaffected by creep. For this reason the dynamic modulus is approximately equal to the initial tangent modulus determined in the static test and it is higher than the static (secant) modulus.

The following relationship between static (E_s) and dynamic modulus (E_d) was derived from the measurements on cement bound materials reported by Kolias and Williams (1978), as reproduced in Figure C1.

$$E_s = 1.08\, E_d - 9.07 \qquad (R^2 = 0.97) \qquad \text{(C1)}$$

The relationship between static and dynamic modulus is material dependent and at low modulus values the difference between the two measurements becomes

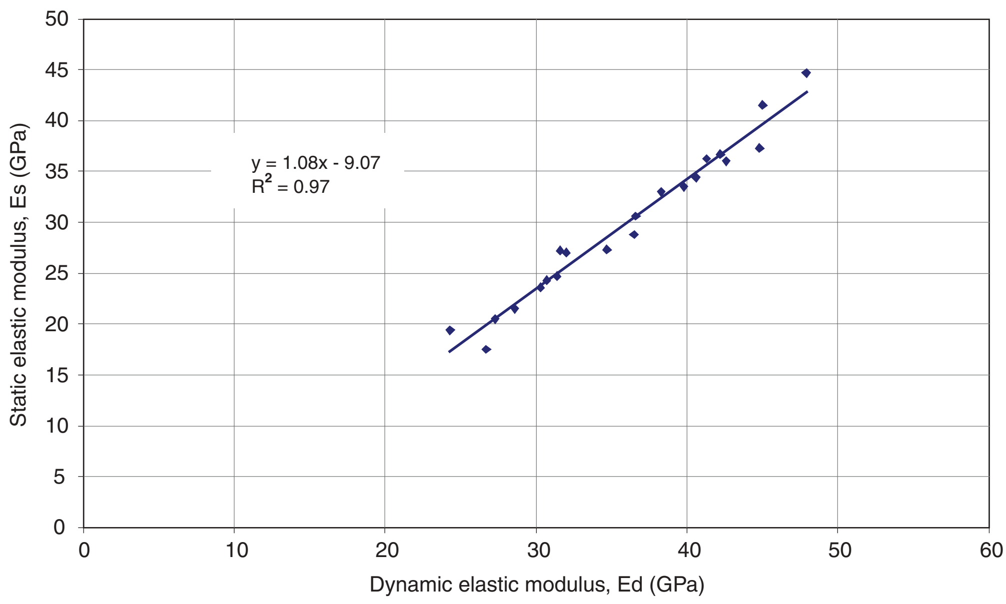

Figure C1 Relationship between dynamic and static modulus for CBM greater. For example, Figure C2 shows the relationship between compressive strength and dynamic and static modulus of slag bound material (SBM). This illustrates that the two curves diverge for lower modulus values.

C2.3 Material strength

In the French design guide (LCPC/SETRA, 1998) the direct tensile strength of hydraulically bound material is taken to be 80% of the indirect tensile strength. Also the indirect tensile strength is approximately 75% of the flexural strength (Raphael, 1984). These two relationships imply that the direct tensile strength is approximately 60% of the flexural strength.

C3 Summarising remarks

1 Initially cold recycled materials can be introduced based on the current UK material characterisation parameters of dynamic modulus and flexural strength with a longer term view to adopting the parameters defined in the proposed new European Standards.

2 At present there is only limited data available on 360 day values of dynamic modulus and flexural strength of hydraulically bound materials in general, and even less information available on static modulus and direct tensile strength. It is therefore recommended that further testing be carried out to develop more robust material characterisation values.

C4 References

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Raphael J M (1984). Tensile strength of concrete. ACI Journal, vol. 80, no. 2.

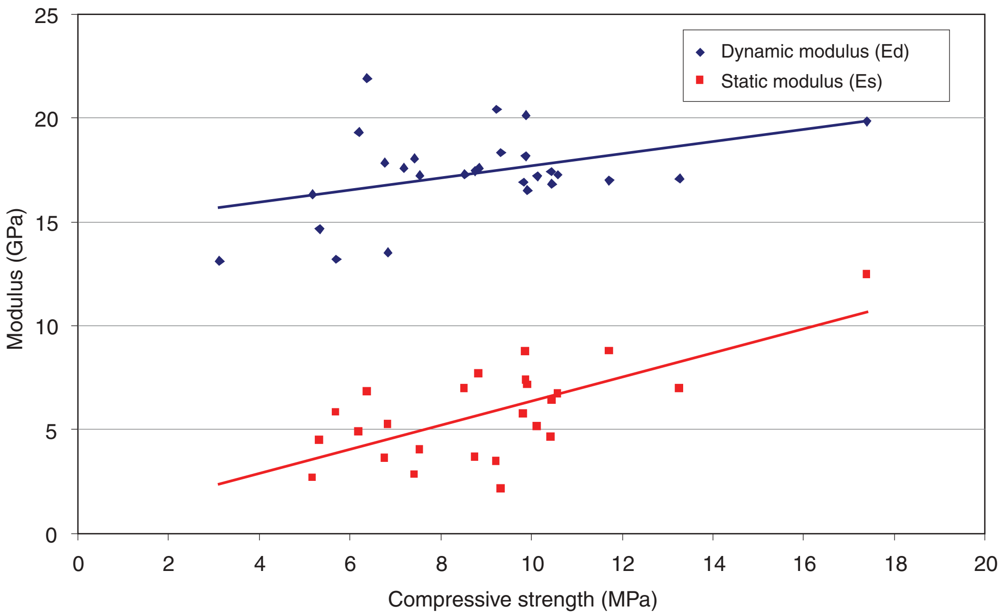

Figure C2 Relationship between compressive strength and modulus for SBM

Abstract

Recycling of existing pavement materials, and the re-use of alternative aggregates, has become an increasingly important factor in the UK for maintenance of highways. The 'linear quarry' concept of using the existing highway as a source of road-stone aggregates has gained considerable favour in recent years following the introduction of the first nationally consistent guidelines in 1999. Since that time, sustainability and environmental issues have continued to receive more attention which has resulted in the demand to consider recycling in the maintenance of a larger proportion of the primary and secondary road network. *In situ* and *ex situ* variants of cold recycling techniques are now feasible and many large and specialist contracting organisations can offer these services, with the benefit of reduced consumption of energy, fuel and materials. The report, based upon a three year programme of work, provides an end-performance based design guide and specification for cold recycled materials, no matter how they are produced, and covers a wide range of cold-mix recycled materials involving a range of binders and binder blends. Materials are classified into families, which enables materials produced with new binders or combinations of binders to be introduced with relative ease. Advice is given for a wide range of traffic conditions ranging from the lightly traffic roads to heavily trafficked trunk roads. The pavement designs utilise 1-year material properties, thus enabling slow curing materials to be used in an equivalent manner to traditional materials. The specifications and advice should facilitate more prudent use of natural resources and assist in the protection of the environment in line with Government Policy.

Related publications

Development of a more versatile approach to flexible and flexible composite pavement design by M E Nunn. 2004 *(In preparation)*

TRL473 *In-service performance of recycled asphalt roadbase* by M A Megan and J F Potter. 2000 (price £25, code E)

TRL386 *Design guide and specification for structural maintenance of highway pavements by cold in-situ recycling* by L J Milton and M Farland. 1999 (price £50, code L)

TRL 216 *Road haunches: a guide to re-usable materials* by J F Potter. 1996 (price £35, code J)

VR1 *Foamix: Pilot scale trials and design considerations* by M E Nunn and N Thom. 2002 (price £40, code HX)

SR 675 *In-situ recycling of asphalt wearing courses in the UK* by G D Goodsall. 1981 (price £20)

LR1132 *The structural design of bituminous roads* by W D Powell, J F Potter, H C Mayhew and M E Nunn. 1984 (price £20, code A)

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