TRANSPORT RESEARCH LABORATORY

Design guide and specification for structural maintenance of highway pavements by cold in-situ recycling

Prepared for CSS, Colas Limited and the Pavement Engineering Group, Highways Agency

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Executive Summary

Recycling of existing pavement materials has become an increasingly important feature of the maintenance of highways in the UK. As a result of this, and in conjunction with efforts to rationalise standards for reinstatement, patching and of haunching (edge of carriageway strengthening), each of which promote the re-use of materials and cold in-situ recycling techniques, it was considered that nationally consistent guidelines for Highway Engineers for the wider use of recycling techniques in structural maintenance of highway pavements would be beneficial. In particular, guidance on the appropriate use of recycling, including binder selection and structural design of cold in-situ recycling, for the reconstruction of the structural course and/or the foundation platform of the pavement was required. This would promote the concept of the existing highway being a 'linear quarry' from which aggregates can be reclaimed.

Consequential environmental benefits are a reduction in the extraction of primary aggregates, a reduction in the use of energy, a reduction in the amount of construction traffic servicing maintenance sites, a reduction in traffic congestion from shorter duration roadworks and the sustainable development and improvement of the road network. The general public, central and local government and the transport industry are all beneficiaries.

This report describes research carried out under the *Linear Quarry Project*. The work was jointly sponsored by the Highways Agency, County Surveyors Society and Colas Limited. Guided by a Steering Group whose members were drawn from the Highways Agency, Local Highway Authorities, Colas Limited and TRL, the aims were to promote the use of cold in-situ recycling by providing evidence of acceptable in-service performance and to provide guidance on structural design and a draft specification. Pathfinder methods for the measurement of end-product performance are also included.

The report addresses three specific aspects of the research:

- measurement of the condition of medium to heavy trafficked roads recently recycled using cold in-situ techniques and the determination of their life expectancy compared with design traffic;
- construction of a road trial on the A3088 in Somerset to investigate the performance of both cement bound and foamed bitumen bound cold in-situ recycled materials; and
- the production of a structural design method for cold in-situ recycling, a specification and a method of performance assessment.

The report is divided into two parts. Part 1 comprises the Design Guide, which is supported by appendices that describe the research methodology and worked examples. Part 2 contains the Specification and Notes for Guidance on the Specification; the specification clauses are presented separately for cement bound material and bitumen bound material, so that they may be included in standard contract documentation.

The Design Guide contains information and advice relating to environmental considerations and site evaluation, which are necessary for the design for cold in-situ recycled materials and their use in structural maintenance of highway pavements. The design process includes flow charts, decision trees and methodologies for layer thickness determination on a graphical basis for use by designers. The many variables associated with recycling existing roads inevitably mean that there are a number of aspects to be carefully considered by the designer. The Guide provides a refined structural solution for those who give due consideration to all of the options but, at the same time, it has been kept relatively straightforward to use.

Appendix A, outlines the research carried out and presents the summarised findings of the monitoring of the performance of recently recycled materials on medium to heavily trafficked roads and of the road trials in Somerset. Appendix B contains worked examples which demonstrate how the proposed design processes may be applied.

The Specification and Notes for Guidance on the Specification for cold in-situ recycled material are presented as free standing sections; the separate specification clauses may be used unchanged or adapted for inclusion within the standard contract documentation for structural maintenance works. Furthermore, the possibility exists within the Specification to adopt non-destructive test methods to establish end-product performance of the in-situ recycled layer. By reference to the associated Notes for Guidance, the designer is able to make reasoned decisions relating to the site specific items of the specification contained in the respective Specification Appendices.

The information contained in this report offer the latest best practice advice on the design, supervision and construction of cold in-situ recycling works, used for structural maintenance of highway pavements. Whilst the previously used recipe and method specification was adequate for lower trafficked roads, end-product performance specification is seen as an appropriate means of specifying recycled materials in their own right, using performance criteria stated in terms of engineering properties, thereby allowing the recycled material to be considered for more heavily trafficked sites on an equitable basis to conventional materials.

As the process becomes more accepted and greater volumes of material are recycled, the design guidance given in this report may be subject to development in the light of the increased data available.

General introduction

Recycling of existing pavement materials has become an increasingly important feature in the UK for the maintenance of highways. The concept of using the existing highway as a 'linear quarry' from which roadstone aggregates can be reclaimed has been gaining favour for both environmental and economic reasons. Although plant and procedures for such techniques have been used in the UK for some time, there have been no nationally consistent guidelines on their use. This report gives advice on the appropriate use, binder selection and structural design of in-situ recycling, to reconstruct the foundation and/or structural course of road pavements.

In the context of structural maintenance of highway pavements, the term 'cold in-situ recycling' refers to the procedures using specialist plant to pulverise and stabilise existing road materials, in-place, at ambient temperature, with the addition of hydraulic cement and/or bitumen binders. For the purposes of this report and in line with common practice within the United Kingdom the bitumen binder referred to is foamed bitumen; in a world context however, bitumen emulsions are also frequently used. The hydraulic binders referred to are Portland cement or Portland blast furnace cement or Portland pulverised fuel ash cement.

Foamed bitumen is a bituminous binder produced by injecting cold water under controlled conditions, sometimes with certain additives, into hot penetration grade bitumen before application through specially designed nozzles on a spray bar. The foamed bitumen expands to 10 - 15 times the original volume of the penetration grade bitumen.

The cold, in-situ recycling technique is currently accepted and encouraged for lightly trafficked roads as a valuable alternative reconstruction method and is currently permitted for Highways Agency's roads up to a design traffic level of 5 million 8 tonne standard axles (msa). When used by a Local Highway Authority the design is usually based on advice from the specialist contractor and is often governed by the practical restraints of the site.

By setting out nationally consistent guide lines on the appropriate use of the recycling technique, binder selection and the structural design of the layer produced, this document seeks to encourage and extend the scope of cold in-situ recycling. Particular attention is paid to upgrading roads containing unbound granular and bitumen or cement bound roadbases by cold, in-situ recycling to produce flexible or flexible composite pavements for heavier traffic conditions than have previously been permitted.

In Part 1 of the report structural designs are given for pavements carrying cumulative traffic levels up to 20 msa. Guidance is also given on the design of the recycled mixture and the pavement assessment and construction operations necessary to build a satisfactory recycled pavement.

Part 2 of this report sets out Specification Clauses and associated Notes for Guidance for the construction of the pavement structural layer using cold in-situ recycling with cement and cold in-situ recycling with foamed bitumen. The specifications have been written with the aim of moving away from recipe/method requirements towards those of end-product performance, measured by in-situ non-destructive tests or by laboratory tests on core specimens extracted from the finished pavement. However, to ensure durability from the cold in-situ recycling techniques it has been found necessary to maintain some detailed method specification clauses.

The guidance given is based on the results of a three year research programme in which a review and detailed study of selected recycled in-service roads carrying medium to heavy traffic was complemented by a full scale, monitored trial on the A3088 Cartgate Link in Somerset. Both foamed bitumen and cement binders were considered.

A complementary report by Milton (1999) (the contents of which are summarised in Appendix A to this report) describes in more detail the investigative studies used to provide the data on which the guidance in this report is based; this and the other unpublished TRL reports cited are available, at cost, on direct personal application only, from the Transport Research Laboratory.

Part 1: Design guide

1 Introduction

The guidance and advice contained herein are based on a three year research programme reviewing the performance of in-service roads which had been maintained using cold in-situ recycling techniques and the construction and monitoring of two full-scale trials.

Particular attention has been paid to upgrading roads containing unbound granular and open textured roadbases by cold in-situ recycling, to produce flexible or flexible composite pavements for heavier traffic conditions than have previously been permitted. Design traffic levels routinely up to 10 million standard 8 tonne axles (msa) and where good quality aggregates exist in the road, to 20 msa or possibly more, have been addressed.

2 Environmental considerations

The use of cold, in-situ recycling can often be a practical, cost effective and environmentally beneficial alternative to using conventional materials. However, before using a recycled material it is necessary to assess the risk of early deterioration in relation to the potential benefits, particularly when viewed in terms of the current environmental and waste management issues that affect Highway Authorities.

2.1 Sustainable development

The 1992 Earth Summit in Rio De Janiero placed an obligation on the 150 governments attending to promote sustainable development to secure a viable future for our planet.

The objective and conclusion papers of the conference, issued as Agenda 21, set out how countries should work towards sustainability. This involves reducing the use of finite resources, increasing energy efficiency, minimising waste and protecting the natural world. Agenda 21 is having considerable effect on the way Highway Authorities now have to plan and implement their new construction and maintenance works. Details are given in the document Agenda for Change (1993).

2.1.1 UK strategy for sustainable development

> *'It is Government policy to encourage conservation and facilitate the use of reclaimed and marginal materials, wherever possible, to obtain environmental benefits and reduce the pressures on sources of natural aggregates'*. (Williams, 1995).

Related to highways, the suggested way forward is through broadening the specifications and increasing the technical scope for using by-product and recycled materials in road pavements. However, these changes should follow research into the technical feasibility and relative performance of these alternative materials. The introduction of the Landfill Levy for demolition and waste construction materials should encourage more recycling of these materials.

2.1.2 Minerals planning guidance

The Department of the Environment publication MPG6 (1994), Minerals Planning Guidance for Aggregate Provision sets out four objectives for sustainable development in relation to minerals planning. The first two are:

- to conserve minerals as far as possible, whilst ensuring an adequate supply to meet the needs of society;
- to minimise production of waste and to encourage efficient use of materials including appropriate use of high quality materials and recycling of wastes.

Therefore, in the likelihood that 'traditional' aggregate sources will become increasingly constrained, alternative sources must be considered and developed, including the greater use of secondary aggregates. Recent research indicates that secondary aggregates account for about 10 per cent of aggregate consumption in the UK at present. MPG6 envisages this rising to 12 per cent by 2006, comprising a total of some 5.2 million tonnes per annum.

MPG6 stresses the need to use all aggregate efficiently by minimising wastage and avoiding the use of higher grade material if lower grade will suffice. Whilst specifications for construction materials must have an adequate margin of safety, over-specification tends to occur and materials are used, often with performance characteristics higher than required for the purpose. The reasons for this stem from the relatively low cost of primary aggregate and the perceived lower risk element using virgin materials.

2.2 Waste management

2.2.1 Environmental Protection Act 1990

The Environment Protection Act (1990) introduces strict controls over waste management activities for the protection of health and the environment. It also encourages the minimisation, reuse and recycling of waste and exempts from licensing control a significant range of wastes and activities where genuine recycling takes place.

2.2.2 Regulations

The Waste Management Licensing Regulations (1994) extend and amend the provisions of Part 2 of the Environmental Protection Act 1990, taking account of European directives.

Deciding whether a substance is waste or not under these terms is not a simple matter. In order to be a waste substance or object, it must fall under one of the categories set out in Part 2 of schedule 4 of the Regulations and be discarded, be intended to be discarded or be required to be discarded (being incapable of further use in their present form).

Therefore, there are substances generated by Highway Authorities and/or their contractors, which are a waste and others that are not. For what constitutes a waste reference should be made to the regulations and to the associated circular for guidance on this matter. Next, if it is a waste, then a range of exemptions may apply. Such exemptions include:

- manufacture of roadstone or aggregate from waste which arises from demolition and construction works and the storage of these wastes at the place where the activity is to be carried out provided that the total amount treated at that place does not exceed 100 tonnes and the total quantity of waste stored does not exceed 50,000 tonnes in the case of roadstone from road planings and in any other case 20,000 tonnes (exemption number 13);
- the storage in a secure place on any premises of waste articles (eg. aggregate, kerb stones) which are to be used for construction work which are capable of being used in their existing state - maximum quantity 100 tonnes for a maximum 12 months (exemption number 17);
- the storage on a site of waste which arises from demolition and construction provided it is suitable for relevant work which will be carried on at that site, or if it is not produced on the site, it must be used within three months of deposit (exemption number 19).

In the case of asphalt planings, up to 50,000 tonnes can be stored for up to three months.

There is an over-riding requirement that any activity should be carried out in such a manner as not to cause pollution of the environment or harm to human health and the operator must comply with the Waste Management Duty of Care (1991).

3 Cold in-situ recycling

3.1 Applications

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.

The technique is applicable to all classes of road, at this stage with designs routinely applicable to traffic levels up to 10msa and in circumstances where thick layers of good quality aggregates are known to exist in the road, to 20msa or possibly more.

Cold in-situ recycling can involve the following types of pavement, binder system and pavement layers:

Pavement types:	- flexible
	- flexible composite
Binder systems:	- portland cement
	- lime
	- emulsion bitumen (+ lime/cement)*
	- foamed bitumen (+ lime/cement)
Pavement layers:	- sub-base (foundation course)
	- roadbase (structural course)
	- combination of the two

Subject to the nature of the existing road foundation materials and the ability to stabilise these materials, the repair of the structural layers of a road pavement by recycling is an opportune time to improve the overall structural life of the pavement by increasing its effective thickness and structural life capability to avoid major maintenance for the next 20 to 40 years. Wherever possible, the recycling alternative should make maximum use of the existing construction materials and thus, minimise imported material products.

3.2 Current specifications

In-situ recycling processes, typically, produce the Structural Course (also known as the roadbase) and the foundation platform (also known as the sub-base) in one operation. Therefore the conventional specifications for these two pavement layers are frequently not applicable to the in-situ recycling technique. However, current specifications and design manuals do address the process in the terms of conventional terminology and their contents are summarised as follows.

3.2.1 Sub-base materials

Cold in-situ recycling is currently considered appropriate for cemented sub-bases as CBM1 for flexible pavements and CBM2 for flexible and flexible composite pavements (DMRB (HD 25/94); MCHW 1). For any design traffic level; any reclaimed surfacing, roadbase, sub-base or capping material could provide 100 per cent of the aggregate for a new CBM1 or CBM2 sub-base produced by in-situ pulverisation and mixing.

3.2.2 Roadbase materials

Cold in-situ recycling is currently considered appropriate for foamed bitumen bound roadbases for flexible pavements (DMRB (HD35/95) (HD31/94); MCHW1). For traffic levels up to 5 msa; any reclaimed surfacing, roadbase, sub-base or capping material could provide 100 per cent of the aggregate.

For flexible composite reconstruction the minimum seven day compressive strength requirement for the cement bound roadbase is 10 N/mm^2. The MCHW1 specifies that such material be plant mixed and therefore the technique of in-situ recycling is precluded for these pavement types.

3.3 Implementation procedure

The life cycle and deterioration of the foundation platform and/or structural course of a highway pavement usually occurs over an extended period, during which time the structure of the overlying pavement may be reconstructed and/or overlaid using an assortment of techniques; leaving in place a variety and mixture of materials.

** For the purposes of this report and in line with common practice within the United Kingdom the bitumen binder referred to is foamed bitumen, however in a world context bitumen emulsions are also frequently used.*

Furthermore, the foundation platform and structural layers are often composed of materials of outdated specification comprising unbound granular and open textured bituminous materials. Therefore, prior to recycling work, it is vitally important that the site is evaluated to identify the nature and consistency of the materials present in the layers provisionally selected for recycling. Guidance on the evaluation of the site, including assessment of the reclaimed materials, is given in Section 4.

Environmental issues referred to in Section 2 must also be addressed, and any wastes or potential wastes identified and classified for either storage or disposal. In appropriate cases, the presumption would be to obtain an exemption from the regulations to store the reclaimed materials, if the materials were likely to be suitable for recycling. Guidance should be sought from the local Waste Regulation Authority to verify the 'waste definition' related to particular materials.

The next stage is to evaluate the structural design options in relation to the nature of the reclaimed material and different materials that may be manufactured from these reclaimed materials by recycling.

The structural design thicknesses for materials produced by cold in-situ recycling have been developed by building on recent experience gained by the UK recycling industry and by reference to design procedures used in other countries. Ideally, the subgrade reaction to traffic loading, design traffic level, speed of traffic and the characteristic strength properties of the recycled materials, should all be taken into account in the design procedure. However, their particular influence is not always clear.

It is recognised that the use of in-situ recycling techniques will necessitate additional site and material assessments to minimise risk and that greater effort for checking specification compliance is likely to be beneficial in maintaining the standard of the end product. However, the extra investigational work and testing, must be balanced against the potential financial savings associated with re-using materials as well as the environmental benefits.

4 Site evaluation

4.1 Identification of sites for structural maintenance

The reasons for first assessing that a road pavement is in need of structural maintenance may be various, from simple visual inspection to advanced deflection measurement surveys. Although a great deal of useful information may already be provided by these surveys, irrespective of the remedial strategy ultimately decided, sites should be identified for maintenance in terms of:

- Location;
- Length of deterioration;
- Width of deterioration;
- Type and severity of deterioration;
- Condition of drainage; and
- Edge detail and verge condition.

In the event that the deterioration is identified as being a failure of 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 [Published Article PA/SCR243, TRL, 1994].

Practical Guide to Haunching [County Surveyor's Society, Report ENG/1/9, 1991].

Road Haunches: A Guide to Re-useable Materials [TRL Report TRL216, 1996].

If the deterioration is identified as being a structural failure of the road in the running lane(s), then the issues raised in Flow Chart A should all be addressed, to decide whether the site is suitable for structural maintenance using the cold in-situ recycling process. To answer these questions, the site evaluation should be organised and implemented as described below.

4.2 Investigation of existing pavement construction

4.2.1 General considerations

In keeping with the environmental objectives, each site should be investigated with a view to determine the suitability of the existing materials for re-use; either as reclaimed raw materials for re-use elsewhere or for in-situ recycling. Therefore a thorough assessment should be made of the existing pavement materials, either separately or as a mixture, to determine whether or not, all or part of the reclaimed product is acceptable for re-use.

The investigation methods and techniques described in HD 30/97 (DMRB 7) may be used as the basis of the detailed assessment. However, the site work and laboratory testing will need to be adapted to suit the recycling process and related to the particular site conditions. Previous experience has shown that a properly conducted site evaluation for cold in-situ recycling, followed by the laboratory design process and enhanced quality control testing during the works, is essential if a well engineered solution is to be completed.

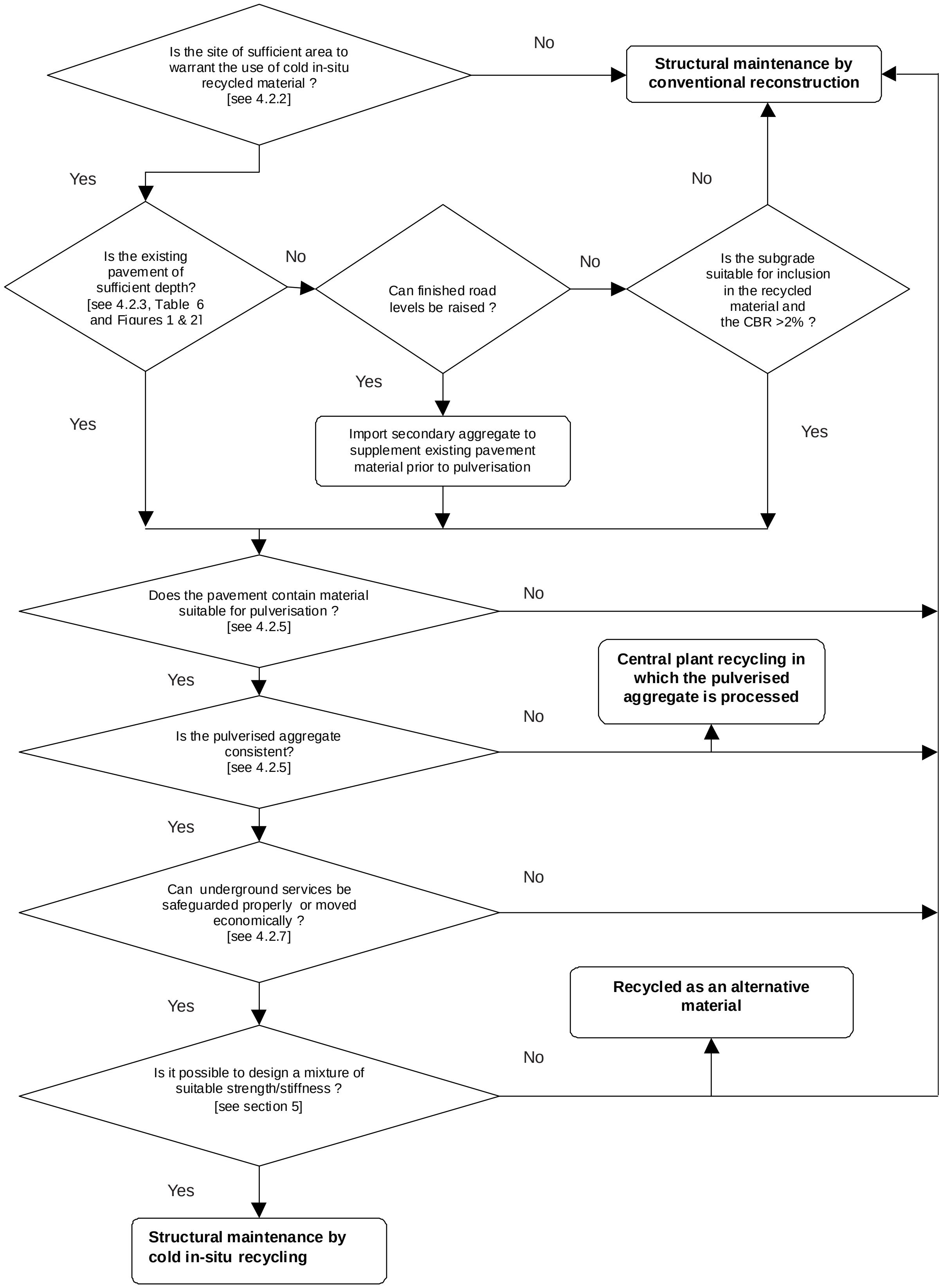
4.2.2 Job size

The recycling of a road pavement necessitates the use of a substantial amount of plant and equipment unique to such works, which involves significant mobilisation costs. Therefore, in order to achieve the economies of scale offered by this process, it is desirable that each job size is above a suitable minimum area or can be combined with similar works in the nearby district. A minimum programme of work in the order of 3,000m^2 is offered as a reasonable guide, but in particular circumstances, where conventional methods of reconstruction are onerous or precluded, smaller scale recycling works may still offer an alternative cost effective solution.

4.2.3 Depth of existing pavement

The use of the cold in-situ recycling process will also normally depend on whether there is sufficient thickness of existing pavement to accommodate the designed thickness

Flow Chart A: Site Evaluation



of the reconstructed structural course, with remaining underlying material to act as a suitable foundation.

Although, in situations where the depth of the existing pavement is insufficient to accommodate the new pavement design and the finished level cannot be raised, it may be possible to include the existing subgrade into the recycled material, in which case, the pulverised mixture may contain cohesive fines that require additional modification prior to stabilisation. Alternatively, if the finished levels can be raised, the required pavement thickness may be achieved using imported secondary aggregate material.

4.2.4 Investigation framework

The fieldwork needed to achieve a reasonable level of confidence will depend on the specific site conditions, but in general, trial pits excavated at a frequency of not less than 1 per 500 m^2 should suffice. However, particular attention should be paid to unsupported edge conditions and areas where previous reinstatements have been made, since these are likely to contain variable materials, possibly of poor quality, including contamination by subgrade soils which may be cohesive in nature. In these situations, the location and frequency of trial pits should be decided on site and/or intermediate cores extracted, of sufficient size and number, to determine the full extent and nature of the various material conditions.

Trial pits must be of sufficient size and depth to provide a clear view of the consistency and thickness of the various construction materials. Also, to allow extraction of adequate representative material for laboratory testing to determine factors such as:

- Atterberg limits, natural moisture content and CBR of the subgrade;
- thickness and nature of the various pavement and foundation layers;
- grading of the pulverised aggregates available as raw materials for the recycled mixture, and
- compressive strength of lean concrete bases if suspected of being too strong for planing or pulverisation. (i.e. compressive strength greater than 15 N/mm^2.)

Guidance for the site investigation requirements for cold recycling projects on medium to heavily trafficked sites are given in Table 1. Whereas a similar logic exists for investigation of lower trafficked sites, in practice the rate of sampling and testing for these roads may be substantially less, to reflect the relative importance and value of the works involved.

4.2.5 Suitability and consistency of existing materials

Where available, as-constructed records are always useful, but it is important to carry out sufficient cores or trial pits to check these data, since the actual as-constructed situation does not always reflect in detail, what was recorded or any subsequent changes that may have taken place since.

Modern designed pavements are normally consistent and contain only a small number of standard materials. For older pavements, however, that have been built up and altered over many years, construction details are mostly unknown and often exhibit significant changes within short distances. In these cases the site assessment and recycling design process is particularly difficult, since a separate mixture design is required for these areas defined both by plan areas and depth. However, dependent of traffic loading, a judgement needs to be made of the importance of such detailed design, particularly for traffic loading below 2.5msa (Type 3 and 4 roads).

Non-destructive testing of the existing pavement by such techniques as deflection testing, visual assessment and the use of ground penetrating radar are recommended, in conjunction with the cores and trial pits, to determine the consistency of the pavement layers throughout the site. Ground radar, may be particularly useful in indicating changes in construction layer thicknesses and the location of density and moisture content anomalies.

In the event that the existing pavement materials are recognised in general to be re-usable as a pulverised aggregate but too inconsistent to allow any reasonable design, section by section, consideration may be given to the alternative recycling process using plant mixed material. In this process the opportunity is available to clean and process the existing variable materials in to a reconstituted well graded aggregate (Table 1).

4.2.6 Preparation of representative test specimens

For any assessment related to the design of recycling works, it is particularly important that any sample obtained is fully representative of the pavement to be recycled. 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. However, since actual

pulverised aggregate is not generally available during the pre-contract investigation, the design process must rely on test specimens derived from samples crushed in the laboratory. A variety of laboratory crushing methods are currently available, however, none are believed to be specifically designed to recreate the pulverised aggregate produced by a recycler or planer.

Modern pulverisers and planers, however, tend to produce aggregates of finer grading

when compared with pulverised material from older machines, related to the power and effectiveness of the milling process. Therefore, separate guidance from the plant manufacturer may be necessary.

4.2.7 Underground services

Because of their disruptive potential within in-situ recycling works, particularly if disturbed or damaged, it is vital to accurately locate and record the depth of all underground services. If a pipe or cable lies within 150mm 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. Although, additional enquiries and investigation

Table 1 Guidance on site investigation requirements for cold in-situ recycling projects on medium to heavily trafficked sites

Pavement type/condition	*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 200m 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 200mm diameter core from each distinct reinstatement/repair that has an area greater than $25m^2$ or extends full width for more than 5m in any lane. Plus minimum of one full-depth 200mm 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 200mm diameter cores at target frequency of 1 per 100m 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 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 200mm 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.

will probably be needed to establish the location and depth of service connections to adjacent properties, since 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.

4.3 Risk assessment

The use of recycling techniques uniquely involves a number of risks which should be assessed prior to implementing any work. These risks are often difficult to quantify in terms of any standard measure, but their consideration and equitable allocation may provide the best chance for improved design and supervision techniques.

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 recycling works, such situations are more likely to play a part in the final outcome, since the materials present are intended to form part of the finished works. Furthermore, for cold in-situ recycling, the potential for variability of materials to be included in the works can be higher.

To offset this risk, greater understanding of shared risk should be accepted, where both parties to the contract are given the opportunity to satisfy themselves and agree that the existing pavement materials in the sections of the works defined by the contract, are capable of being recycled by pulverisation to form the primary aggregate component of the new in-situ recycled mixture. Also, that the recycled mixture is capable of being designed and produced to meet the specified end-product performance requirements.

However, for the purposes of competitive tender arrangements, the Client is normally expected to organise and implement the site investigation works separately, as part of the general design process. 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 also need to be assessed in the light of likely life cycle costs. In which case, 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 and construction risks.

4.3.1 Design risks

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 of moisture, density and strength of the subgrade where these properties need to be taken account in the design process.

The fatigue life of cemented pavements is very sensitive to thickness and stiffness. It is imperative that the pavement thickness design and material parameters are achieved in construction otherwise substantial reductions in performance may occur. Also, the type of binder will affect the workability and setting time which is important in being able to achieve the required layer density.

The foamed bitumen or cement content will also influence the stiffness and strength of the recycled mixture. An inadequate quantity may lead to the material being susceptible to moisture, whereas too much bitumen could lead to premature deformation problems or too much cement to increased likelihood of thermal cracking.

4.3.2 Construction risks

Because the recycling process is generally much quicker than conventional reconstruction techniques, there is a corresponding reduced risk as a result of exposure of the lower pavement layers to inclement weather and traffic during construction.

One of the most critical parts of the construction procedure is the compaction of the recycled material. Any delay after mixing 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 stiffness.

In urban situations, the risk of causing nuisance and possible risk to health by dust must be assessed when recycling by pulverisation. In addition, the effects from the use of the pulveriser 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.

5 Design of cold in-situ recycled material

5.1 Pulverised aggregate

The nature and grading of the aggregate produced by pulverisation using any of the recycling machines currently available, will depend largely on the nature, thickness and proportions of the existing road material to be recycled. Although, in situations where the depth of the existing pavement is insufficient to accommodate the new pavement design and the finished level cannot be raised, it may be necessary to include subgrade material into the recycled structural layer, in which case, the pulverised mixture may contain a cohesive soil component that requires modification using lime or cement prior to stabilisation. Alternatively, if the finished levels can be raised, the required pavement thickness may be achieved using imported aggregate, which could also be derived from other recycling works in the locality.

5.1.1 Grading

Ideally, the particle size distribution of the pulverised aggregate, immediately prior to stabilisation, including any supplementary aggregate and/or filler, should be equivalent to a uniformly graded aggregate of 50mm nominal size, complying with the Zone A grading envelope described in Table 2. However, in a recycled aggregate there is the likelihood that a significant proportion of particles are broken pieces of the original material, comprising a conglomerate of aggregate and old binder.

In certain circumstances, pulverised aggregate falling within Zone B grading envelope may be acceptable, provided the results of mixture design tests demonstrate that an acceptable recycled material can be produced consistently using this aggregate.

For cement bound recycled material, the aggregate component may consist of reclaimed aggregate made from 100 per cent of bituminous surfacing, roadbase, sub-base, capping or subgrade material. Normally, the cement bound recycling option is relatively insensitive to the aggregate grading, nevertheless there is a recommended upper limit of 35 per cent passing the 75 micron BS sieve.

Table 2 Particle size distribution of granular material for cold in-situ recycling

	Percentage by mass passing	
Sieve size (mm)	*Zone A*	*Zone B*
50	100	–
37.5	94 - 100	–
20	66 - 100	100
10	48 - 75	75 - 100
5	35 - 57	57 - 95
2.36	25 - 42	42 - 77
0.6	13 - 28	28 - 52
0.3	10 - 24	24 - 45
0.075	5 - 20	20 - 35

i *Zone A material - ideal material.*

ii *Zone B material - suitability of material from this zone is subject to the results of material performance tests on trial mixtures.*

iii *Granular material to be stabilised should contain not more than 2% of organic matter determined in accordance with BS 1377: Part 3: Clause 3.*

iv *Aggregate grading should have a coefficient of uniformity [C^u] exceeding 10.*

In comparison, bitumen bound recycled material is often highly sensitive to the pulverised aggregate grading, particularly the fines component. In recycled mixtures the bitumen has a tendency to mix and conglomerate with the fines while only partially coating the coarse aggregate component. As a result, it has been found that the amount passing the 75 micron BS sieve should ideally, be restricted to the range of not less than 5 per cent and not more than 20 per cent, none of which should be clay.

Finer material may be tolerated, provided any clay fraction is modified by treatment with lime or cement to form a non-cohesive component. This pre-treatment would normally be required if the percentage of pulverised aggregate passing the 75 micron BS sieve was greater than 20 per cent and the Plasticity Index of the material passing the 425 micron BS sieve was greater than 6. Conversely, any material that is too coarse may be modified to meet the desired grading, by augmenting the finer material using either pit sand or PFA as a filler.

5.1.2 Moisture content

The moisture content of the pulverised aggregate prior to stabilisation is equally important as grading, since it is of primary importance in controlling the workability of the mixture and therefore, governs the degree of compaction that may be achieved. The optimum moisture content would normally be considered as the target moisture content, but in practice for recycled mixtures, the specified moisture content depends to a certain extent, on the binder used and whether a filler has been added in any great quantity.

For cement bound mixtures, experience has shown that the best results are obtained by targeting a moisture content in the range 0% to +4% of optimum moisture content determined in accordance with BS 1924: Part 2: 1990. As expected, this achieves a workability higher than would normally expected for conventional CBM, but is required if thick-lift, full-depth compaction is to be achieved. However, enhancement of the density may be countered by a lower compressive strength resulting from the changed water/ cement ratio. In those cases where only small proportions of filler are mixed with the pulverised aggregate, the optimum moisture content of the pulverised aggregate will normally suffice as the control datum, since the moisture absorbed by filler is mostly balanced by the suppression of the optimum value. Where the addition of filler accounts for more than 4 per cent by mass, the moisture control datum should be based on the optimum moisture content of the pulverised aggregate including the filler.

For the pulverised aggregate stabilised using foamed bitumen binder, the ‘fluid’ component of the binder will enhance the workability of the mixture and aid the thick lift compaction of the material. Therefore, a target moisture content in the range ±2% of optimum moisture content, determined in accordance with BS 1924: Part 2: 1990, is considered appropriate to achieve adequate thick-lift, full-depth compaction. Also, where more than 4 per cent by mass of adhesion agent and/or filler are added to the pulverised aggregate, the optimum moisture content should be determined using the modified aggregate.

Where the moisture content prior to stabilisation fails to meet the target range, the moisture content should be adjusted either by aeration to reduce the moisture content or by controlled addition of water, if the moisture content is lower than required. For the cement bound material, any controlled addition of water may be carried out at the same time as the stabilisation pass of the recycling machine, but in these circumstances a greater degree of care and control are needed to ensure that the single pass operation is completed without mistake.

5.2 Primary binder agent

The majority of the cold in-situ recycling works completed nationally have used hydrated lime or Portland cement as the primary binder agent. More recently, because of the particular health and safety issues assigned to the use of lime and the problem of thermal cracking in the stronger cement bound structural layers, a variety of alternative binder agents have been used, including bitumen emulsion, foamed bitumen and slow curing hydraulic binders.

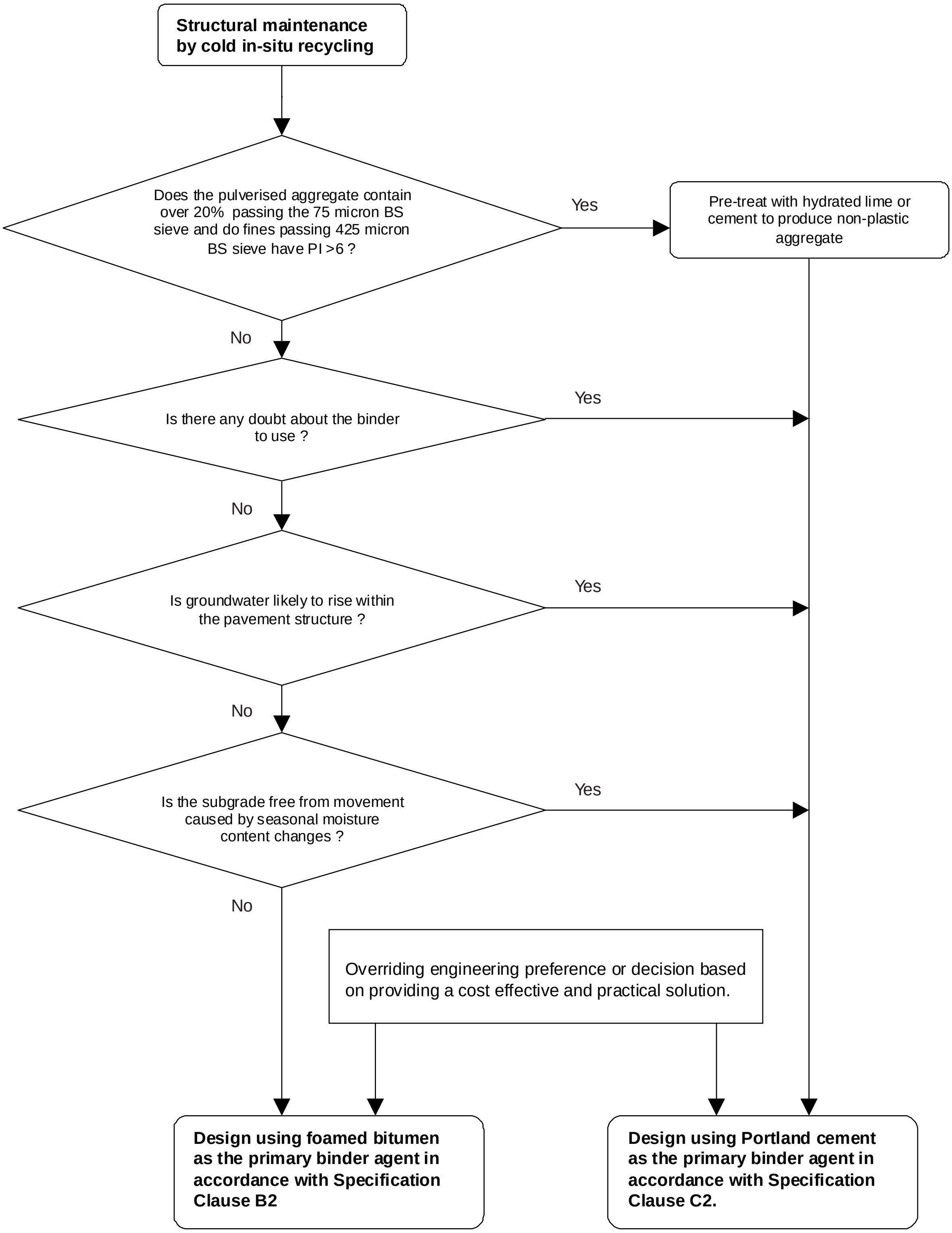
However, for the purpose of this guidance document related to UK conditions, only foamed bitumen or Portland cement are recommended for use as the primary binder agent. The process of selection between these binders is outlined in Flow Chart B.

5.2.1 Portland cement

Portland cement as a binder for in-situ recycling works to produce a flexible composite pavement structure, is adaptable to most conditions and apart from the thermal cracking of stronger mixes, it has the following advantages:

- readily available at reasonable cost;
- current accepted methods of working to satisfy H&S requirements;
- is generally suitable for mixing with a wide range of pulverised aggregates comprising existing pavement materials;

Flow Chart B: Primary Binder Agent Selection



- tolerant of adverse wet weather (often the case in the UK);
- tolerant of contamination by plastic fines and organic material; and
- may be used, based on the Highways Agency Specification for Highway Works (MCHW1) clauses for either cement stabilised or cement bound materials and the standard design criteria for these materials.

5.2.2 Foamed bitumen

Foamed bitumen as a binder for in-situ recycling works to produce a flexible pavement structure, is adaptable to a wide range of situations, although if there are any doubts that foamed bitumen may not perform satisfactorily, cement is likely to offer a safer option where adverse conditions exist. However, foamed bitumen binder offers the following advantages:

- significant energy savings compared with conventional hot-mix materials;
- is generally suitable for mixing with a wide range of pulverised aggregates comprising existing pavement materials;
- same day construction cycle to completion, with no extended curing period;
- less susceptible to moisture content than bitumen emulsion; and
- can be stockpiled, relocated and reworked if necessary in their early life.

The original method of producing foamed bitumen involved the expansion of a paving grade bitumen into a foam by the injection of saturated steam. But to provide a more controlled expansion and increased bubble life, a patented system was developed involving the injection of between 1 and 2 percent cold water under controlled conditions and with air and foaming agents into a hot penetration grade bitumen stream, through specially designed nozzles and spraybar (Lee, 1980).

An increase in the bitumen foaming temperature or the water content has the effect of increasing the expansion ratio but decreasing the life of the foam bubbles. To provide the best combination for useful application, a compromise between expansion ratio and life of the foam bubbles is required.

It is possible to use penetration grade bitumen from grade 40 to over 200 as the base bitumen for foaming. Higher penetration grades tend to foam better, but the lower grades produce material of higher stiffness. On balance, the foamed bitumen recommended for cold in-situ recycling is based on penetration grade 100, as the binder that achieves the highest stiffness, consistent with a reasonable coating ability.

The significant properties of the foamed bitumen are:

- low apparent viscosity;
- ten fold increase in volume over volume of hot liquid bitumen; and
- lower surface or interfacial tension.

It is these properties that enable the bitumen to coat moist, cold aggregate surfaces, particularly the fine aggregate portion. The resultant mixture is easily worked cold and can be readily compacted with conventional roller compaction plant. The process does not require the evaporation of a solvent or excess water prior to compaction and the material can be reworked if necessary up to about 48 hours after processing.

The curing regime of foamed bitumen mixtures is critical for long term success since these materials rely much upon early life strength for ongoing development of stiffness properties. However, provided that the density achieved is at least 95 per cent refusal density, opening to traffic can be achieved in a one day construction cycle.

5.3 Prelimary mix appraisal and design process

The design procedures adopted to date, have been developed by various organisations for their own local needs, although in general, most design processes for in-situ recycled material are based on the determination of compressive strength for cement bound material or the stiffness modulus for bitumen bound material, for a recycled layer of specified thickness, to carry a required traffic loading over a period of time.

In practice, since the material to be stabilised does not exist until after the pulverisation process, the initial mix appraisal or design process often becomes a matter of experience by the specialist contractors using their particular pulverisation/stabilisation plant, to gain an understanding of the near optimum component design.

Also, since the results of strength, stiffness and other tests performed on laboratory prepared specimens are highly dependent on the curing regime of the specimens, which is unlikely to be recreated on site, these tests are valid only for comparison and assessment of the optimum mixture condition. The values obtained do not necessarily relate to the in-situ condition of the material.

Furthermore, where the site evaluation has identified significant and discrete variation of existing pavement materials between different sections of the site, each section should be subject to a separate mixture design.

Details of the procedures to carry out a preliminary mix appraisal and design, for both cement bound and foamed bitumen bound materials are given in the relevant specifications in Part 2 of this report. At this stage, these requirements are based on the current industry practices, but are open to development if more representative specimens and test results can be verified.

For the preliminary mix appraisal, the source material is obtained from bulk representative samples extracted from the road during the site evaluation. Each appraisal will require at least 100kg of proportionally representative source material.

Each aggregate sample is crushed and processed in the laboratory to produce a ‘pulverised aggregate’ test specimen having a particle size distribution curve meeting the Zone A or Zone B grading as described in Table 2. There are currently a variety of laboratory crushing methods used, including the simple mechanical vibratory hammer approach. However, no crushing system has been specifically designed to recreate the pulverised aggregate produced by the recycling machine or planer. Therefore, where it is found difficult to achieve sufficient crushing of the recycled aggregate sample in the laboratory, to obtain sufficient fine material, (which is often the case where the existing road materials contain HRA), a suitable quantity of fine material, either crushed rock fines, pit sand or PFA, may be added and thoroughly mixed with the crushed material, to obtain the required grading. The finer grading should not be achieved by excessive laboratory crushing, since this would not reflect pulverisation in the field, which tends not to cause breakage of the existing aggregate component.

Ideally, the optimum moisture content of the pulverised and mixed aggregate is determined in accordance with BS 1924: Part 2: 1990. In the laboratory trial mixtures, sufficient water should be added to target the optimum moisture content, with appropriate allowance made for any change to the optimum condition caused by additives to the mixture. If lime is required for stabilisation and/or modification of any plastic soil component within the mix, the correct proportions of soil and lime should be included in the trial mixture.

5.3.1 Cement bound recycled materials

For lower traffic situations, cold in-situ cement bound recycling is often used to provide a new foundation and/or structural course which would be designed to have an average 7 day cube compressive strength of 4.5 N/mm^2 or 7 N/mm^2 (i.e either CBM1 or CBM2 equivalent). In normal circumstances, this recycled layer would then be overlain by surface dressing or plant mixed bitumen bound materials to form a new pavement at a higher level.

For higher traffic loading, used as the main structural course, the recycled layer would normally be designed to have an average 7 day cube compressive strength of 10 N/mm^2 (i.e CBM3 equivalent). In theory, this could be considered structurally equivalent to plant mixed CBM of equal compressive strength. In practice, however, the in-situ recycling process is subject to potential problems and increased risks that are less applicable to the plant mixed option, including:

- variability of aggregate grading;
- non-uniformity of distribution and mixing of binding agent;
- variability of moisture content, often dependent on weather;
- variability of recycled thickness; and
- difficult compaction at bottom of thick lift construction.

In consequence, the design thickness used for earlier recycling works in the UK was based on a factor of safety of 25 per cent applied to the design thickness for equivalent plant mixed material (Walsh 1988). Later works tended to use a factor of 20 per cent, including the design of phase 2 of the A3088 Cartgate Link road trial.

For the stronger recycled structural course mixtures, the potential for thermal cracking and reflective cracking of the bituminous surfacing, is the same as that for conventional plant mixed CBM. To restrict or overcome this problem, consideration could be given to the process of inducing transverse cracks in the structural course prior to laying the surfacing materials.

The cement contents used to manufacture the sets of test specimens should normally be similar to the plant mixed equivalent, except in the case of in-situ recycled mixtures where a minimum cement content of 3 per cent by weight is recommended. This absolute minimum value is applied to ensure there is adequate cement available for distribution throughout the mixture during the relatively short period of in-situ mixing. Subject to this minimum value, the designed cement content will normally be the minimum cement content that achieves the required average compressive strength.

To ensure durability of the material in the presence of adverse groundwater conditions, the average compressive strength determined after 7 days immersion in water of five test specimens of the target composition mixture, should not be less than 80 per cent of the average compressive strength of five control specimens when subjected to the test procedure described in BS 1924: Part 2: 1990, clause 4.3. Furthermore, after the 7 days immersion the test specimens should show no signs of cracking of swelling.

5.3.2 Bitumen bound recycled materials

Irrespective of how well the in-situ recycling of foamed bitumen bound material is carried out, the nature and variability of the materials which are the feedstock of the recycling process, will result in the recycled mixture having a stiffness equivalence factor of less than unity, when compared to conventional plant produced materials. Performance assessment of some of the earlier recycled pavements, using either the Deflectograph or Falling Weight Deflectometer, have indicated that the typical stiffness equivalence factor for recycled foamed bitumen bound roadbase is in the order of 0.7 to 0.75, when compared with dense bitumen macadam (DBM) containing penetration grade 100 bitumen.

A mixture design based on binder film thickness would be inappropriate for a recycled material, since the distribution and coating characteristic of the foamed bitumen is significantly different to that of the plant hot-mix. In general, the larger particles remain substantially uncoated with the bitumen adhering mostly to the finer particles, forming a fines/bitumen mortar matrix. The design principle for such material is to waterproof the fines and provide enough adhesion within the matrix to hold the material together and at the same time, to achieve efficient aggregate packing for low air voids content.

The optimum added foamed bitumen content of recycled mixtures is often not very well defined, and adequate stiffness may be obtained over a wide range of bitumen contents. Hence the specification of added bitumen content is not so critical and for earlier recycling works in the UK, a typical binder content range for either penetration grade 100 or 200 bitumen was 3.5% ± 0.75%.

This target range appeared to achieve near optimum stiffness conditions for the pulverised aggregate from a range of typical UK roads in need of rehabilitation. However, in response to concerns about durability of the recycled material, related mainly to the partially coated nature of the course aggregate, an absolute minimum added bitumen content of 3.5% is recommended.

Existing bitumen in pulverised aggregate would not normally be activated in the stabilisation process in the sense of mixing with the new binder, although the effect of the residual bitumen in the finished mixture may influence the stiffness achieved.

In the mix appraisal and design process, the laboratory prepared aggregate is thoroughly mixed with measured proportions of the appropriate foamed bitumen binder and any adhesion agent, to produce trial mixtures of different bitumen content. The type and grade of the bitumen used in the trial mixture should be the same as that intended for the finished works.

To date there are no specified means for producing laboratory manufactured foamed bitumen, particularly since there are a variety of methods that may be used in the field. Therefore, it is recommended that the anticipated bitumen supplier is consulted, in conjunction with the manufacturer of any foaming agent used, in an attempt to replicate as closely as possible, the characteristics of the foamed bitumen to be used, particularly in terms of the size and sustainability of the air bubbles during mixing.

At least four 150mm diameter x 75mm to 100mm high, cylinder test specimens (briquette specimens) should be produced for each of the trial mixtures, compacted to refusal by vibratory compaction in a cylindrical metal mould, using the compaction mould assembly and vibrating hammer described in BS598: Part 104.

Also, because of the relatively small size of the cylinder test specimens, great care is required in ensuring a uniform distribution of the courser aggregate particles within the test sample, with particular concern that the perimeter of the cylinder does not contain segregated aggregate, leading to a voided load contact area in the test rig.

Regarding the specified curing programme for the specimens prior to testing, including baking of the specimens for 72 hours at 60^0C, this is not an attempt to represent the curing conditions in the field, but is a standardised attempt to model the longer term ageing process of the recycled material. The drawback of using the baking technique is that it can disguise the true early life stiffness of the recycled material, in favour of a higher set of values that may be appropriate in the longer term.

6 Pavement design

6.1 Definitions

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

Subgrade: Underlying natural soil or rock.

But 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.

Foundation platform: A layer which protects the subgrade and provides a consistent stable platform upon which the structural course can be adequately compacted.

This layer will normally comprise the undisturbed lower sections of the existing pavement. But in situations where there is insufficient depth of existing pavement to satisfy the current design, this platform may be constructed in part or whole, using cold in-situ recycling.

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 traffic loading.

This layer will normally comprise cold in-situ 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.

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.

6.2 Road categories

As a starting point in any design, it is necessary to determine the category of the road to be recycled. This depends on the amount of commercial traffic to be carried in one lane, or one direction, over a 20 year design life. The categories are given in Table 3 and are the same as those specified for the HAUC specification for reinstatement of openings in highways (1992).

Table 3 Road type categories

Road type category	*Traffic design standard (msa)*
1	More than 10 up to 30*
2	More than 2.5 up to 10
3	More than 0.5 up to 2.5
4	Up to 0.5

** The research to date for in-situ recycling has been for traffic levels up to 20 msa; engineering judgement must be used to increase design traffic loading.*

Guidance on how to assess the traffic levels is given in TRL Report TRL216 (Potter, 1996)

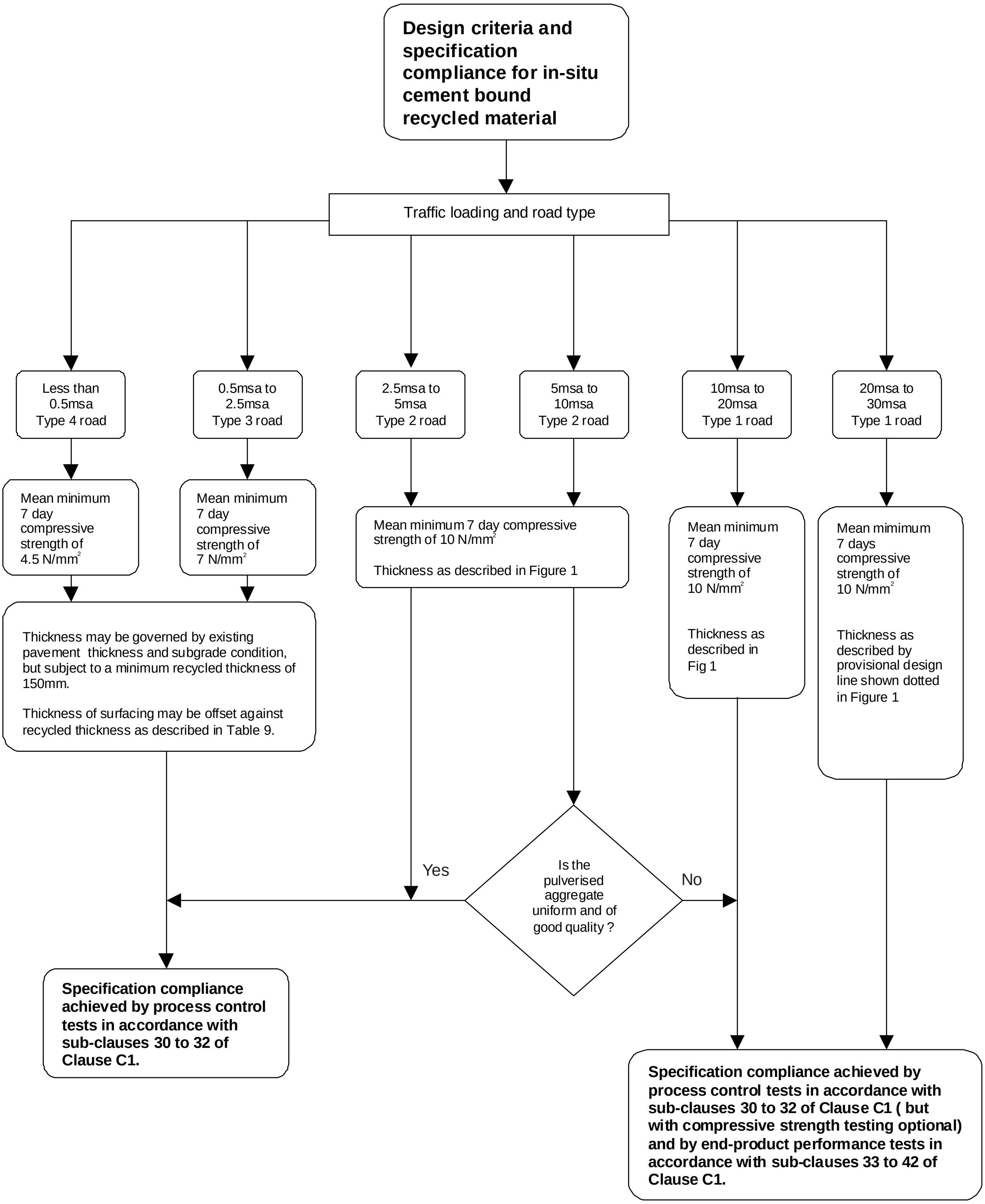
In addition the design criteria and specification compliance programmes for the different traffic loadings are as described in Flow Chart C for cement bound recycled material and Flow Chart D, for foamed bitumen bound materials.

6.3 Design for Type 1 and Type 2 roads

For Type 1 and Type 2 roads, the design of the structural course using cold in-situ recycled material, assumes that the existing pavement contains a foundation platform equivalent to those given in Table 4.

Where the thickness of the existing foundation is found to be below the requirements of Table 4 it may be possible

Flow Chart C: Design criteria and specification compliance programme for in-situ cement bound recycled material



Flow Chart D: Design criteria and specification compliance programme for in-situ bitumen bound recycled material

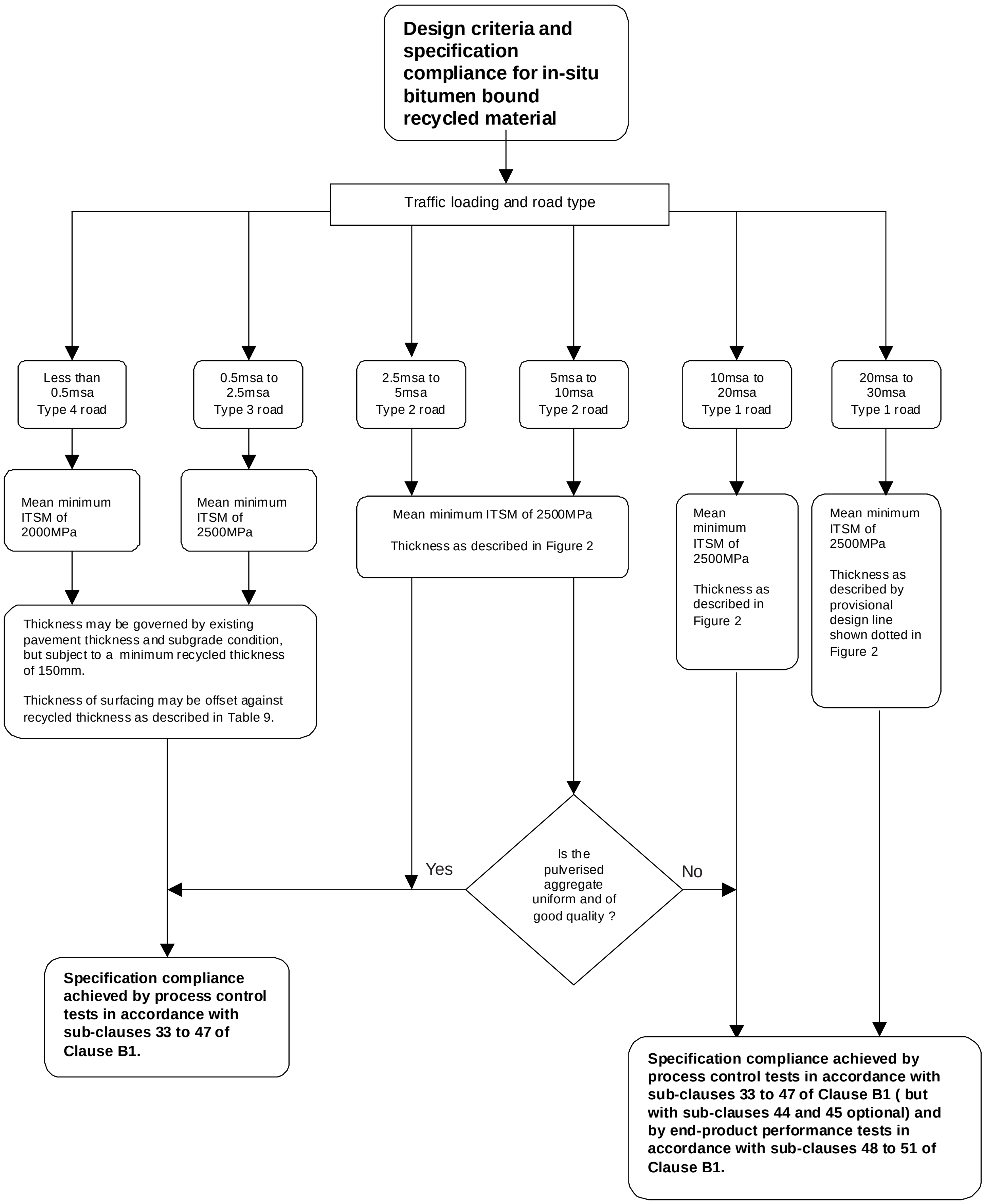


Table 4 Assumed foundation platform thickness of existing pavement of Type 1 and 2 roads

Foundation platform thickness (mm)							
Subgrade CBR 2-4		*Subgrade CBR 5-7*		*Subgrade CBR 8-14*		*Subgrade CBR >15*	
Granular	*Remaining bound construction*	*Granular*	*Remaining bound construction*	*Granular*	*Remaining bound construction*	*Granular*	*Remaining bound construction*
300	85	250	70	200	60	150	40

to upgrade its effectiveness by incorporating an extra depth of the stabilised layer as the foundation. However, caution should be exercised if the attempt to upgrade the thickness of the foundation results in the disturbance of existing materials that have been in place for many years; are over consolidated and are currently performing satisfactorily as the foundation. Furthermore, for the Type 1 and 2 roads, it is strongly recommended to avoid mixing subgrade material into the recycled mix.

If there is any doubt as to the bearing capacity of the foundation platform this should be determined as part of the investigation phase, using a Dynamic Cone Penetrometer (DCP) or similar. If found to be less than 100MPa then the thickness of the stabilised layer should be increased in accordance with the equivalence factors given in Table 5, which relate the thickness of granular foundation to the equivalent thickness of in-situ recycled materials.

Table 5 Thickness conversion factors relative to granular foundation material

In-situ recycled end product	*Equivalence factor*	*Thickness deficit factor*
Cement stabilised material with 7 day compressive strength of 10 N/mm^2	0.3*	0.45
Cement stabilised material with 7 day compressive strength of 7 N/mm^2	0.4*	0.65
Cement stabilised material with 7 day compressive strength of 4.5 N/mm^2	0.5*	1.0
Foam bitumen stabilised material with ITSM of 2500MPa	0.4**	0.65

* *Source BS 7533: Table 4 (1992)*

** *Derived from Ullidtz and Peattie (1980)*

However, this is an iterative process, since the increase in thickness of recycled material will cause the thickness of foundation platform to be deminished still further, which in turn should be offset. Therefore, for design purposes, any required increase in thickness of the stabilised layer will be determined in accordance with the respective thickness deficit factors given in Table 5.

For example, if a recycled pavement has been designed assuming that the remaining pavement materials are equivalent to a foundation platform comprising granular material, but are deficient in thickness by 100mm, the increase in thickness of the stabilised layer can be specified as:

For cement stabilised recycled material (10 N/mm^2): = 0.45 x 100mm = 45mm

For cement stabilised recycled material (4.5 N/mm^2): = 1.0 x 100mm = 100mm

For foamed bitumen bound recycled material: = 0.65 x 100mm = 65mm

The recommended depth of cold in-situ recycling for the structural course for road category types 1 and 2 are given in Figure 1 and Figure 2 for cement bound and foamed bitumen bound constructions respectively. These figures relate the design traffic loading to the thickness of the structural course and the associated thickness of surfacing.

Where the design thickness of the recycled layer is in excess of 225mm, which is the maximum thickness normally considered acceptable for the compaction of a single lift for standard unbound and bound materials, consideration should be given to the use of heavier than usual compactors, to avoid the situation where a density profile is developed, such that the lower part of the layer does not achieve the same density as the upper part.

This effect may be minimised when applying compaction at the earliest possible time using either heavy vibratory compaction or using a compactor capable of 'kneading' the material at depth, as is the case using a tamping roller. To date in the UK, heavy compaction for cold in-situ recycling works has been carried out almost exclusively using the heavy vibratory roller option, although more recently, a heavy combined pneumatic tyre roller (PTR) and vibratory drum roller has been trialed, but their field performance has yet to be verified.

From past monitored works, it is evident that the vibratory compaction did not always achieve full depth compaction of thicker layers. Therefore, where the stabilised material is assessed as having a poor workability, it is recommended that consideration be given to the use of heavy tamping rollers for the initial deep-seated compaction, particularly for layers having a compacted thickness in excess of 225mm, followed by grading of the surface and final compaction using the conventional heavy vibratory compaction. This is similar to the compaction methodology commonly used in Australia for thick-lift construction.

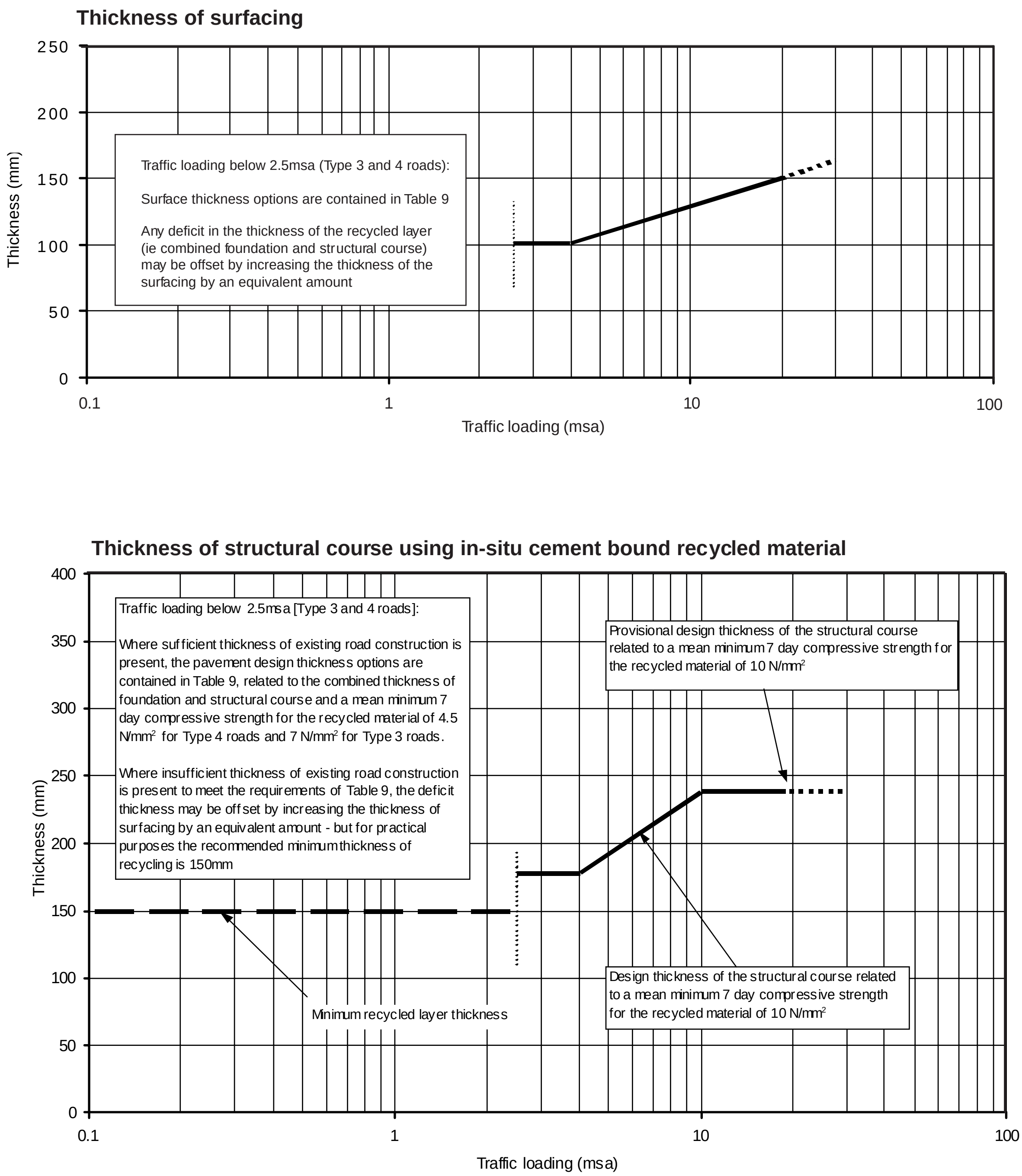


Figure 1 Pavement layer thicknesses using in-situ cement bound recycling

Use of the in-situ recycling process for traffic levels above 20 msa would require extrapolation beyond reasonable expectation. However, there is a practical thickness limit of about 300mm, above which, adequate compaction of a single, thick lift of recycled material would be too difficult to achieve, even using the heavy compaction process described above. Recycling using a two layer process is feasible, but the compromised in-situ working, caused by the need to temporarily stockpile the top layer whilst recycling the bottom layer, would reduce the energy saving and advantage gained by the in-situ recycling process.

Where the subgrade CBR is less than 2 per cent the use of the cold in-situ recycling technique is not recommended for any level of traffic loading.

Design examples for Type 1 and 2 roads related to typical site conditions are included in Appendix B.

6.4 Design for Type 3 and Type 4 roads

This section is included for the completeness of the design guide, although the sites examined in the current study were designed for heavier traffic loading conditions.

Therefore, the design proposals are based primarily on the earlier findings of performance reviews reported by Kennedy on behalf of the Department of the Environment, Energy Efficiency Office (ETSU 1994). The design also takes into account the criteria published in TRL Report 216 (Potter 1996), which refers to the cold in-situ recycling of road haunches.

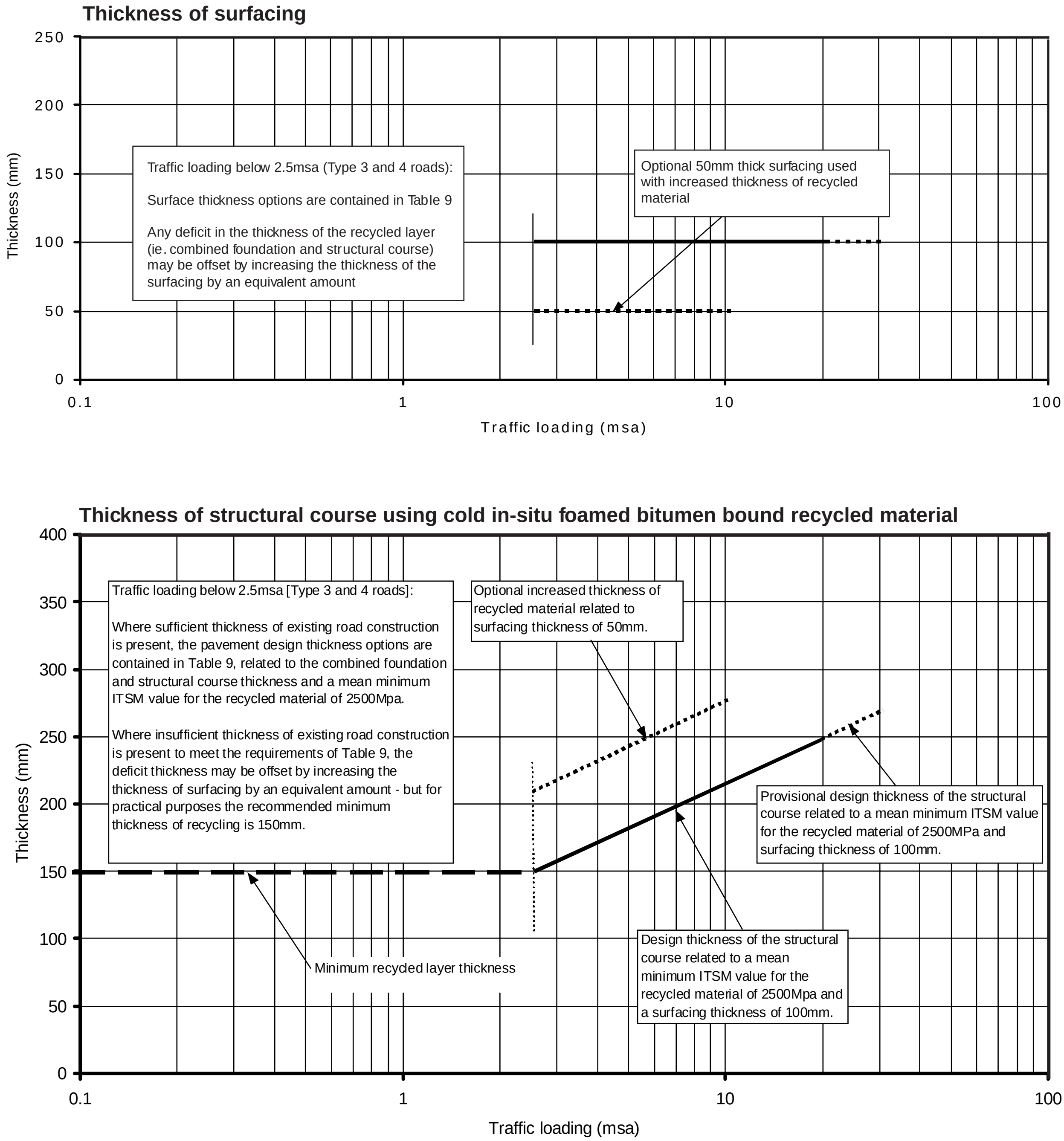


Figure 2 Pavement layer thicknesses using cold in-situ foamed bitumen bound recycling

The ETSU performance review of roads reconstructed by cold in-situ recycling from 1985 to 1987, showed clearly that the performance of Type 3 and 4 roads, recycled to a depth of between 150 to 250mm, was rated as satisfactory or better in more than 97 per cent of cases. Furthermore, the very few defects reported after an average six years life, were all associated with poor edge detail and no fault related to the performance of the cold in-situ recycled layer.

Therefore, since the design thicknesses recommended for road haunch design refer to the same order of recycled thicknesses used for reconstruction of the monitored sites, ranging between 150 and 300mm, the design thicknesses for wider areas of recycled reconstruction are considered to be satisfied by the same criteria, although slightly modified in detail to account for the different construction processes and scale of the works. The design thicknesses are detailed in Table 6, listed against three surfacing thickness options.

In comparison with the design for Type 1 and 2 roads, these design thicknesses relate to the thickness of the combined structural course and foundation layer. Furthermore, the validity of the design process is contingent on the process control testing being carried out as specified, to ensure that the in-situ recycled material is stabilised and compacted to the specified standard.

Design examples for Type 3 and 4 roads related to typical site conditions are contained in Appendix B.

Table 6 Thickness of pavement layers using cold in-situ recycled materials as the combined structural course and foundation platform in Type 3 and Type 4 roads

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

n/r not recommended

For intermediate thicknesses of surfacing, the thickness of recycled material may be interpolated from the above data.

7 Specification for cold in-situ recycled material

7.1 General

The process of cold in-situ recycling for the structural maintenance of highway pavements has been developed and used in a variety of countries, each with their own local requirements, often related to climate and geology. Consequently, the types of road available for recycling are diverse. As a result, the specification for recycling works has been derived from a variety of component material designs and construction methods, aimed mostly at producing materials of quasi standard form and expecting that their performance would be similar to the equivalent plant mixed option.

These recipe and method specifications have served the industry reasonably well, particularly in the UK, because there is more likely to be a quickly changing geology profile linked with a wide array of historic road pavements. However, the recycled materials produced from this potentially varied feedstock, often referred to as secondary, reclaimed or waste aggregate, has attracted the suggestion of being inferior in some way. This suggestion is not deserved.

Therefore, as a means of encouraging the use of recycled material, a move towards end product performance specifications is seen as a positive step. The specification of recycled materials in their own right, using performance targets stated in terms of engineering properties, allows the recycled material to be considered for more heavily trafficked sites, on an equitable basis to standard plant produced materials.

Specified and closely monitored performance targets should offer the engineer a greater degree of confidence in the prediction of life for the recycled treatment. In consequence, the cost effectiveness of the recycled option, in comparison with normal reconstruction methods, may be more readily demonstrated.

7.2 Material composition and process control clauses

7.2.1 Cement bound material

Because of the similarities between the materials, significant sections of the specification clauses for CBM given in the Specification for Highway Works apply equally well for the recycled option. In fact, the Specification for Highway Works refers directly to the option of using a mix-in-place method of construction for CBM1 and CBM2 mixtures. In consequence, many of the associated NG clauses, as given in the accompanying Notes for Guidance on the Specification for Highway Works, are equally applicable.

One exception to the guidance relates to the curing period and use by traffic, since in the structural maintenance situation, there is often a requirement to maintain immediate access through and within the site, for residents and service traffic. In addition, for most recycling contracts, any access restriction will inevitably delay the works programme.

However, any damage to the recycled layer by early trafficking may be mitigated by ensuring that adequate compactive effort has been applied and high density achieved. In addition, the use of a higher cement content for early strength gain could be employed. Conversely, it could be argued that early life trafficking is beneficial to the structural course by establishing a closer spaced pattern of crack, thus making the finished road less prone to reflective cracking problems. In addition, provided the as-installed performance measured by dynamic plate loading or penetrometer technique, to determine elastic modulus, meets the targets set by the specification, no problem is foreseen.

A further aspect for consideration, relates to the compaction of thick lifts of recycled material up to 300mm thick. Although the process control for compaction of such 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 tyre roller (PTR) may also be considered worthwhile as a finishing roller. The compaction options are discussed further in Section 8.

7.2.2 Foamed bitumen bound material

Although this material is generally labelled as a bitumen bound material, it is unlike any standard hot plant mixed bitumen bound material. The foamed bitumen tends to combine more readily with the fines component of the pulverised aggregate, forming a ‘mortar’ matrix, which fills the voids between the partially coated coarse aggregate. In addition, cement is commonly used as an adhesion agent, in which case a component of the stiffness is likely to derive from the hydration of the cement. Therefore, unlike the cement bound option, the specification or notes for guidance for standard bitumen bound plant mixes are not readily applicable to the cold in-situ recycled product.

Experience has found that a base bitumen with penetration grade 100 most often offers the best compromise between workability during the laying process and the compacted stiffness of the material. But subject to the results of the mixture design, base bitumen with a higher penetration grade may be used.

To ensure adequate mixing of the foamed bitumen with the aggregate, the minimum expansion rate of the foam should be 10, linked with a minimum half-life of 10 seconds. Also, in the interests of durability, irrespective of the results of the design tests, the absolute minimum added bitumen content should be 3.5 percent. The uniformity of mixing should be continuously inspected visually by the contractor and work should stop if bitumen streaks or blotches are observed.

Compaction control is essentially the same as for the cement bound option, and provided adequate stability of the layer is achieved, early life trafficking is seen as no problem. The collapse of the foam will take place shortly after mixing to allow development of stiffness by a curing process, which involves hardening of the bitumen and cement bound mortar. As an additional safeguard, the as-installed performance measured by either the dynamic plate loading or penetrometer technique, should be able to demonstrate that the layer has achieved a required stiffness, before proceeding with the construction of the overlying pavement.

7.3 End-product performance clauses

Throughout the current research project, the development of the end-product performance specification for the cold in-situ recycled materials has passed through different stages. The initial intention was to define performance in terms of either the compressive strength of cored cement bound material or by the Indirect Tensile Stiffness Modulus (ITSM), obtained for the bitumen bound material.

The above option was set aside, however, when it was decided that the destructive coring should only be performed as a last resort. This decision was reinforced by the difficulties experienced on the Cartgate trial and several of the other monitored sites, where the coring itself was sometimes found difficult and insufficient test specimens were obtained, to the extent that there was no certainty of consistently extracting whole cores from the road. The current specification now retains the core testing option only as the last resort rejection method.

The choice of non-destructive testing as a means of acceptance, but not rejection, now relies on the pavement stiffness reaching a value pre-stated in the contract, obtained using the analysis of the FWD survey data. Where the FWD stiffness values do not reach the required level, then the coring and testing of core samples option may be invoked.

Prior to either of the above assessments, the specification also requires that the as-installed performance of the stabilised layer is evaluated using a dynamic plate loading or penetrometer technique to determine values of elastic modulus at points on a closely spaced grid pattern. The average elastic modulus for the assessment areas must comply with a stated minimum standard and furthermore, before proceeding with the surfacing construction, repeated values shall be expected to demonstrate that the respective elastic modulus values have increased by a stated minimum percentage.

8 Construction

8.1 Pulverisation and stabilisation

Road pulverisation and stabilisation involves the use of specialised plant that operates to the specified depth plus construction tolerances. To ensure adequate pulverisation and mixing of materials it is recommended that the drive performance of the machine is at least 260kW, which should be capable of carrying out an initial pulverisation to a depth of about 450mm.

Most stabilisers are manufactured with the mixing box located centrally, which incorporate special rotors designed to pulverise or mix the material within the mixing hood. The use of smaller agricultural equipment is no substitute, since they are predominantly designed to work on cohesive soils and therefore, are not designed to produce pulverised granular aggregate of the required grading for construction purposes.

Since the powerful equipment can easily damage services, the Overseeing Organisation should identify if any services or obstructions are present. The time required to lower any services should be taken into account within the works programme.

The specialist manufactured plant will almost certainly incorporate all the features and facilities necessary to complete the works in accordance with the current recycling specification. Some will be larger and more powerful than others, whereas others may incorporate more refined control systems.

The systems normally employed to control the depth of pulverisation relate the depth of rotor to the vertical position of the wheels. Therefore, to ensure that the appropriate depth of pulverisation or stabilisation is carried out consistently, it is particularly important that a working platform is prepared prior to the stabilisation process, having a known uniform level profile.

8.2 Added water and moisture control

Although the control of moisture content is of prime importance for optimum compaction conditions, there is currently no automated process available that can ensure the provision of moisture at a uniform and optimum level during the recycling process. It is vital therefore, that the process is controlled by an experienced operator who has access to controls for added water, particularly when the water is sprayed directly in the mixing box at the time of stabilisation.

The stabiliser should ideally, be fitted with a separate water pumping and injection system for metering the added water, regulated to the ground speed of the machine. An experienced operator will normally assess the moisture content of the mix relative to the target optimum by squeezing samples of the material regularly by hand and be guided by test results at the commencement or during any job so as to 'calibrate' personal judgement. The operator must assess the moisture content immediately behind the stabiliser and be prepared to make quick adjustments as the machine may be progressing forward at a rate of 4-6 metres per minute.

8.3 Application of cement or lime

Cement may be required either as the primary binder or as a supplementary binder to act as an adhesion agent or help improve the short term properties of the compacted material. Currently, hydrated lime is only used as a plasticity modifier for cohesive fines within the pulverised aggregate, although as in the past, it was used as a primary binder agent.

Specialist spreaders are vital for the application of these materials, which should incorporate control systems to ensure that the rate of spread is achievable to a target accuracy of ±0.5 percent of the specified spread rate. The associated construction tolerance for the rate of spread would normally be ±10 percent of the specified value.

The particle size of the different cements and lime may vary and such behaviour should be noted as it may affect the accuracy of application. The use of consistent sources and standard routines for storage and loading of the spreader is recommended to minimise any variation.

8.4 Application of foamed bitumen

Because of the short life span of the foamed bitumen, usually defined in terms of its 'half-life' (i.e. time taken in seconds for the foamed bitumen to settle to one half of the maximum expanded volume) it is necessary for the foaming process to be incorporated into the spraybar of the recycling machine, for immediate distribution and mixing with the pulverised aggregate in the mixing hood. The reduced viscosity and greater volume of the foamed bitumen enables it to be distributed and mixed with the damp cold aggregate.

A typical stabiliser has computer-controlled devices on board that calculate the application rate of the binder as the stabiliser moves along the pavement. The pumping and injection equipment for the foamed bitumen should ideally be a separate spraybar system, and one that allows variable widths of binder to be applied.

An inspection or test jet must be fitted to ensure that the flow of bitumen and the required expansion and half-life qualities of the foamed bitumen are achieved. The bitumen jets must be of a self cleansing design and bitumen lines should be heated for reasons of safety.

The spraybar control systems incorporated into the stabiliser should ensure that the rate of spread is achievable to a target accuracy of ±0.5 per cent of the specified spread rate, in order to achieve a constructed tolerance for added bitumen of ±0.6 per cent of the target binder content. As a means of verification, dipping in the tanker before and after a run can be used to verify the computer collected data.

8.5 Compaction

Compaction is a critical part of the stabilisation process and demands particular care. This is especially the case for thicker layers of construction, where there is the possibility for a density profile to develop during compaction, such that the lower part of the layer does not achieve the same density as the upper part.

This effect may be minimised when applying compaction at the earliest possible time using either heavy vibratory compaction or using a compactor capable of 'kneading' the material at depth, as is the case using a tamping roller. To date in the UK, heavy compaction for cold in-situ recycling works has been carried out exclusively using the vibratory roller option.

However, from the results of the monitoring reported in Part 1 of TRL Project Report PR/CE/193/98 (Milton, 1999), it is evident that the vibratory compaction was not always able to achieve full depth compaction of thick layers. Therefore, where the stabilised material is assessed to have a poor workability, it is recommended that heavy tamping rollers should be considered, particularly for layers having a compacted thickness in excess of 250mm.

When using heavy vibratory compactors, caution should be exercised where there is any danger of vibratory damage to shallow culverts, underground services or adjacent buildings due to the transmission of vibrations.

The use of a pneumatic tyre roller (PTR), is sometimes advocated as a finishing roller, particularly for the cement bound material. However, whereas the PTR may tend to assist in the compaction of the lower level material, great care is required to ensure that the near surface material does not dry out or stiffen too quickly, which may result in disruption and shear displacement of the near surface material caused by the narrow loading under the individual tyres. Thus resulting in an unstable surface finish and the necessity to remove unacceptable material.

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Part 2: Specification and notes for guidance on the specification

Clause C1 In-situ recycled cement bound material

Scope

1 In-situ recycled cement bound material shall be designed and produced to form the foundation or main structural layer of a road pavement. The primary aggregate source shall be obtained by cold in-situ pulverisation of all or part of the existing road structure. The stabilising agent shall be hydraulic cement with Portland cement as the main component. The aggregate grading may be adjusted by the addition of a filler. Lime may also be used to modify any cohesive subgrade soil incorporated in the pulverised layer.

2 Prior to commencing the pulverisation and stabilisation works, the Contractor shall demonstrate to the satisfaction of the Overseeing Organisation, using the results of the mix design procedures described in Clause C2, that the existing pavement materials in the sections of the works defined in Specification Appendix (Item 1), are capable of being recycled by pulverisation to form the primary aggregate component of a in-situ recycled cement bound material which can meet the specified end-product performance requirements.

Component materials

Aggregates and fillers

3 The pulverised road material and any supplementary aggregate and/or filler shall normally be granular material with not less than 5% and not more than 20% passing the BS 75 micron sieve [Zone A graded material]. Approval for use of pulverised granular material containing up to 35% passing the BS 75 micron sieve [Zone B graded material] shall require confirmation by the Overseeing Organisation subject to the results of the mixture design procedures described in Clause C2.

4 The pulverised granular material shall contain not more than 2% of organic matter determined in accordance with BS 1377: Part 3: Clause 3.

Cement, filler and lime

5 The constituents and required quality standards of hydraulic cement, filler and lime delivered to site shall be certified by the supplier, whose manufacturing and delivery processes shall be implemented using quality management systems in accordance with the ISO 9000 series of standards and certified by an accredited body.

6 The primary binder shall be Portland cement or Portland blast furnace slag cement or Portland pfa cement in accordance with sub-Clause 3 of Clause 1001 in the Specification for Highway Works.

7 PFA used as a filler shall be in accordance with BS 3892: Part 1.

8 Lime for lime stabilisation (or as a modifier for plastic fines) shall be either quicklime or hydrated lime, as stated in Specification Appendix (Item 2), complying with sub-Clause 3 of Clause 615 in the Specification for Highway Works.

Water

9 Water for moisture content control of the pulverised granular material shall normally be obtained from a water company supply and used without testing. Water from an alternative source shall comply with BS 3148 and be approved by the Overseeing Organisation.

Pulverisation and stabilisation

10 The Contractor shall satisfy the Overseeing Organisation that the plant used for pulverisation is capable of uniformly pulverising the existing road in a single pass, to a depth required by the contract. The plant used for stabilisation shall be capable of uniformly mixing controlled amounts of water and cementing agent(s) into the full depth of the pulverised layer. For either operation, the plant shall be equipped with a means for controlling the depth of processing to ±15mm of the required depth.

11 The plant used for stabilisation shall be equipped with a spraybar system within the mixing chamber capable of uniformly distributing water at a monitored and controlled rate. Evidence confirming the capabilities of the plant and calibration of flow meters, shall be submitted to the Overseeing Organisation prior to the stabilisation works commencing.

12 The material shall be pulverised and stabilised in a single layer if the compacted thickness is 300mm or less. If the compacted thickness is greater than 300mm, the material shall be pulverised and stabilised in a minimum number of layers between 100mm and 300mm thick. Where more than one layer is required, the Contractor shall satisfy the Overseeing Organisation that the lower layer has achieved adequate stability in accordance with sub-Clause 27 of this Clause before proceeding with the overlying layer.

Pulverisation process

13 Pulverisation of the existing road structure shall be carried out in a systematic pattern, to the required depth, to ensure that all parts of the existing road designated in Specification Appendix (Item 1) are included in the works. An overlap of at least 150mm shall be made between adjacent passes of the machine. Any material missed along hard edges or around obstructions shall 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 shall be graded to the required level profile and nominally compacted.

14 All longitudinal and transverse joints shall be clean cut and vertical. Where work continues adjacent to previously recycled material transverse joints shall be reformed a minimum 0.5m into the previously treated construction. Where a layer of material for stabilisation is placed over a layer previously stabilised, the depth of pulverisation/ stabilisation of this layer shall be set to cut into the underlying stabilised layer by at least 20mm.

15 Excess pulverised material shall be removed by grader and/or excavator for use elsewhere on the site or transported to stockpile at locations given in Specification Appendix (Item 3). The surface of the layer shall be graded to the required level profile and nominally compacted.

16 Moisture content of the pulverised aggregate immediately prior to stabilisation shall be measured in accordance with BS 812: Part 109 using the high temperature method. The moisture content shall be uniform throughout the layer within the range 0% to +4% of optimum moisture content for the unstabilised aggregate, including any designed proportion of filler, determined in accordance with BS 1924: Part 2: 1990.

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

18 Aeration of the affected area shall be achieved by full depth passes of the recycling machine to disturb and loosen the material and assist the evaporation of excess moisture. The material shall be kept in a loose condition until subsequent moisture content tests show that the treated material has reached the required moisture content range. The layer shall be re-graded nominally to level and compacted in preparation for stabilisation.

19 Increase in moisture content of the affected area shall be carried out by the controlled addition of water through an adjustable spraybar system in conjunction with full depth passes of the recycling machine to achieve a uniform distribution of the water throughout the layer. Increments of water shall be added and mixed in until subsequent moisture content tests show that the material has reached the required moisture content range. The layer shall be re-graded nominally to level and compacted in preparation for stabilisation.

Stabilisation process

20 Stabilisation shall not be carried out during or after periods of rainfall where the duration and intensity are likely to cause the stabilised mixture to exceed the specified moisture content criteria and compromise the stability of the layer under compaction (as described in Sub-Clause 27 of this Clause). Stabilisation of frozen materials shall not be permitted.

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

22 Cement binder, filler, hydrated lime or quicklime shall be spread full-width on the surface of the layer using a mechanical spreader capable of distributing the material(s) in a uniform controlled manner. The rate of spread of these materials shall be calculated to achieve mixture composition determined in accordance with Clause C2 and monitored as the spreading operation proceeds in accordance with sub-Clause 31 of this Clause.

23 The stabilisation shall 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 150mm between adjacent passes of the machine. Where necessary, additional water shall be introduced and distributed through the spraybar system, directly into the rotor and mixing box of the stabiliser.

24 The layer of stabilised material shall 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 shall be re-filled by grading the adjacent stabilised material into the space using a minimum amount of re-working.

25 The compaction of each layer shall be carried out using compaction plant approved by the Overseeing Organisation, until such time as the in-situ density complies with the minimum compaction field requirements in Table 10/8 of the Specification for Highway Works and the stabilised layer provides a stable and dense tight surface. Any open or segregated surface area shall be blinded using a dry crushed rock fines.

26 Sub-clause for induced cracking deleted.

27 The stability of the layer under compaction shall be deemed adequate if the finished surface does not move, rut or exhibit transverse cracking under the load of subsequent construction traffic.

28 Where required by the Overseeing Organisation, the stability of a layer in any area shall be assessed after a curing period of at least 24 hours by channelled trafficking using a rigid three-axle tipper truck loaded to a gross mass of 24 tonnes (assumed equivalent to three standard axles). The vertical deformation shall be measured in all wheeltracks at monitoring points on each of 5 transverse sections set 1m apart after 5, 15, 30 and 40 passes of the truck. The mean vertical deformations at the above trafficking increments shall be plotted against the respective number of truck passes and the mean vertical deformation corresponding to 100 standard axles shall be interpolated. The layer shall be deemed acceptable if the mean vertical deformation corresponding to 100 standard axles is less than 10mm.

29 On completion of compaction the surface shall be sealed using a sprayed membrane of Class K1 - 70 bitumen emulsion complying with Clause 920 in the Specification for Highway Works. The bitumen emulsion shall be sprayed at the rate stated in the Specification Appendix (Item 4). Where the surface is opened to traffic, the sealing membrane shall be blinded with fine aggregate or sand applied at a rate of 5.5 to 7.0 kg/m^2.

Process control

30 The sampling and testing of the in-situ recycled cement stabilised roadbase shall be carried out as required for cement bound materials [CBM] in accordance with Clauses 1040 and 1041 in the Specification for Highway Works.

31 The rate of spread of cement, filler, hydrated lime or quicklime shall be measured by weighing the amount of material retained on each of five trays or mats of known area laid in the path of the spreading machine. The trays shall be positioned approximately at points equally spaced along a diagonal bisecting the area of coverage. The mean rate of spread and percentage addition of the material shall be determined and recorded for each assessment area.

32 As directed by the Overseeing Organisation, where lime has been used to modify a cohesive soil component of the pulverised aggregate, the acceptability of the modified materials shall be tested in accordance with sub-Clause 13 of Clause 615 in the Specification for Highway Works.

End product performance of in-situ recycled cement bound material

33 The end-product performance of the in-situ recycled cement bound material shall be assessed on the basis of measurements and tests carried out in areas of 800m^2 or part thereof completed each working day, which shall match the areas defined in sub-Clause 1 of Clause 1040 in the Specification for Highway Works.

34 Within 24 hours of completion, the as-installed performance of the stabilised layer shall be evaluated using a dynamic plate loading or penetrometer technique to determine values of elastic modulus at points on a nominal 2m grid pattern. The elastic modulus at each point and the mean elastic modulus for the assessment area shall comply with the minimum standards stated in the Specification Appendix (Item 5). Additionally, before proceeding with construction of the overlying pavement, the evaluation process shall be repeated to demonstrate that the elastic modulus value at all points and that of the mean value have increased over the respective as-installed values by not less than the percentage values stated in the Specification Appendix (Item 5). Where these criteria are not met, the full extent of non-compliant material shall be determined and appropriate remedial measures implemented. Remedial action shall comprise either a delay in construction to allow further curing and stiffening of the layer or a repeat of all or part of the recycling process, followed by re-evaluation, until a compliant material is achieved.

35 Within 270 days of completion of the surfacing works a Falling Weight Deflectometer survey shall be carried out and analysed in general accordance with HD 29/94 (DMRB 7.3.2, 1994). In particular, the measurements shall be taken on the finished road surface in the nearside wheelpath, at a uniform and maximum spacing of 10m. The survey shall be carried out during a period when the pavement temperature at a depth of 50mm is within the range 15 to 25^{0}C. The FWD results shall be analysed using a linear elastic FWD back-analysis computer program, with the pavement modelled as a two layer system. Layer 1 shall represent the combined design thickness of the bound materials (i.e. the combined recycled material and overlying surfacing materials) and layer 2 shall represent the unbound foundation layer of infinite depth. End-product performance shall be defined in terms of the calculated stiffness of layer 1, uncorrected for temperature. Compliance shall be achieved when not more than 15% of the calculated values within each assessment area fall below the stiffness value specified in the Specification Appendix (Item 6).

36 In the event that the layer 1 stiffness requirement of sub-Clause 35 of this Clause are not met, the full extent of the non-compliant material shall be determined by further investigation involving coring and laboratory testing. For each area of non-compliance, cores shall be extracted through the full depth of the stabilised layer at locations directed by the Overseeing Organisation, at a minimum rate of one x 150 mm diameter core per 75m^2.

37 The Contractor shall be responsible for extraction of the cores with the minimum of force or disruption. Air flush coring shall be allowed for materials that are disturbed by water flush coring. After extraction, each core shall be labelled and photographed and prior to testing, shall be stored in sealed polythene bags, in a uniformly supported position, at a temperature of $20^{0}C \pm 5^{0}C$. The thickness of the recycled layer shall be measured and recorded.

38 Reinstatement of all core holes shall be completed before opening the area to traffic. All backfill materials shall comply with the 'Specification for the Reinstatement of Openings in Highways' issued by the Highway Authorities and Utilities Committee.

39 If, at any of the prescribed core locations, it is not possible to extract an intact core of suitable size or condition for the end-product performance testing, using a maximum of three attempts in an area of 1.5m radius, the material in the vicinity shall be deemed not to comply with the end-product performance specification.

40 In the laboratory, each core extracted successfully shall be trimmed to remove surfacing materials and any underlying material prior to the measurement of core density and air voids content in accordance with the standards listed in Table C1/1.

41 Following the measurement of density and air voids content, each core shall be prepared and tested to determine the compressive strength of the core, in accordance with the procedures and standards given in Table C1/2

42 The results obtained shall be used to judge the expected performance of the recycled stabilised material in the works, in relation to the performance of standard CBM roadbase materials. The recycled stabilised material in the assessment area shall be deemed acceptable if the compliance criteria described in Table C1/3 are met.

Clause C2 In-situ recycled cement bound material - mixture design and characterisation

1 Mixture design characterisation of in-situ recycled cement bound material for each site, or section of site, including details of the cementing agent and/or stabilising agent(s) and their quantities, shall be submitted to the Overseeing Organisation at least one week prior to commencement of the recycling works. Where the site investigation has identified significant variation of existing pavement materials between different sections of the site, a mix design shall be submitted for each section of the site. The proposed plan area and depth of the different sections, covered by each mixture design, shall be approved by the Overseeing Organisation.

2 The mixture design for in-situ recycled cement bound material shall use the same method of mixture design as that used for plant mixed CBM specified in Clauses 1035 to 1039 in the Specification for Highway Works, except that the aggregate shall be crushed and processed in the laboratory, using a method approved by the Overseeing Organisation, to replicate as closely as possible the aggregate expected from pulverisation in the works. The permitted CBM alternatives and equivalent recycled mixture designs for each part of the Works shall be as described in the Specification Appendix (Item 1).

Table C1/1 Procedures and standards to be used to determine the density of core samples of in-situ recycled cement bound material

Procedure	Procedure Stage	Standard to be Used
Core preparation for density testing.	Measurement of core dimensions and accuracy of measurement. Methods of trimming core to length.	BS Draft prEN 12504.
	Test specimen type, shape and moisture condition.	ISO 6275.
Core testing for density.	Apparatus specification. Measurement of volume dimensions. Volume by water displacement. Measurement of mass. Equations for density. Accuracy and units of density.	ISO 6275.
	Core density as a proportion of theoretical density.	SHW Clause 1003.

Table C1/2 Procedures and standards to be used to determine the compressive strength of core samples of In-situ recycled cement bound material

Procedure	Procedure stage	Standard to be used
Core preparation for strength testing.	Measurement of core dimensions and accuracy of measurement. Assessment of voids. Maximum and minimum dimensions for strength testing.	BS Draft prEN 12504.
	Methods of capping core.	ISO 4012.
	Suitability of core for strength testing. Storage of cores before capping.	BS 1881: Part 120.
Core testing for strength.	Type of strength test. Minimum period of testing after end-preparation. Method of curing core prior to testing. Measurement of core test specimen dimensions and accuracy. Equation for calculating core strength.	BS Draft prEN 12504.
	Testing machine specifications Rate of loading.	ISO 4012.
	Correction for length/diameter ratio and orientation of coring. Equations for deriving equivalent in-situ cube strength.	BS 1881: Part 120.
	Correction for excess voidage.	BS 1881: Part 120.

Table C1/3 Compliance criteria for in-situ recycled cement bound material based on results of tests on cores extracted from the works

Property	Individual cores	Mean from cores in each surveyed area
Core density relative to refusal density	93% minimum	95% minimum
Excess voidage *	3.0% maximum	2.0% maximum
Layer thickness [from core measurement]	± 25mm of specified	± 15mm of specified
Equivalent cube compressive strength	**CBM equivalence	**CBM equivalence

* Excess voidage of a core is defined as the amount by which the actual air voids content exceeds the air voids content of the fully compacted moulded cube of the same cement bound material.

** Compliance criteria is quoted in relation to the design 7 day cube compressive strength appropriate to the equivalent CBM classification of the recycled material.

3 The laboratory crushed and processed aggregate with a particle [or 'lump'] sized distribution complying with sub-Clause 3 of Clause C1, shall be thoroughly mixed with measured proportions of the cement to produce trial mixtures with different cement contents. The type and grade of the cement used in the trial mixtures shall be the same as that used in the finished works.

4 If lime is required for stabilisation and/or modification of clay included from pulverisation of the upper subgrade layer, the same proportion of lime shall be added into the trial mixture.

5 The cement content of the in-situ recycled cement bound mixture shall be determined in the same manner as the cement content for plant mixed CBM, to achieve the requirements in Table 10/8 in the Specification for Highway Works. The minimum cement content shall be 3% by weight.

6 The mixture design process shall be repeated until an acceptable mixture design is achieved. To achieve this the target composition of the mixture shall be systematically adjusted and the mixture design tests repeated.

7 In addition to the requirements of Table 10/8 in the Specification for Highway Works the average compressive strength determined after 7 days immersion in water of five test specimens of the target composition mixture, prepared in accordance with sub-Clause 3 of this Clause, shall be not less than 80% of the average compressive strength of five control specimens when subjected to the test procedure described in BS 1924: Part 2: clause 4.3. After 7 days immersion the specimens shall not show any signs of cracking or swelling.

Specification appendix

Site specific details and requirements to be stated in the Contract for in-situ recycled cement bound material:

Item 1	Site description, location details and depth of recycling:	
	Overall location - reference to plans	
	Section details - reference to plans & sections	
	Location of services - reference to plans & sections	
	Depth of recycled layer	......mm.
Item 2	Type of lime required for modification of cohesive soils	......
Item 3	Location of places to stockpile excess pulverised materials awaiting re-use elsewhere	
Item 4	Rate of application of bitumen emulsion sealant spray	......l/m^2
Item 5	Minimum elastic modulus within 24 hours obtained using a dynamic plate or penetration test:	
	Single point value	......MPa
	Mean value	......MPa
	Minimum percentage increase of single point elastic modulus values	...... %
	Minimum percentage increase of mean elastic modulus value	...... %
Item 6	Stiffness value below which not more than 15% of FWD derived stiffness values shall fall for combined surfacing and recycled material	......MPa

Publication appendix

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Clause B1 Cold in-situ recycled bitumen bound material

Scope

1 Cold in-situ recycled bitumen bound material shall be designed and produced to form the foundation or main structural layer of the road pavement. The primary aggregate source shall be obtained by cold in-situ pulverisation of all, or part, of the existing road structure. The primary binder (stabilising agent) shall be a foamed penetration grade bitumen, with cement or lime as an adhesion agent. The aggregate grading may be adjusted by the addition of a filler. Lime may also be used to modify any cohesive subgrade soil incorporated in the pulverised layer.

2 Prior to commencing the pulverisation and stabilisation works, the Contractor shall demonstrate to the satisfaction of the Overseeing Organisation, using the results of mix design procedures described in Clause B2, that the existing pavement materials in the sections of the works defined in the Specification Appendix (Item 1), are capable of being recycled by pulverisation to form the primary aggregate component of a cold in-situ recycled bitumen bound material which can meet the specified end-product performance requirements.

Component materials

Aggregates and fillers

3 The pulverised pavement material and any supplementary aggregate and/or filler shall normally be granular material with not less than 5% and not more than 20% passing the BS 75 micron sieve [Zone A graded material]. Approval for use of pulverised granular material containing up to 35% passing the BS 75 micron sieve [Zone B graded material] shall require confirmation by the Overseeing Organisation, subject to the results of the mixture design procedures described in Clause B2.

4 The pulverised granular material shall contain not more than 2% of organic matter determined in accordance with BS 1377: Part 3: Clause 3.

Bitumen binder

5 The primary binder shall be foamed bitumen. The base bitumen shall comply with BS 3690: Part 1 and shall normally have a penetration grade 100. Subject to the results of the mixture design procedures described in Clause B2 and approval of the Overseeing Organisation, the base bitumen may have a penetration grade up to 200.

6 Other than foaming agent(s), bitumen modifiers shall not be used unless approved by the Overseeing Organisation for special purposes or conditions.

7 The binder shall be transported to the site in tankers capable of maintaining the required temperature and a homogeneous binder consistency and transferred to the stabilising plant in a controlled and uniform manner.

8 The foaming of the bitumen shall be carried out within the spraybar system of the recycling machine and immediately mixed with the pulverised aggregate, at which point the foamed bitumen shall have a volume of not less than 10 times the volume of the base penetration grade bitumen.

Cement, filler and lime

9 The constituents and required quality standards of hydraulic cement, filler and lime delivered to site shall be certified by the supplier, whose manufacturing and delivery processes shall be implemented using quality management systems in accordance with the ISO 9000 series of standards and certified by an accredited body.

10 Hydraulic cement as a filler or adhesion agent shall be Portland cement, Portland blast furnace cement or Portland pfa cement, in accordance with sub-Clause 3 of Clause 1001 in the Specification for Highway Works.

11 PFA, used as a filler, shall be in accordance with BS 3892: Part 1.

12 Lime for lime stabilisation (or as a modifier for plastic fines) shall, as required in the Specification Appendix (Item 2), be either quicklime or hydrated lime, complying with sub-Clause 3 of Clause 615 in the Specification for Highway Works.

Water

13 Water for moisture content control of the pulverised granular material, shall normally be obtained from a water company supply and used without testing. Water from an alternative source shall comply with BS 3148 and be approved by the Overseeing Organisation.

Pulverisation and stabilisation

14 The Contractor shall satisfy the Overseeing Organisation that the plant used for pulverisation is capable of uniformly pulverising the existing road structure in a single pass, to the depth stated in the Specification Appendix (Item 1). The plant used for stabilisation shall be capable of uniformly mixing controlled amounts of water and binder agent(s) into the full depth of pulverised layer. For either operation, the plant shall be equipped with a means for controlling the depth of processing to ±15mm of the required depth.

15 The plant used for stabilisation shall be equipped with a spraybar system within the mixing chamber capable of producing and uniformly distributing foamed bitumen binder at a monitored and controlled rate. An accessible sampling jet shall also be fitted that produces foamed bitumen having the same characteristics as that produced by the main spraybar. Flow rate meters for measuring the supply rate of hot bitumen and other liquid additives to the mixture shall be capable of recording the correct rate of flow during all states of pipeline flow (i.e. fully or partially charged). Evidence confirming the capabilities of the plant and calibration of flow meters, shall be submitted to and approved by the Overseeing Organisation prior to the stabilisation works commencing.

16 The material shall be pulverised and stabilised in a single layer if its compacted thickness is 300mm or less. If the compacted thickness is greater than 300mm, the material shall be pulverised and stabilised in the minimum number of layers between 100mm and 300mm thick. Where more than one layer is required, the Contractor shall satisfy the Overseeing Organisation that the lower layer has achieved adequate stability in accordance with sub-clause 31 of this Clause before proceeding with the overlying layer.

Pulverisation process

17 Pulverisation of the existing road structure shall be carried out in a systematic pattern, to the required depth, to ensure that all parts of the existing road designated in the Specification Appendix (Item 1) are included in the works. An overlap of at least 150mm shall be made between adjacent passes of the machine. Any material missed along hard edges or around obstructions shall 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 shall be graded to the required level profile and nominally compacted.

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

19 Excess pulverised material shall be removed by grader and/or excavator for use elsewhere on site or transported to stockpile at locations given in the Specification Appendix (Item 3). The surface of the layer shall be graded to the required level profile and nominally compacted.

20 Moisture content of the pulverised aggregate immediately prior to stabilisation shall be measured in accordance with BS 812: Part 109 using the high temperature method. The moisture content shall be uniform throughout the layer within the range ±2% of optimum moisture content for the unstabilised aggregate including any designed proportion of filler, determined in accordance with BS 1924: Part 2.

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

22 Aeration of the affected area shall be achieved by full depth passes of the recycling machine to disturb and loosen the material and assist the evaporation of excess moisture. The material shall be kept in a loose condition until subsequent moisture content tests show that the treated material has reached the required moisture content range. The layer shall be re-graded nominally to level and compacted in preparation for stabilisation.

23 Increase in moisture content of the affected area shall be achieved by the addition of water through an adjustable spraybar system in conjunction with full depth passes of the recycling machine to achieve a uniform distribution of the water throughout the layer. Increments of water shall be added and mixed in until subsequent moisture content tests show that the material has reached the required moisture content range. The layer shall be re-graded nominally to level and compacted in preparation for stabilisation.

Stabilisation process

24 Stabilisation shall not be carried out during or after periods of rainfall where the duration and intensity are likely to cause the stabilised mixture to exceed the specified moisture content criteria and compromise the stability of the layer under compaction (as defined in sub-Clause 31 of this Clause). Stabilisation of frozen materials shall not be permitted.

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

26 Immediately prior to stabilisation, any filler and/or adhesion agent shall be spread uniformly over the full-width of the layer using a mechanical spreader capable of distributing the material(s) in a uniform controlled manner. The rate of spread of these materials shall be calculated to achieve the mixture composition determined in accordance with Clause B2 and monitored as the spreading operation proceeds in accordance with sub-Clause 35 of this Clause.

27 The stabilisation shall 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 150mm between adjacent passes of the machine. The bitumen binder shall be introduced as a foamed bitumen and distributed through the spraybar system, directly into the rotor and mixing box of the stabiliser. The penetration grade bitumen shall be supplied to the spraybar of the recycling machine by pumped pipeline from on-board tanks or from a tanker moving in tandem with the recycling machine. The rate of supply of the bitumen and any foaming agent, calculated to achieve the target binder content determined in accordance with Clause B2, shall be controlled and monitored as described in sub-Clause 36 of this Clause.

28 The layer of stabilised material shall 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 shall be re-filled by grading the adjacent stabilised material into the space using a minimum amount of re-working.

29 The compaction of each layer shall be carried out using compaction plant approved by the Overseeing Organisation, until such time as the in-situ density complies with sub-Clauses 40 and 41 of this Clause and the stabilised layer provides a stable and dense tight surface. Any open or segregated surface area shall be blinded using a dry crushed rock fines.

30 The stability of the layer under compaction shall be deemed adequate if the finished surface does not shove, rut or exhibit transverse cracking under the load of subsequent construction traffic.

31 Where required by the Overseeing Organisation the stability of a layer in any area shall be assessed after a curing period of at least 24 hours by channelled trafficking using a rigid three-axle tipper truck loaded to a gross mass of 24 tonnes (assumed equivalent to three standard axles). The vertical deformation shall be measured in all wheeltracks at monitoring points on each of 5 transverse sections set 1m apart after 5, 15, 30 and 40 passes of the truck. The mean vertical deformations at the above trafficking increments shall be plotted against the respective number of truck passes and the mean vertical deformation corresponding to 100 standard axles shall be interpolated. The layer shall be deemed acceptable if the mean vertical deformation corresponding to 100 standard axles is less than 10mm.

32 On completion of compaction the surface shall be sealed using a sprayed membrane of Class K1 - 70 bitumen emulsion complying with Clause 920 in the Specification for Highway Works. The bitumen emulsion shall be sprayed at the rate stated in the Specification Appendix (Item 4). Where the surface is opened to traffic, the sealing membrane shall be blinded with fine aggregate or sand applied at a rate of 5.5 to 7.0 kg/m^2. A curing period of not less than 36 hours shall be allowed before the surfacing is laid.

Process control

33 The condition or quality of the pulverised material or stabilised mixture shall be assessed for specification compliance on the basis of each 800 m^2 area of the works or part thereof, completed in the same working day.

34 The moisture content specified in sub-Clause 20 of this Clause shall be monitored using test specimens extracted from three bulk samples of pulverised aggregate taken from points evenly spaced along a diagonal bisecting the assessment area. The bulk samples shall comprise material taken from the full depth of the pulverised layer. The depth of pulverisation relative to the designed road level shall be measured and recorded at each point. The samples shall also be tested to determine the particle (or 'lump') size distribution in accordance with BS 812: Part 103 (or by an amended method to obtain an early assessment of grading, provided correlation with the standard test method can be demonstrated). Where appropriate, the residue of the three samples shall be combined to form one bulk sample and the bitumen content of the pulverised aggregate determined in accordance with BS 598: Part 102. If any adjustment of moisture content is carried out prior to stabilisation, subsequent samples shall be taken and further moisture content tests completed.

35 The rate of spread of cement, filler, hydrated lime or quicklime shall be measured by weighing the amount of material retained on each of five trays or mats of known area laid in the path of the spreading machine. The trays shall be positioned approximately at points equally spaced along a diagonal bisecting the area of coverage. The mean rate of spread and percentage addition of the material shall be determined and recorded for each assessment area.

36 The rate of supply of bitumen binder and any other fluids to the stabilising plant shall be set and continuously monitored using the appropriate flow rate meters on the stabilising plant. As a check at the start of each work period, the rate of supply of bitumen shall be determined from before and after dip measurements of the storage/delivery tanks, related to an area of stabilisation of not more than 250m^2. The calculated supply rate of bitumen for each test area shall be recorded.

37 As directed by the Overseeing Organisation, where lime has been used to modify a cohesive soil component of the pulverised aggregate, the acceptability of the modified materials shall be tested in accordance with sub-Clause 13 of Clause 615 in the Specification for Highway Works.

38 After stabilisation, prior to final compaction of the stabilised mixture, five samples of the stabilised material shall be obtained. Each sample shall be taken from a point equally spaced along a diagonal bisecting the area under consideration. The location of each sampling point shall be recorded. Each sample shall comprise at least 40kg of material taken from the full depth of the layer. The depth of stabilisation relative to the designed road level shall be measured and recorded at each point. Where appropriate and as directed by the Overseeing Organisation, the depth measurements shall be made using a stringline stretched between points of known level.

39 In the field, each sample of the stabilised material shall be mixed in a tray and sufficient representative material taken to produce a 150mm cube specimen, made in accordance with Clause 1040 of the Specification for Highway Works. The refusal density for each cube sample shall be determined to the nearest 10kg/m^3. The remainder of each sample shall be retained in a sealed condition for subsequent testing on site or in the laboratory, as described in sub-Clauses 42, 43 and 46 of this Clause.

40 After trimming and final compaction of the stabilised layer, the in-situ bulk density shall be measured close to the material sampling points, using a nuclear density gauge in direct transmission mode, to a depth within 25mm 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.

41 The in-situ bulk density values obtained shall be compared with the refusal density value obtained from the cube specimens at the respective sampling points. The average in-situ bulk density of each set of five values shall be at least 95% of the cube refusal density, with no individual in-situ density value less than 93% of the respective refusal density.

42 Either on site or immediately on arrival at the laboratory, each of the five samples shall be tested for moisture content in accordance with BS 1377: Part 2.

43 Either on site or within 24 hours of arrival at the laboratory, one 150mm diameter x 75mm to 100mm high cylinder test specimen [briquette specimen] shall be manufactured from each of the five samples, compacted in a PRD mould to a target density of the average in-situ bulk density measured in the field. The final density of each briquette specimen shall be measured and using the respective moisture content values, the dry density values shall be determined.

44 The curing history of the five briquette specimens prior to testing shall be recorded, which shall, as soon as possible after manufacture, include a period of 72 hours at a nominal temperature of 60^{0}C. Immediately before testing each briquette specimen shall be conditioned in air for a minimum period of 12 hours at 20^{0}C and then tested in accordance with BS DD 213 to determine the Indirect Tensile Stiffness Modulus (ITSM) of the material. After removal from the test apparatus, each briquette shall be immersed in water at 20^{0}C for a minimum period of 24 hours, then retested to determine the ITSM of the material in a saturated state.

45 The air voids content of each briquette shall be determined in accordance with BS 598: Part 104 except that the maximum density for the partially coated product, used in the air void content calculation, shall be standardised using the maximum density determined for a fully coated laboratory prepared specimen. A sample of loose pulverised aggregate obtained prior to the addition of foamed bitumen shall be dried to constant mass at 50^{0}C. Sufficient hot penetration bitumen shall then be added in increments to the dried aggregate in a mechanical mixer until the mixture is visually fully coated (using in the order 4% of added bitumen). The coated specimen shall be tested to determine maximum density as specified in DD 228 Issue 2.

46 The residue of the five samples of stabilised material shall be combined to form one bulk sample. From this bulk sample, four sub-samples shall be obtained. Three sub-samples shall be tested to determine the particle size distribution and one sub-sample to determine bitumen content in accordance with BS 598: Part 102. The added bitumen content shall be the measured bitumen content of the stabilised mixture, less the bitumen content of the pulverised aggregate prior to stabilisation.

47 The specification compliance criteria for the process control tests shall be as described in Table B1/1

End product performance of cold in-situ recycled bitumen bound material

48 The end-product performance of the cold in-situ recycled bitumen bound material shall be assessed on the basis of measurements carried out in areas of 800m^2 or part thereof completed each working day which match the areas defined in sub-Clause 33 of this Clause.

49 Within 24 hours of completion, the as-installed performance of the stabilised layer shall be evaluated using a dynamic plate loading or penetrometer technique to determine values of elastic modulus at points on a nominal 2m grid pattern. The elastic modulus at each point and the mean elastic modulus for the assessment area shall comply with the minimum standards stated in the Specification Appendix (Item 5). Additionally, before proceeding with construction of the overlying pavement, the evaluation process shall be repeated to demonstrate that the elastic modulus value at all points and that of the mean value have increased over the respective

Table B1/1 Compliance criteria for process control tests on recycled bitumen bound material

Material property or characteristic	Individual results	Mean from test set
Relative in-situ density	93% minimum	95% minimum
Aggregate grading [BS 598: Part 102]	In accordance with sub-Clause 3 of this Clause	
Added bitumen content [BS 598: Part 102]	Target ± 0.6% ##	N/A
Moisture content [BS 1377: Part 2]	Optimum ± 3%	Optimum ± 2%
Layer thickness [site measurement]	± 25mm of specified	± 15mm of specified
Cement content [site rate of spread measurements]	Target ± 2%	Target ± 1%
Indirect Tensile Stiffness Modulus (ITSM) - dry specimens	2000MPa minimum	2500MPa minimum
ITSM - water saturated specimens	1500MPa minimum	2000MPa minimum
Percentage air voids content	12% maximum	9% maximum

Subject to the absolute minimum added bitumen content stated in the Specification Appendix (Item 7)

as-installed values by not less than the percentage values stated in the Specification Appendix (Item 5). Where these criteria are not met, the full extent of non-compliant material shall be determined and appropriate remedial measures implemented. Remedial action shall comprise either a delay in construction to allow further curing and stiffening of the layer or a repeat of all or part of the recycling process, followed by re-evaluation, until a compliant material is achieved.

50 Within 270 days of completion of the surfacing works a Falling Weight Deflectometer survey shall be carried out and analysed in general accordance with HD 29/94 (DMRB 7.3.2, 1994). In particular, the measurements shall be taken on the finished road surface in the nearside wheelpath, at a uniform and maximum spacing of 10m. The survey shall be carried out during a period when the pavement temperature at a depth of 50mm is within the range 15 to 25^{0}C. The FWD results shall be analysed using a linear elastic FWD back-analysis computer program, with the pavement modelled as a two layer system. Layer 1 shall represent the combined design thickness of the bound materials (i.e. the combined recycled material and overlying surfacing materials) and layer 2 shall represent the unbound foundation layer of infinite depth. End-product performance shall be defined in terms of the calculated stiffness of layer 1, uncorrected for temperature. Compliance shall be achieved when not more than 15% of the calculated values within each assessment area fall below the stiffness value specified in the Specification Appendix (Item 6).

51 In the event that the layer 1 stiffness requirement of sub-Clause 50 of this Clause is not met, the full extent of the non-compliant material shall be determined by further investigation involving coring and laboratory testing. For each area of non-compliance, cores shall be extracted through the full depth of the stabilised layer at locations directed by the Overseeing Organisation, at a minimum rate of 1 x 150 mm diameter core per 75m^2.

52 The Contractor shall be responsible for extraction of the cores with the minimum of force or disruption. Air flush coring shall be allowed for materials that are disturbed by water flush coring. After extraction, each core shall be labelled and photographed and prior to testing, shall be stored in sealed polythene bags, in a uniformly supported position, at a temperature of 20^{0}C ± 5^{0}C. The thickness of recycled layer shall be measured and recorded.

53 Reinstatement of all core holes shall be completed before opening the area to traffic. All backfill materials shall comply with the 'Specification for the Reinstatement of Openings in Highways' issued by the Highway Authorities and Utilities Committee.

54 If, at any of the prescribed core locations, it is not possible to extract an intact core of suitable size or condition for the end-product performance testing, using a maximum of three attempts in an area of 1.5m radius, the material in the vicinity shall be deemed not to comply with the end-product performance specification.

55 In the laboratory, each of the cores extracted successfully shall be trimmed to remove surfacing materials and any underlying material prior to cutting into core test specimens between 75mm and 100mm high. Where possible, three test specimens shall be obtained from each core, one from the upper surface, one from the centre and the other from the lower half.

56 All core test specimens thus obtained shall be tested in accordance with the standards described in Table B1/2.

57 The results obtained shall be used for assessing the expected performance of the stabilised material in the works, in relation to the known performance of BS specified roadbase materials. The stabilised material in the trial area shall be deemed acceptable if the compliance criteria described in Table B1/3 are met.

Table B1/2 Testing standards for core specimens of recycled bitumen bound material

Test	Standard
Bulk density Air voids content Indirect Tensile Stiffness Modulus	BS 598: Part 104 & sub-Clause 39 of this Clause BS 598: Part 104 & sub-clause 45 of this Clause BS DD 213: 1996

Table B1/3 Compliance criteria for recycled bitumen bound material - core specimens from the works

Material property or characteristic	Individual cores	Mean from core set
Core density relative to refusal density Air voids content Layer thickness [from core measurement] Indirect Tensile Stiffness Modulus - dry [BS DD 213]	93% minimum 9% maximum ± 25mm of specified 2000 MPa minimum	95% minimum 7% maximum ± 15mm of specified 2500 MPa minimum

Clause B2 Cold in-situ recycled bitumen bound material - mixture design and characterisation

1 Mixture design and characterisation of cold in-situ recycled bitumen bound material for each site, or section of site, including details of filler, binder, adhesion and/or stabilising agent(s) and their quantities, shall be submitted to the Overseeing Organisation at least one week prior to commencement of the recycling works. Where the site investigation has identified significant variation of existing pavement materials between different sections of the site, a mix design shall be submitted for each section of the site. The proposed plan area and depth of the different sections, covered by each mixture design, shall be approved by the Overseeing Organisation.

2 The testing standards used for the mixture design of the recycled bitumen bound mixture shall be those listed in Table B2/1.

3 The aggregate used in the design and characterisation process shall be obtained from the appropriate section of the works and shall be representative in terms of component material proportions, to the in-situ pavement layers to be pulverised. The laboratory manufactured aggregate shall be pulverised or crushed such that it closely replicates the nature and grading of the in-situ pulverised aggregate and that the aggregate particle size distribution shall comply with sub-Clause 3 of Clause B1.

4 The laboratory prepared aggregate shall be thoroughly mixed with measured proportions of the bitumen binder and adhesion agent(s), to produce at least three trial mixtures with different added bitumen contents. The type and grade of the bitumen and adhesion agent(s) used in the trial mixtures shall be the same as those used in the finished works.

5 The different added bitumen contents of the trial mixtures shall be set at increments of between 0.5% and 1.0% in the range 3.0% to 6.0%, with appropriate allowance made for residual binder in any crushed asphalt component. From each trial mixture, four 150mm diameter x 75mm to 100mm high, cylinder test specimens (briquette specimens) shall be manufactured, compacted to refusal by vibratory compaction in a cylindrical metal mould, using the compaction mould assembly and vibrating hammer described in BS598: Part 104. The bulk density of each cylinder shall be determined.

6 The briquette specimens shall be cured for a period of 72 hours at a nominal temperature of 60^0C. Following this, the briquette specimens shall be conditioned in air for a minimum period 12 hours at 20^0C and then immediately tested in accordance with BS DD 213 to determine the ITSM. After further conditioning of the briquettes, immersed in water at 24^0C for a minimum period of 24 hours, the ITSM tests shall be repeated on each specimen.

7 The characteristics of the mixture to be used in the works, including any added water, shall be determined using the optimum ITSM (dry) values. If peak conditions are not clearly displayed then plateau characteristics shall be accepted and the lowest added bitumen content for which all the criteria defined in Table B2/2 are met, shall be used in the works subject to a minimum of 4.0% for mixtures containing only pulverised unbound or cement bound aggregate and 3.0% for mixtures containing only pulverised bitumen bound materials.

8 On the basis of the foregoing test results, the contractor shall declare details of the Job Standard Mixture(s) for the works setting out target aggregate grading and type, tolerance on the target gradation, added water content, adhesion agents, binder content and tolerances. The method of compaction shall be described such that the material to be utilised in the works meets the mixture characterisation parameters.

Table B2/1 Testing standards for the design and characterisation of recycled bitumen bound material

Test	Standard
Moisture content	BS 1377: Part 2
Bulk Density	BS 598: Part 104
Air Voids Content	BS 598: Part 104 & sub-Clause 45 of Clause 970AR
Grading and Binder Content	BS 598: Part 102
Indirect Tensile Stiffness Modulus [ITSM]	BS DD 213: 1996

Table B2/2 Acceptable design and characteristic requirements for recycled bitumen bound material

Property or characteristic	Individual specimens	Mean from test set
Moisture content	N/A	Optimum ±2%
Indirect Tensile Stiffness Modulus [dry]	2000MPa	2500MPa
Indirect Tensile Stiffness Modulus [wet]	1500MPa	2000Mpa
Bitumen content	N/A	Target ±0.5%
Particle size distribution	N/A	Zone A or Zone B
Air voids content	Maximum 9%	Maximum 7%

Specification appendix

Site specific details and requirements to be stated in the Contract for in-situ recycled foamed bitumen bound material:

Item 1	Site description, location details and depth of recycling:	
	Overall location - reference to plans	
	Section location details- reference to plans & sections	
	Location of services- reference to plans & sections	
	Depth of recycled layer	......mm
Item 2	Type of lime required for modification of cohesive soils	......
Item 3	Location of places to stockpile excess pulverised materials awaiting re-use elsewhere	
Item 4	Rate of application of bitumen emulsion sealant spray	......l/m^2
Item 5	Minimum elastic modulus within 24 hours obtained using a dynamic plate or penetration test:	
	Single point value	......MPa
	Mean value	......MPa
	Minimum percentage increase of single point elastic modulus values	...... %
	Minimum percentage increase of mean elastic modulus value	...... %
Item 6	Stiffness value below which not more than 15% of FWD derived stiffness values shall fall for combined surfacing and recycled material.	......MPa
Item 7	Absolute minimum added bitumen content	......%

Publication appendix

British Standards Institution (1984). *Bitumen Road Emulsions (Anionic and Cationic)*. BS 434. Part 1: Specification for bitumen road emulsions. London, British Standards Institution.

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British Standards Institution (1990). *Testing aggregates*. BS 812. Part 109: Methods for determination of moisture content. London, British Standards Institution.

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Notes for guidance on the specification for cold in-situ recycled materials

General advice for design and construction of cold in-situ recycled materials is published in Volume 7 of The Design Manual for Roads and Bridges (DMRB).

These notes, related directly to the associated Specification for Cold In-situ Recycled Materials, offer the Design Consultant, Overseeing Organisation and Contractor the latest best practice advice on the respective design, supervision and execution of cold in-situ recycling works, used for structural maintenance of highway pavements.

Dependent on the type of pavement and specific site conditions, the cold in-situ recycling process may be used to form the structural course for a reconstructed pavement or the structural course and foundation platform as a combined layer. Alternatively, it may be used to provide a foundation course for a new overlying pavement construction.

Site evaluation

Identification of sites for structural maintenance by cold in-situ recycling.

Structural maintenance of a road pavement may be required for a variety of reasons, when the running surface of the pavement becomes unserviceable and the cost of local repairs too expensive to sustain, due to the underlying pavement structure being incapable of offering the support required.

In the event that the deterioration is identified as being a failure of the road haunch, any remedial measures should be investigated and implemented in accordance with TRL Report 216, *Road Haunches: A Guide to Re-usable Materials* (Potter, 1996).

If the deterioration is identified as being a general structural failure of the running lanes then any remedial measures should be investigated and implemented in accordance with TRL Report 386, *Design Guide and Specification for structural maintenance of highway pavements by cold in-situ recycling* (Milton and Earland, 1999).

In keeping with the objectives of sustainable development, each site should be investigated with the prime aim to determine the suitability of the existing materials for re-use. Irrespective of the remedial strategy ultimately to be implemented, the limits and condition of the site should be identified, including the following details for completion of the Specification Appendix (Item 1):

- location, length and width of the site;
- construction of existing pavement;
- type and severity of deterioration;
- subgrade bearing capacity and condition;
- location and condition of drainage;
- location and condition of services;
- edge detail and verge condition, and
- future traffic loading.

To achieve the economies of scale and energy savings offered by the in-situ recycling process, a minimum programme of works in the order of 3,000m^2 is suggested as a general guide, which could be a combination of a number of locally close smaller schemes. However, in particular circumstances, where conventional methods of reconstruction are onerous or precluded, smaller scale recycling works may still offer a cost effective solution.

The use of the cold in-situ recycling process may also depend on whether there is sufficient thickness of existing pavement available for recycling. Although, in certain circumstances, it may be possible to include subgrade material into the recycled structural course, provided a non-plastic pulverised aggregate is produced naturally or by modification using lime or cement. Alternatively, it might be possible to import additional material suitable for recycling.

Investigation framework

Any pre-contract site evaluation forming the first stage of the design process, should be planned and implemented to ensure that sufficient information is obtained, to demonstrate to the Overseeing Organisation whether or not, the recycling option is feasible. In addition, this evaluation should offer any prospective contractor all information necessary to plan their own working practices and to tender on an equitable basis to achieve the targets set by an end-product performance specification.

The sampling and testing proposals for cold in-situ recycling projects on medium to heavily trafficked sites are summarised in Table 4 of TRL Report 386. However, the actual scope of investigation carried out should reflect the nature and variation of the existing pavement materials.

Sites known to contain a variety of materials of uncertain origin should be evaluated more fully than those that are known to contain consistent layers of standard materials. The limits of each section of works should be identified and listed separately in the Specification Appendix (Item 1). Also, sufficient representative information should be collected to satisfy the design process within each of these sections.

Alternative recycling strategies

The situation may arise where, for the purposes of designing and implementing in-situ recycling, the variation of thickness and/or materials is beyond a section by section definition. Although, as a mixed stockpile of materials from various parts of the site, it provides suitable feedstock for a recycled aggregate.

In such cases, despite being less environmentally sustainable compared with the in-situ process, in terms of transport movements and energy used, alternative recycling strategies could be considered using central or mobile crushing, screening and mixing plants.

To encourage and advance the cause of sustainable development still further, attention should be paid to the removal from site of excess pulverised aggregate, which could be used to strengthen other roads and lanes in the area. Local co-operation between different highway authorities should be sought and programmes of maintenance works on different parts of the local road network co-ordinated. Locations for stockpiles of excess materials should be included in the Specification Appendix (Item 3).

Representative test specimens

For any assessment related to the design of recycling works, it is particularly important that any sample of aggregate obtained for testing is typical of the pavement to be recycled. Either as a mixed sample in representative proportions or alternatively, in separate components for recombining later.

Ideally, the test specimens should also represent the grading and particle shape of the pulverised aggregate. Development and use of mini-planers designed for trenching works, used as an in-situ sampling tool, may offer a means of obtaining such samples. However, to date, pulverised aggregate is not generally available during the pre-contract investigation and the design process relies on test specimens derived from samples crushed in the laboratory. A variety of laboratory crushing methods and devices are currently employed, but none is specifically designed to recreate the pulverised aggregate produced by a recycling machine.

Where it is recognised that the laboratory crushing process is not achieving sufficient fine material - which is often the case where the feedstock material contains a significant proportion of hot rolled asphalt - the finer grading should not be obtained by further excessive crushing, since this would not reflect the pulverisation in the field, which tends not to cause breakage of the existing aggregate component. Although not ideal, the grading of the test specimen could be contrived to satisfy the specified grading envelop by the transfer of fine material from other sub-samples of the laboratory crushed material.

Alternatively, the grading of the test specimens could be made to meet the specified grading envelop by the addition of crushed rock fines, pit sand or PFA, particularly if their addition is considered beneficial to the performance of the recycled material in the field. Therefore, if the design using these test specimens is accepted, the proportion of fine material added to the material pulverised in the field should ideally, equal the proportion of the same fine material used in the design process.

Underground services, ducts and culverts

Because of their potential for disrupting the recycling works, all known services, ducts and culverts within 150mm of underside of the recycled layer should be accurately located and included with the site details given in the Specification Appendix (Item 1).

Risk assessment

Before making a Contract involving the use of cold in-situ recycled materials, which are inherently more variable than plant produced new materials, the additional risks should be identified, apportioned and their management pre-planned to the satisfaction of all parties concerned. For this reason, the Client, Overseeing Organisation and Contractor should be satisfied and be agreed that the existing pavement materials in all sections of the works, as defined in Specification Appendix (Item 1), are capable of being recycled by pulverisation, to form the primary aggregate component of a new cold in-situ recycled mixture. Also, that the mixture designed in accordance with either Clause C2 for cement bound material or B2 for foamed bitumen bound material, is capable of being produced to meet the end-product performance requirements.

Component materials

Pulverised aggregate

The nature and grading of the aggregate produced by pulverisation will depend largely on the nature, thickness and proportions of the existing road materials. In situations where the depth of the existing pavement is insufficient to accommodate the new pavement design, it may be necessary to include subgrade material into the recycled structural layer or treat the subgrade as the only foundation, compensated by an equivalent increase in thickness of the recycled layer. Alternatively suitable additional aggregate could be imported provided site level changes are acceptable.

Normally the cement bound recycling option is reasonably insensitive to the aggregate grading, nevertheless an upper limit of 35 per cent by mass passing the 75 micron BS sieve is specified.

In comparison, the foamed bitumen bound option is often highly sensitive to the fines component, since the foamed bitumen has a tendency to mix and conglomerate with the fines. As a result, the amount passing the 75 micron BS sieve should ideally, be restricted to the range of not less than 5 per cent and not more than 20 per cent, none of which should be clay.

Finer material may be tolerated, provided any clay fraction is modified using either hydrated lime or Portland cement. This pre-treatment is normally required if the percentage of aggregate passing the 75micron BS sieve is greater than 20 per cent and the Plasticity Index of material passing the 425 micron BS sieve is greater than 6.

Conversely, any material that is too coarse may be modified by the addition of fine material to meet the specified grading. Crushed rock fines, pit sand, PFA or lime filler are examples of materials most commonly used.

Moisture

The moisture content of the pulverised aggregate during stabilisation and compaction is as important as the grading, since it is a prime feature controlling the workability and therefore, the degree of compaction that is achievable.

For compaction of granular material used in construction, the moisture content is usually targeted on the optimum moisture content determined in accordance with BS 5835. However, for in-situ recycled mixtures, the specified moisture content is dependent on the binder content, targeted slightly on the wet side of optimum moisture content determined in accordance with BS 1924: Part 2. Furthermore, the constituents of the mixture to determine optimum moisture content are dependent on the proportion of filler added in the field.

For cement bound mixtures, experience has shown that best compaction results are achieved using a specified moisture content range of optimum moisture content to +4% of optimum moisture content. But for foamed bitumen bound material, since the foam contributes to the fluid content of the mixture, a specified moisture content range ±2% of optimum moisture content is recommended.

In those cases where only a small amount of filler is added in the field, the optimum moisture content of the unmodified pulverised aggregate will normally suffice for moisture content control purpose, since the moisture absorbed by the filler is mostly balanced by the suppression of the optimum value. However, where the addition of filler in the field accounts for more than 4 per cent by mass, the moisture content control should be based on the optimum moisture content determined for the modified aggregate.

Binder agents

Primary binder agents:

The selection of the primary binder agent for a particular recycling contract will depend to a great extent on the site conditions, cost factors, and the design requirements in terms of either a flexible or flexible composite pavement. But for UK conditions the current recommended choice is restricted to Portland cement or foamed bitumen.

Portland cement is readily available at reasonable cost and apart from the potential for thermal cracking of stronger mixes, it has the advantage of being adaptable to a wide range of site conditions. Methods for safe working are well established and it is currently an accepted binder for mix-in-place CBM1 and CBM2, as described in Table 10/8 of the Specification for Highway Works.

In practice it is possible to use penetration grade bitumen from grade 40 to over 200 as the base bitumen for foaming. However, higher penetration grades which tend to foam better, are likely to produce mixtures of significantly lower stiffness. Experience in the UK has shown that on balance, a base bitumen of penetration grade 100 achieves the highest possible mix stiffness consistent with an acceptable foaming and coating ability.

The stiffness gain of foamed bitumen bound mixtures is slower than that achieved by the cooling of hot-mix bitumen mixtures and is influenced by the ambient conditions which dictate curing rate.

In winter conditions and particularly in colder districts, the use of higher penetration grade bitumen may more easily achieve the specified degree of compaction. However, this is likely to produce a lower stiffness material, which should be checked as part of the design process, bearing in mind that a mix of lesser stiffness will require a thicker construction to achieve equal performance.

Foamed bitumen has a low apparent viscosity, high volume and low surface tension characteristics which enable moist, cold aggregate surfaces to be coated, particularly the fine aggregate portion. The process does not require the evaporation of a solvent or excess water prior to compaction and the material can be reworked if necessary, up to 48 hours after processing.

The success of foamed bitumen mixtures rely upon early life stability derived from aggregate interlock for pre-trafficking and ongoing development of stiffness. However, provided the density achieved is at least 95% refusal density, experience has shown that opening to traffic in a one day construction cycle is feasible within the contract. Although, a curing period of at least 36 hours should be allowed before commencing with the surfacing, to avoid a situation where the bitumen from the recycled layer could imigrate into the hot applied surfacing.

Supplementary binder agents:

Portland cement is commonly used as a supplementary binder in foamed bitumen bound mixtures, added in the proportion of about 2 per cent by mass, to act as an adhesion agent between the bitumen and damp aggregate. By using this amount of cement, it is likely to contribute significantly to the development of strength and in consequence, a partially cemented bitumen bound hybrid material is formed.

Lime may be added as filler or as the modifier for plastic fines within the pulverised aggregate. Despite the practical advantages of using quicklime related to water absorbtion and control of spreading, the stringent safety measures lead to the conclusion that hydrated lime is the preferred option for inclusion in the Specification Appendix (Item 2).

Pulverisation and stabilisation

Road pulverisation and stabilisation involves the use of specialised stabiliser plant that operates to the specified depth plus construction tolerances. To ensure adequate pulverisation and mixing of materials to full depth, it is recommended that the drive performance of the recycling machine is at least 260kW.

Stabilisers are manufactured with a height adjustable mixing box situated close to road level, incorporating a special toothed rotor designed to pulverise or mix the material within the mixing hood. The use of smaller agricultural equipment is no substitute, since they are usually designed to work on cohesive soils and therefore, are not designed to produce pulverised granular aggregate of the required grading or shape for construction purposes.

Since the powerful stabiliser plant can readily damage services, the Overseeing Organisation should identify if any services or obstructions are present and include their details in the Specification Appendix (Item 1). The time required to lower any services should also be taken into account within the works programme.

A specialist manufactured stabiliser plant will almost certainly incorporate all the features and facilities necessary to complete the works in accordance with the current recycling specification. Some will be larger and more powerful than others, whereas others may incorporate more refined control systems.

The systems normally employed to control the depth of pulverisation relate the position of the rotor relative to the vertical position of the wheels. Therefore, to ensure that the appropriate depth of pulverisation or stabilisation is carried out consistently, it is particularly important that a working platform of known level profile is prepared prior to the operation of the stabiliser.

Process control

This section provides guidance for the Overseeing Organisation to help supervise the works, but in addition, describes the best practice for the Contractor to follow, to control the pulverisation and stabilisation processes.

Cement bound material

Because of the similar nature of the cement bound recycled material to that of plant mixed CBM, significant sections of the specification clauses for CBM related to process control given in the Specification for Highway Works apply equally well for the recycled option. In fact, the Specification for Highway Works refers directly to the option of using a mix-in-place method of construction for CBM1 and CBM2 mixtures. In consequence, most of the NG clauses given in the Notes for Guidance on the Specification for Highway Works, are also applicable to in-situ recycling.

One exception to the above guidance, relates to the curing period and use by traffic. In a structural maintenance situation using in-situ recycling, there is often a requirement to maintain immediate access through and within the site, for residents and services traffic. Also, for most recycling contracts, any access restriction will inevitably delay the works programme. Therefore, early life or same day trafficking is sometimes unavoidable.

However, any impairment to the recycled layer by early trafficking may be mitigated by the use of higher cement content for early strength gain or by ensuring that adequate compactive effort has been applied and high density achieved. Provided the as-installed elastic modulus measured by dynamic plate loading or penetrometer technique, meets the targets set by the specification, there should be no problem proceeding with construction of the overlying pavement.

Conversely, without additional cement to enhance strength development, it is possible to argue that early life trafficking could be beneficial to the longer term performance of the pavement, by establishing a closer spaced pattern of crack in the structural course, thus making the surfacing less prone to reflective cracking problems.

Foamed bitumen bound material

Although this material is generally labelled as a bitumen bound material, it is unlike any standard hot plant mixed bitumen bound material. The foamed bitumen tends to combine more readily with the fines component of the pulverised aggregate, forming a ‘mortar’ matrix, which fills the voids between the partially coated coarse aggregate. In addition, cement is commonly used as an adhesion agent, in which case a component of the stiffness is likely to derive from the hydration of the cement. Therefore, unlike the cement bound option, the specification and notes for guidance for standard bitumen bound plant mixes are not readily applicable to this cold in-situ recycled product.

Compaction control using the Nuclear Density Meter is essentially the same as for the cement bound option, and provided adequate stability of the layer is achieved, early life trafficking is seen as no problem. The collapse of the foam will take place shortly after mixing to allow development of stiffness by a curing process, which involves stiffening of the bitumen and cement bound mortar. As an additional safeguard, the as-installed performance measured by either the dynamic plate loading or penetrometer technique, should be able to demonstrate that the layer has achieved a required stiffness, before proceeding with the construction of the overlying pavement.

Added water and moisture control

Although the control of moisture content is of prime importance for optimum compaction conditions, there is currently no automated process available that can ensure the provision of moisture at a uniform and optimum level during the recycling process. It is vital therefore, that the process is controlled by an experienced operator who has access to controls for adding water, particularly when the water is sprayed directly in the mixing box at the time of stabilisation.

The stabiliser should ideally, be fitted with a separate pump and spraybar system for metering the added water, regulated to the ground speed of the machine. An experienced operator will normally assess the moisture content of the mix relative to the target optimum by squeezing samples of the material regularly by hand and be guided by test results at the commencement or during any job so as to ‘calibrate’ personal judgement. The operator must assess the moisture content immediately behind the stabiliser and be prepared to make quick adjustments as the machine may be progressing forward at a rate of 4-6 metres per minute.

Application of cement or hydrated lime

Cement may be required either as the primary binder or as a supplementary binder to act as an adhesion agent or to help improve the short term properties of the compacted material. In comparison, hydrated lime is only used occasionally, most often as a plasticity modifier for cohesive fines within the pulverised aggregate.

Specialist spreaders are vital for the application of these materials, which should incorporate control systems to ensure that the rate of spread is achievable to a target accuracy of ±0.5 per cent of the specified spread rate.

The particle size of cement and lime as supplied may vary and such behaviour should be noted as it may affect the accuracy of application. The use of consistent sources and standard routines for storage and loading of the spreader is recommended to minimise any variation.

Application of foamed bitumen

Because of the short life span of the fully foamed bitumen during the mixing process, usually defined in terms of its ‘half-life’ (i.e. time taken in seconds for the foamed bitumen to settle to one half of the initial expanded volume), it is necessary for the foaming process to be incorporated into the spraybar of the recycling machine, for immediate distribution and mixing with the pulverised aggregate in the mixing hood. The reduced viscosity and greater volume of the foamed bitumen enables it to be distributed and mixed with the damp cold aggregate.

To ensure adequate mixing of the foamed bitumen with the aggregate, the minimum expansion ratio of the foam should be 10, linked with a minimum half-life of 10 seconds. Also, in the interests of durability, irrespective of the results of the design tests, the absolute minimum added bitumen content should be 3.5 per cent. The uniformity of mixing should be continuously inspected visually by the contractor and work should stop if bitumen streaks or blotches are observed.

A typical stabiliser has computer-controlled devices on board that calculate the application rate of the binder as the stabiliser moves along the pavement. The stabiliser should ideally, be fitted with a separate pump and spraybar system for metering the added bitumen and one that allows variable widths of binder to be applied. The bitumen jets should be of a self cleansing design and for reasons of safety, bitumen lines should be heated.

The spraybar control systems incorporated into the stabiliser should ensure that the rate of spread is achievable to a target accuracy of ±0.5 per cent of the specified spread rate, in order to achieve a construction tolerance for added bitumen of ±0.6 per cent of the target binder content. As a means of verification, dipping in the tanker before and after a stabilisation run can be used to verify the computer collected data.

An inspection or test jet should ideally be fitted to ensure the flow of bitumen and that the required expansion and half-life qualities of the foamed bitumen are achieved.

Compaction

Compaction is a critical part of the stabilisation process and demands particular care. This is especially the case for thicker layers of construction, where there is the possibility for a density profile to develop during compaction, such that the lower part of the layer does not achieve the same density as the upper part.

This effect may be minimised when applying compaction at the earliest possible time using either heavy vibratory compaction or using a compactor capable of ‘kneading’ the material at depth, as is the case using a tamping roller. To date in the UK, heavy compaction for cold in-situ recycling works has been carried out almost exclusively using the heavy vibratory roller option, although more recently, a heavy combined pneumatic tyre roller (PTR) and vibratory drum roller has been trialed, although their field performance has yet to be verified.

From past monitored works, it is evident that the vibratory compaction did not always achieve full depth compaction of thicker layers. Therefore, where the stabilised material is assessed as having a poor workability, it is recommended that consideration be given to the use of heavy tamping rollers for the initial deep-seated compaction, particularly for layers having a compacted thickness in excess of 225mm, followed by grading of the surface and final compaction using the conventional heavy vibratory compaction. This is similar to the compaction methodology commonly used in Australia for thick-lift construction.

When using heavy vibratory compactors, caution should be exercised where there is any danger of vibratory damage to shallow culverts, underground services or adjacent buildings due to the transmission of vibrations.

The use of a pneumatic tyre roller (PTR), is often advocated as a finishing roller, particularly for the cement bound material. However, whereas the PTR may tend to assist in the compaction of the lower level material, care is required to ensure that the near surface material does not dry out or stiffen too quickly, which may result in disruption and shear displacement of the near surface material caused by the narrow loading under the individual tyres - thus resulting in an unstable surface finish and the necessity for removing loosened unacceptable material.

Surface sealant

The type and rate of spread of the bitumen sealant, as stated in the Specification Appendix (Item 4), should comply with the recommendations given in BS434.

End-product performance specification

The process of cold in-situ recycling for the structural maintenance of highway pavements has been developed and used in a variety of countries, each with their own local requirements, often related to climate and geology. Consequently, the types of road available for recycling have been diverse. As a result, previous recycling specifications have been derived from a variety of component material designs and construction methods that were generally aimed at producing materials of quasi standard form with anticipated performance similar to the plant mixed option.

Whilst the recipe and method specification has served the industry well for the lower trafficked roads, end-product performance specification is seen as a means of specifying recycled materials in their own right, using performance targets stated in terms of engineering properties, allowing the recycled material to be considered for more heavily trafficked sites on an equitable basis to standard plant produced materials.

The end-product performance assessment is designed to follow a three stage procedure, to allow the construction to proceed at the same time as giving the Overseeing Organisation the opportunity to verify the acceptability of the product at the earliest possible time.

As-installed stiffness using a dynamic plate or penetrometer test

The as-installed performance of the stabilised layer, within 24 hours of completion of compaction, is evaluated using a dynamic plate loading or penetrometer technique to determine values of elastic modulus at points on a closely spaced grid pattern. Furthermore, before proceeding with the surfacing construction, repeated values should be expected to demonstrate that the elastic modulus values have increased by a reasonable amount, as an indication that the curing/stengthening process has started. The first repeat measurements should normally be made after 24 hours and thereafter, at intervals dependent on the measured rate of increase of elastic modulus.

The single point and mean value of elastic modulus for the assessment areas, also their respective percentage increase, must comply with the minimum standards stated in the Specification Appendix (Item 5).

Experience to date using a dynamic (light) plate loading technique, has determined that fresh, well compacted cold in-situ recycled material typically achieves a single point elastic modulus value (E_{vd}) in the range 40 to 70 MPa. Therefore, the as-installed performance of a acceptable constructed layer, based on at least 100 point evaluations, is expected to display an initial minimum mean value of elastic modulus in excess of 50 MPa, with no single point value less than 30 MPa. Prior to surfacing, an increase of 20 per cent for single point values and 30 per cent for the mean value, would be indicative that the curing process is underway. For the as-installed condition and initial stage of curing, these values should be applied to both the cement bound and bitumen bound materials.

For other plate loading or penetrometer test methods an equivalent correlation shall be provided to the satisfaction of the Overseeing Organisation.

Pavement stiffness from falling weight deflectometer (FWD) survey

The current status of the FWD and associated elastic stiffness evaluation does not allow the procedure to be used as a rejection method. However, if acceptably high stiffness modulus values are determined consistently, as described in the Specification Appendix (Item 6), the method should provide the Overseeing Organisation with sufficient confidence and a means of acceptance for either the cement bound or foamed bitumen bound materials.

Experience to date using the FWD survey and analysis, as described in the Specification, suggests that a pavement stiffness value for the combined bound layers of the pavement (i.e. recycled layer plus surfacing) in the order of 5000 MPa for the cement bound option and 2500 MPa for foamed bitumen bound option, below which not more than 15 per cent of the derived values shall fall, offers an acceptable performance standard.

Compressive strength/stiffness measurements of core specimens

The development of the end-product performance specification for the cold in-situ recycled materials has passed through various stages, in which the initial intention was to determine the performance of cored specimens, in terms of either the compressive strength of cement bound material or the Indirect Tensile Stiffness Modulus (ITSM) of bitumen bound material.

The above option was set aside, however, when it was decided that the destructive coring should only be performed as a last resort. This decision was reinforced by the experience gained on some monitored sites, where the core extraction itself was difficult, such that a suitable number of test specimens could not be obtained.

The rate of success for extraction of cores from cold in-situ recycled material is generally enhanced by using air flush coring, in comparison with the success rate achieved using the more usual water flush method. Also, removal of the cored asphalt surfacing layers, before proceeding with the coring into the recycled material, was found to improve the success rate of core extraction.

In the event that acceptance is not achieved using the FWD survey and analysis, the current specification uses the core testing option as the last resort performance assessment. Therefore, if carried out after the FWD survey, as late as possible within the Contract maintenance period, it should maximise the success rate for the extraction of cores and offer the best opportunity for obtaining suitable test specimens and achieving the required ITSM values.

Mixture design and characterisation

The design procedures adopted to date, have been developed by various organisations for their own local needs, although in general, most mixture design procedures for cold in-situ recycled materials are based on the determination of compressive strength for cement bound material or the stiffness modulus for bitumen bound material, related to a recycled layer of specified thickness, to carry a required traffic loading over a stated period of time.

In practice, since the feedstock material to be stabilised does not usually exist until after pulverisation, the initial mix appraisal or design process is often a matter of experience by the specialist contractors using their particular recycling plant, to gain an understanding of the near optimum component design.

Also, since the results of stiffness and other tests performed on laboratory prepared specimens are highly dependent on the curing regime of the specimens, which is unlikely to be recreated on site, these tests are realistically only valid for comparison and assessment of the optimum mixture condition. Therefore, the values obtained do not necessarily relate to the in-situ condition of the material.

The details of the procedures given in Clauses C2 and B2 of the Specification are based on the current industry practices, which are open to development if more representative specimens and test results can be verified.

Cement bound mixtures:

For lower traffic situations, cold in-situ cement bound recycling is often used to provide a new foundation and/or structural course, designed to have an average 7 day cube compressive strength of 4.5 N/mm^2 or 7 N/mm^2 (i.e either CBM1 or CBM2 equivalent strength).

For higher traffic loading, the recycled layer is used as the main structural course, designed to have an average 7 day cube compressive strength of 10 N/mm^2 (i.e CBM3 equivalent). In ideal circumstances this material might be considered structurally equivalent to plant mixed CBM of equal compressive strength. In practice, inherent variability of the feedstock materials, short mixing period and practical difficulties associated with thick-lift construction, will require a factor of safety applied to the design thickness.

For the stronger recycled mixtures, the potential for thermal cracking and reflective cracking of the bituminous surfacing is similar to that for conventional plant mixed CBM. Therefore, the thickness of surfacing layers should normally be the same as specified for a conventional flexible composite pavement carrying the same traffic loading.

The cement contents used in the design process for recycled mixtures are similar to that required for the plant mixed equivalent, except that an absolute minimum cement content of 3 per cent by weight is recommended, to ensure there is adequate cement available for distribution throughout the mixture during the short period of in-situ mixing.

Bitumen bound mixtures:

The main objective of the design process for foamed bitumen bound recycled material is to check that an adequate level of stiffness is achieved using an optimum added bitumen content, when mixed with a pulverised aggregate derived from the existing road construction also containing the correct proportions of any adhesion agent and/or added filler.

The target stiffness for all levels of traffic is generally accepted as a NAT measured individual ITSM value of 2000 MPa and an average value of 2500 MPa.

Experience has shown that the stiffness for recycled mixtures is generally insensitive to variations of added bitumen content, with an adequate stiffness achieved for an added bitumen content over a plateau optimum range of 3 to 6 per cent, subject to the recommended absolute minimum added bitumen content of 3.5 per cent to account for durability.

Any existing bitumen in pulverised aggregate is not normally activated in the stabilisation process in the sense of mixing with the new binder, although the effect of the residual bitumen in the finished mixture could influence the stiffness achieved.

For the laboratory production of foamed bitumen, it is recommended that the anticipated bitumen supplier is consulted, in conjunction with the manufacturer of any foaming agent used, in an attempt to replicate as closely as possible, the characteristics of the foamed bitumen to be used, particularly in terms of the size and sustainability of the air bubbles during mixing.

The specified curing programme for the specimens prior to testing, including baking of the specimens for 72 hours at 60^{0}C, is not an attempt to represent the curing conditions in the field, but is a standardised attempt to replicate the longer term ageing process of the recycled material. The drawback of using this technique is that it may disguise the true early life stiffness of the recycled material, in favour of a higher set of values that may only be appropriate in the longer term.

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The research was guided by a Steering Committee members were:

S Biczysko (Chairman)	Northamptonshire County Council
J Mercer	Quality Services, Pavement Engineering Group, Highways Agency
M Roy	Somerset County Council **
S Childs	Surrey County Council
T Lomas	Hampshire County Council
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B Hicks	Colas Limited
J Potter	Transport Research Laboratory
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Substitute and supplementary members were:

R Dudgeon	Quality Services, Pavement Engineering Group, Highways Agency.
B McWilliams	W S Atkins - South West (latterly of North Somerset Engineering Consultancy)
G Mountjoy	W S Atkins - South West

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Appendix A: Research methodology

A1 Introduction

The Linear Quarry Project spanned a three year investigative period during which time data were collected from a review and examination of nine in-service roads which had been maintained using cold in-situ recycling techniques, by Local Authorities, over the preceding decade and from the construction and monitoring of full-scale trials on the A3088, Cartgate Link Road, in Somerset.

A complementary report by Milton (1999), summarised below, gives the full details of the investigative studies carried out.

A2 Sites investigated

The in-service sites had been constructed over a range of subgrades and were designed to carry, over a 20 year period, traffic loadings ranging between 2.5 msa and 20 msa. However, despite the fact that much of the earlier cold in-situ recycling work in the UK was undertaken using cement or lime as the primary binding agent, the search for sites carrying revealed only two suitable cement bound sites worthy of further investigation. Details of the in-service sites are given in Table A1.

The site of the full-scale construction trials, on the A3088 was a 15-year-old, two lane single carriageway road that was built as a major access route from the industrial estates and ferry ports to south to the A303 to the north. It was built over much of its length following the near level alignment of an abandoned railtrack, passing through a rural landscape for the most part at grade or on shallow embankment but with short lengths of cutting. The original road had exceeded its design life and distress was present in the form of surface rutting and cracking. Interpretation of deflections from a series of deflectograph surveys showed that the residual life had been exceeded.

The original pavement construction comprised 100mm of asphalt surfacing over 140mm of wet-mix macadam

Table A1 Cold in-situ recycled roads selected for performance and condition measurement

Site location	*Date of works*	*Design 20 year traffic (msa)*	*Specified recycled layer thickness (mm) #*	*Area (m^2)*	*Binder content (%) Bitumen (pen)*	*Lime*	*Cement*	*Subgrade type*	*Site/traffic conditions*
Lake Road, Portsmouth, Hampshire	July 1989	9	220	4950	4.0 (100)	1.0		Hardcore over soft alluvium	Inner urban access/bus route with significant commercial flow
Kingston Road Teddington, London	March 1994	4.5	210	2500	4.0 (100)		2.0	Thames Valley Tertiary deposits	Main urban access route with modest commercial flow
Kingsway, Bedford, Bedfordshire	May 1994	20	300	3256	4.0 (100)		2.0	Hardcore over alluvial deposits	Urban distributor road with mixed traffic/heavy rush hour
A24 London Road, Epsom, Surrey	Oct. 1989	11	250	5080	2.5 (100)	1.0		Hardcore over North Downs Tertiary beds	Urban principal route with low commercial flow
Park Road, Dartford, Kent	Nov. 1987	20	300	4500	4.0 (200)	1.0		Clay-with-flints	Urban distributor road with significant commercial flow
Priory/Knight Road, Strood, Rochester, Kent	July 1987	7	300	4950	4.0 (200)	1.0		Hardcore/ash over soft alluvium	Industrial urban access and through route, parts already carried 13msa over 10 years
Valley Drive, Gravesend, Kent (Winchester/Hillside)	1987	2.5	200	2200	** (200)	**		Coombe valley deposits	Access route to town centre, bus route but otherwise a low commercial vehicle flow
Valley Drive, Gravesend,Kent (St Hildas/Livingstone)	1987	2.5	300	2400			**	Coombe valley deposits	As above
A1078 South Wootton, Kings Lynn, Norfolk	Sept. 1995	10	250	3500	4.0(100)##		** 2.0 ##	Glacial sands and gravels	Access to docks, with significant commercial flow

*** Values not reported*
 # Plus 100mm asphalt surfacing specified for all sites
100m section of foamed bitumen bound material Ch 0 to 100m westbound

roadbase founded on a Type 1 sub-base of variable thickness between 150 and 470mm, built to reflect the changes in the CBR of the subgrade.

The Cartgate Road trial was carried out in two phases in consecutive years. Phase 1 of the trial occupied the full-width of the north and south bound lanes over a length of 1.25km, divided into eight trial sections varying in length between 100m and 150m; the monitored length of each bay was standardised at 100m. In addition, there were two control sections constructed using conventional materials, one of flexible design and the other of flexible composite design.

Four of the trial sections were constructed using a cement stabilised recycled roadbase and four with foamed bitumen bound recycled roadbase. The sections included not only different binder agents and thickness of treatment, but also different combinations of source aggregate, dependent on how much of the existing pavement was removed prior to pulverisation. Details of the designs of the sections are given in Table A2.

For Phase 2 of the Cartgate Road trial two adjacent full-width, 600m long sections were constructed on a further stretch of the A3088 to test the viability of draft specifications for both cement bound and foamed bitumen bound cold in-situ recycled material under normal contractual conditions.

In both sections, the recycled materials comprised aggregates reclaimed from the wet-mix roadbase and sub-base layers of the existing road, which were exclusively constructed using crushed carboniferous limestone from the Mendips. The construction details of each section of the Phase 2 trial are given in Table A3.

A3 Measurement of performance and pavement condition

The performance and condition of each of the nine in-service selected sites was assessed by:

- Extraction of representative cores.
- Visual survey to identify and log surface defects.
- Falling Weight Deflectometer (FWD) survey.
- Laboratory testing of selected core specimens:
  - Bulk density by gamma-ray scanner.
  - Bulk density by weighing in air and water.
  - Indirect tensile stiffness modulus (ITSM) using the Nottingham Asphalt Tester (NAT).
  - Core compressive strength/ estimated cube strength of cement bound material.

The data collected from the in-service road monitoring was supplemented by data collected from the Cartgate Road trials. During construction of the trials the following quality control and compliance testing of the material was carried out:

- Particle (lump) size distribution.
- Monitoring of moisture content.
- Cube refusal density determination.
- As placed density determination by Nuclear Density Meter.
- Thickness of recycled layer.
- Cube compressive strength of moulded samples.
- ITSM of moulded samples (foamed bitumen material only).
- Compositional analysis (foamed bitumen material only).

Following construction of the Cartgate Road trials the performance and condition of the test sections were assessed by:

- Visual inspections.
- Laboratory tests on cores.
  - Bulk density by gamma-ray scanner.
  - Bulk density by weighing in a air and water.
  - Indirect tensile stiffness modulus (ITSM) using the Nottingham Asphalt Tester (NAT).
  - Core compressive strength/ estimated cube strength of cement bound material.
- Falling Weight Deflectometer (FWD) surveys.
- Deflectograph surveys (carried out routinely by the Highway Authority).

A4 Performance compared with original design

Compilation and subsequent analysis of the data collected as outlined above enabled comparisons to be made between the in-service performance of the sites and their original design.

The comparisons for the sites where foamed bitumen binder was used are summarised in Figure A1. The corresponding comparisons for the cement bound materials are summarised in Table A4.

A5 Discussion

The results of the research carried out for roads recycled with foamed bitumen binder, showed that in all but one case the predicted life of the recycled road was at least as long as the design life. Therefore, the plotted dashed line, in Figure A1, was considered to offer a reasonable design curve for traffic loading between 2.5 msa and 20 msa, associated with a standard foundation, dependant on subgrade conditions and 100mm surfacing comprising standard asphalt materials.

Similarly, a consideration of the findings from roads recycled with cement enabled a design curve for these materials to be formulated. As was the case for the bitumen bound design, for traffic loadings between 2.5 msa and 20 msa the cement bound design curve assumes a standard foundation dependant, on subgrade condition and has associated with it a variable thickness of asphalt surfacing.

For both the foam bitumen bound and cement bound in-situ recycled roads carrying less than 2.5 msa the thickness of the recycled material is generally governed by the depth of the existing road construction and the subgrade condition. The design of these lower traffic category roads were based on the findings reported by Kennedy on behalf of the Department of the Environment, Energy Efficiency

Table A2 Details of reconstruction of Cartgate Phase 1 trial sections

Section number (chainage (m))	*Existing construction depth (mm)*	*(Lower) roadbase and foundation construction*	*Bituminous surfacing (and upper r/b)*
1 (1200-1300)	 450	Control Section 1: (Composite construction - CBM3R). 200 mm plant mixed CBM3R lower roadbase. 100mm Type 1 sub-base remains.	50 mm HRA w/c 100 mm DBM b/c or DBM upper r/b
2 (1300-1400)	 450	40 mm HRA wearing course removed. 310 mm basecourse + granular rotovated. Excess 110mm removed. 200 mm recycled to produce CBM3R equivalent lower roadbase.	As above
3 (1400-1500)	 450	40 mm HRA wearing course removed. 350 mm base course + granular rotovated. Excess 100 mm removed. 240 mm recycled to produce CBM3R equivalent lower roadbase.	As above
4 (1500-1600)	 450	100 mm bituminous surfacing removed. 250 mm granular materials rotovated. Excess 50 mm removed. 200 mm recycled to produce CBM3R equivalent lower roadbase.	As above
5 (1600-1675) (1675-1700)	 450 660	100 mm bituminous surfacing removed. 290 mm granular material rotovated. Excess 50 mm removed. 240 mm recycled to produce CBM3R equivalent lower roadbase.	As above
6 (1700-1850)	 660	40 mm HRA wearing course removed. 280 mm basecourse + granular rotovated. Excess 60 mm removed. 220 mm recycled to produce foamed bitumen DBM (100 pen) equivalent roadbase.	50 mm HRA w/c 50 mm DBM b/c
7 (1850-1975)	 660	40 mm HRA wearing course removed. 325 mm basecourse + granular rotovated. Excess 60 mm removed. 265 mm recycled to produce foamed bitumen DBM (100 pen) equivalent roadbase.	As above
8 (1975-2000) (2000-2200)	 660 450	Control Section 2: (Flexible construction - DBM) [NB. excluding existing areas of reconstruction]. 220 mm plant mixed DBM (100 pen) roadbase. Where necessary and subject to proof rolling, excavate to incorporate a minimum 150 mm Type 1 sub-base.	As above
9 (2200-2325)	 710	100 mm bituminous surfacing removed. 220 mm granular materials rotovated. No excess removed. 220 mm recycled to produce foamed bitumen DBM (100 pen) equivalent roadbase.	As above
10 (2325-2450)	 710	100 mm bituminous surfacing removed. 265 mm granular materials rotovated. No excess removed. 265 mm recycled to produce foamed bitumen DBM (100 pen) equivalent roadbase.	As above

Table A3 Details of construction of Cartgate Phase 2 trial sections

Section	*Recycled road base construction*	*Asphalt surfacing details*
1 Cement bound	100mm asphalt surfacing removed; 290mm granular materials rotovated; Excess 50mm removed; and 240mm stabilised with 4% cement to produce lower roadbase.	50mm HRA w/c 100mm DBM b/c
2 Foamed bitumen bound	100mm asphalt surfacing removed; 265mm granular materials rotovated; No excess removed; and 265mm stabilised with 4% foamed bitumen produce roadbase.	50mm HRA w/c 50mm DBM b/c

Table A4 Summary of design life and predicted performance of cement bound recycled pavements

. *Site No*	*Original 20 year design life (msa)*	*Predicted overall life of the recycled pavement (msa)*
Valley Drive, Gravesend St Hildas/Livingston	2.5	10
A1078 South Wooton, Kings Lynn	10	10
A3008 Cartgate Road, Yeovil	22	22

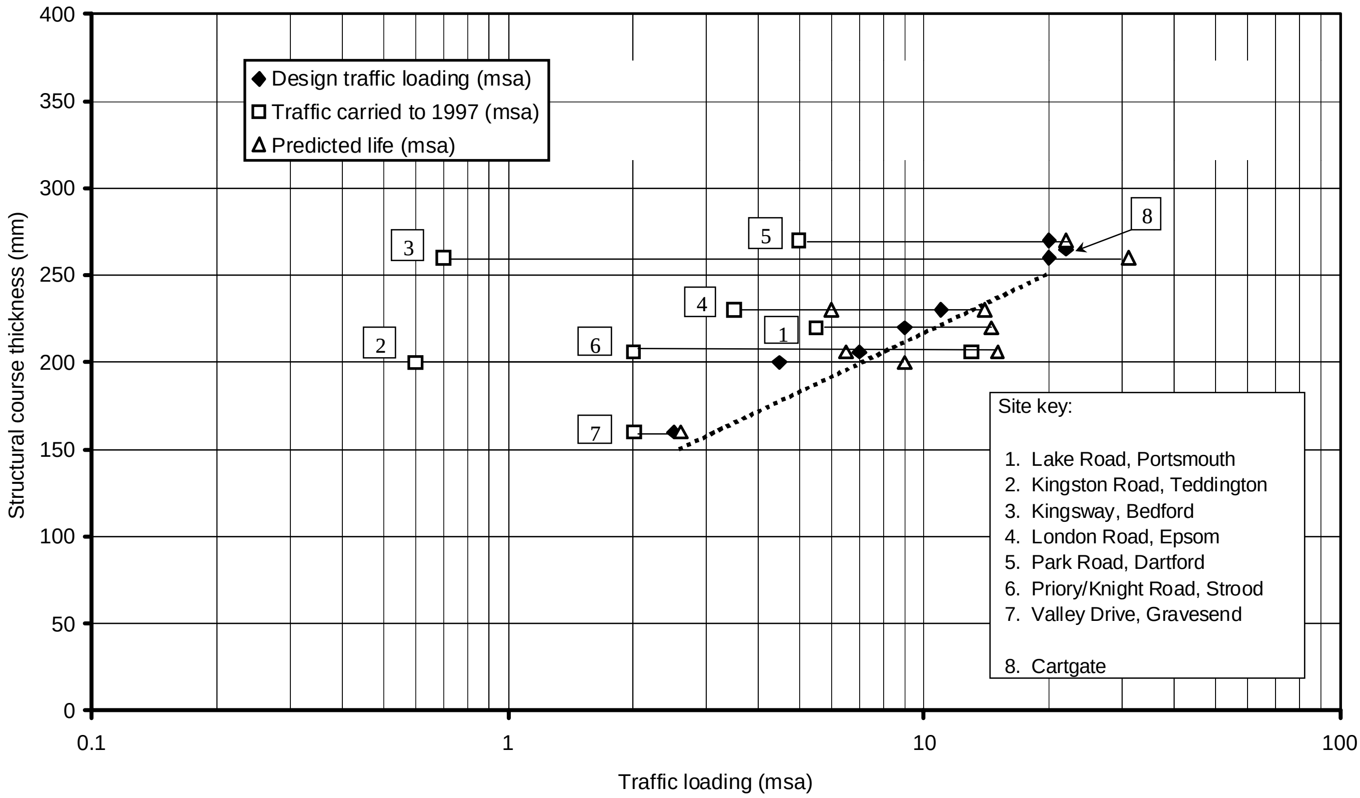

Figure A1 Predicted life in relation to design traffic loading with structural course thickness design line using cold in-situ foamed bitumen bound recycled material

Office (ETSU, 1994) and also takes into account the criteria published in TRL Report TRL216 (Potter, 1996), for the in-situ recycling of road haunches.

The draft specification for in-situ recycling that was prepared for construction of Phase 2 of the Cartgate Road trial was written with the aim of moving away from recipe/method requirements towards those of end-product performance, measured by laboratory tests on core specimens extracted from the finished pavement or by non-destructive in-situ tests. However, to ensure durability from the recycled material some method specifications clauses were retained.

In general terms the draft specification was found to be workable and robust under normal contractual conditions. Following completion of the monitoring of the sites, compilation and analysis of the data gathered enabled the specification to be refined into that which is presented in Part 2 of this Report.

A7 References

Department of the Environment, Energy Efficiency Office (1994). *Performance of roads reconstructed by cold in-situ recycling 1985 - 1987.* Best Practice programme, General Information Report 17, Energy Efficiency Enquiries Bureau, ETSU, Harwell.

Milton L J (1999). *Design guide and specification for structural maintenance of highway pavements by cold in-situ recycling. Part 1: Investigation Reports. Part 2: Development of design guide and specification.* Project Report PR/CE/193/98. Transport Research Laboratory, Crowthorne. (*Unpublished report available on direct personal application only*)

Potter J F (1996). *Road haunches: A guide to re-useable materials.* TRL Report TRL216. Transport Research Laboratory, Crowthorne.

Williams J (1995). *Highways and Conservation.* Paper presented at the 1995 BACMI ACMA Seminar.

Appendix B: Examples to demonstrate the design process

Example 1

Design requirements:
Type 1 road with cumulative traffic loading of 15msa
Existing surface level to be retained

Existing road construction:

Bound layers (mm)	= 250
Granular material (mm)	= 220
5% CBR subgrade	

Cement bound design option:

From Figure 1:

Thickness of surfacing (mm)	= 140
Thickness of structural course (mm)	= 240
Total (mm)	= 380

Referring to Table 4, the thickness of remaining granular foundation is 160mm deficient. Therefore, in accordance with Table 5, the thickness of recycled layer should be increased by 0.45 x 160 = 72mm

Revised design:

Thickness of surfacing (mm)	= 140
Thickness of recycled layer (mm)	= 312
Total (mm)	= 452

But the thickness of recycled material is marginally in excess of the specified maximum of 300mm, which may be offset by an equivalent increase in the thickness of surfacing. (i.e. 10mm thickness of surfacing is approximately equivalent to 12mm thickness of recycled material).

Working design:

Thickness of surfacing (mm)	= 150
Thickness of recycled layer (mm)	= 300
Total (mm)	= 450

Foamed bitumen bound option:

From Figure 2:

Thickness of surfacing (mm)	= 100
Thickness of structural course (mm)	= 235
Total (mm)	= 335

Referring to Table 4, the thickness of remaining granular foundation is deficient by 115mm. Therefore, in accordance with Table 5, the thickness of recycled layer should be increased by 0.65 x 115 = 75mm

Revised design:

Thickness of surfacing (mm)	= 100
Thickness of recycled layer (mm)	= 310
Total (mm)	= 410

But the thickness of recycled material is marginally in excess of the specified maximum of 300mm, which may be offset by an equivalent increase in the thickness of surfacing.

Working design:

Thickness of surfacing (mm)	= 108
Thickness of recycled layer (mm)	= 300
Total (mm)	= 410

Example 2

Design requirements:
Type 2 road with cumulative traffic loading of 7msa
Existing surface level to be retained

Existing road construction:

Bound layers (mm)	= 250
Granular material (mm)	= 300
3% CBR subgrade	

Cement bound design option:

From Figure 1:

Thickness of surfacing (mm)	= 120
Thickness of structural course (mm)	= 220
Total (mm)	= 340

Referring to Table 4, the thickness of remaining granular foundation is deficient by 90mm. Therefore, in accordance with Table 5, the recycled layer should be increased in thickness by 0.45 x 90 = 40mm

Working design:

Thickness of surfacing (mm)	= 120
Thickness of recycled layer (mm)	= 260
Total (mm)	= 380

Foamed bitumen bound option (i):

From Figure 2:

Thickness of surfacing (mm)	= 100
Thickness of structural course (mm)	= 200
Total (mm)	= 300

Referring to Table 4, the thickness of remaining granular foundation is deficient by 50mm. Therefore, in accordance with Table 5, the recycled layer should be increased in thickness by 0.65 x 50 = 32mm.

Working design:

Thickness of surfacing (mm)	= 100
Thickness of recycled layer (mm)	= 232
Total (mm)	= 332

Foamed bitumen bound option (ii):

From Figure 2:

Thickness of surfacing (mm)	= 50
Thickness of structural course (mm)	= 260
Total (mm)	= 310

Referring to Table 4, the thickness of remaining granular foundation is deficient by 60mm. Therefore, in accordance with Table 5, the recycled layer should be increased in thickness by 0.65 x 60 = 40mm

Working design:

Thickness of surfacing (mm)	= 50
Thickness of recycled layer (mm)	= 300
Total (mm)	= 350

Example 3

Design requirements:
Type 3 road
Existing surface level to be raised by 50mm.

Existing road construction:

Bound layers (mm)	= 100
Hardcore	= 250
Ash (mm)	= 50
6% CBR subgrade	

Cement bound design options:

From Table 6:

Thickness of surfacing (mm)	SD	40	100
Thickness of recycled layer (mm)	260	220	160
Total (mm)	260	260	260

But since the surface level is to be raised by 50mm, the obvious approach would be use an overlay of 50mm as the surfacing. Therefore, from interpolation of the above data:

Working design:

Thickness of surfacing (mm)	= 50
Thickness of recycled layer (mm)	= 210
Total (mm)	= 260

However, the surface level could be raised by the importation of aggregate from a quarry or recycled pulverised material from another site.

Alternative design:

Thickness of surfacing	= SD
Thickness of imported aggregate for recycling (mm)	= 50
Thickness of in-situ pavement for recycling (mm)	= 210
Total (mm)	= 260

Foamed bitumen bound option:

From Table 6:

Thickness of surfacing (mm)	SD	40	100
Thickness of recycled layer (mm)	330(N/R)	290	230
Total (mm)	N/R	330	330

Again, the practical approach would be use an overlay of 50mm as the surfacing. Therefore, from interpolation of the above data:

Working design:

Thickness of surfacing (mm)	= 50
Thickness of recycled layer (mm)	= 280
Total (mm)	= 330

In this case an alternative design using a surface dressing and imported aggregate is not appropriate because the maximum recommended depth of recycling would be exceeded.

Abstract

This Report describes research carried out with the aim of promoting the use of cold in-situ recycling for the structural maintenance of highways.

A description of the research methodology is given. Data collected from two full-scale road trials and from nine in-service roads which had been recycled within the previous decade were collated. Using this data a Design Guide for cold in-situ recycling with foamed bitumen and cement binders was produced. A series of flow charts and decision trees guide the reader through the many variables that come to the fore when recycling, in-situ, an existing road. Environmental factors and site evaluation are also given due consideration.

A Specification and Notes for Guidance on the Specification for cold in-situ recycling are presented in a stand-alone format so that the specification clauses are available for inclusion in standard contract documentation for structural maintenance works.

Related publications

TRL216 *Road haunches: A guide to re-usable materials* by J Potter. 1996 (price £35, code J)

SR675 *In-situ recycling of asphalt wearing courses in the UK* by G D Goodsall. 1981 (price £20)

CT20.1 Road building and the environment update (1993-1997). *Current Topics in Transport: selected abstracts from TRL Library's database* (price £20)

CT36.1 Recycling of road materials update (1993-1996). *Current Topics in Transport: selected abstracts from TRL Library's database* (price £20)

CT89.1 Aggregates in road construction update (1996-1998). *Current Topics in Transport: selected abstracts from TRL Library's database* (price £20)

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