ADEPT Guide to Managing Reclaimed Asphalt

Ex Situ Recycling Process – Whole Life Costing Exercise

1. Executive Summary

1.1. Several options are available for dealing with the presence of asphalt containing tar binder are described in the ADEPT *Guide for Managing Reclaimed Asphalt*. These include

- design of overlay with imported new hot mix asphalt to leave the tar bound materials in situ and undisturbed.
- removal of the pavement layers containing the tar bound material, disposing of it and replacing with imported new hot mix asphalt.
- in-situ stabilisation of the pavement layers, including any tar bound material that may be present, possibly followed by overlay comprising imported new hot mix asphalt surface course or surface dressing.
- ex-situ recycling and replacement of the treated / encapsulated material, possibly followed by overlay comprising imported new hot mix asphalt surface course or surface dressing.

1.2. All four solutions have advantages and disadvantages with regard to technical performance, practicality, initial cost and whole life cost. Little work has been undertaken to date to quantify these advantages and disadvantages, particularly with regard to comparison between the four different techniques. A series of carefully designed full scale instrumented trials would be needed to assess long-term comparative performance of the four different processes, and to confirm whole life costing benefits. Confirmation that *Ex-situ Cold-Recycled Bound Material* (CRBM) lasts at least 20 years in service is relatively unproven.

1.3. In order to start the process, a comparison between CRBM and conventional hot mix asphalt has been made in this report. It must be stressed that similar comparisons between the various treatment processes pertinent to remediation of pavements containing tar bound material could be made; these have not been carried out as part of this study due to time and cost constraints. Consequently the findings of this report are limited to assessment of ex situ CRBM.

1.4. Ex situ recycling of reclaimed asphalt containing tar binder involves processing it for re-use in accordance with Manual of Contract Documents for Highways Works (MCHW) Volume 1 Specification for Highway Works Clause 948 *Ex-situ Cold-Recycled Bound Material*. Works must also be carried out in accordance with Environment Agency Regulatory Position Statement 075 *Movement and Use of Treated Asphalt Waste Containing Coal Tar*, ref. MWRP RPS 075 Version 4 Sept 2014.

1.5. One of the aspects of producing and installing Ex-Situ CRBM is whether this technique is cost effective, both in terms of initial treatment and installation, considering the cost of disposal of any tar-bound arisings, as well as the service life of the resulting road construction in which CRBM has been used.

1.6. There are many variables that could influence the durability of CRBM and hence its service life. These include mixture properties, layer thickness, the amount of traffic the road will carry and the condition of the layer onto which the CRBM will be laid. Many of these factors are site specific, and in order to estimate whole life costs, several assumptions are therefore necessary.

1.7. The design principles and assumptions made to enable this comparison are technically complex and outside the scope of the ADEPT *Guide for Managing Reclaimed Asphalt*. Consequently, this detailed technical report has been prepared. This executive summary is used as a basis for a summary in the ADEPT Guide, with a hyperlink to this report.

1.8. Three Whole Life Costing scenarios have been considered with different combinations of inlay thickness (140mm, 190mm, 240mm) and traffic loading. Three traffic loading values selected; low traffic (2.5 million standard axles (msa)), moderate traffic (5 msa) and high traffic (10 msa), equating to 180, 350 and 700 commercial vehicles per lane per day respectively. These construction thicknesses and traffic loadings are considered typical of a local authority network.

1.9. Two different ex situ CRBM materials (Class B3 and B4 CRBM binder course) were compared with conventional Hot-mix Asphalt (AC20 Dense Binder course). Class B4 CRBM is stiffer than Class B3 CRBM, and consequently has different performance characteristics.

1.10. Treatment types used in the Whole Life Costing calculations are described in Table 1 below. The Dense Surface Course is new asphalt to provide a durable skid resistant surface. Patching and surface dressing would also be carried out using new materials.

Treatment Reference	Description
TB4 (140)	140mm Inlay: 40mm Dense Surface Course ; 100mm Class B4 recycled binder course
TB3 (190)	190mm Inlay: 40mm Dense Surface Course; 150mm Class B3 recycled binder course
TB3 (240)	240mm Inlay: 40mm Dense Surface Course; 200mm Class B3 recycled binder course
TAC20 (140)	140mm Inlay: 40mm Dense Surface Course ; 100mm Hot Mix Binder Course (Control)
TB4 (190)	190mm Inlay : 40mm Dense Surface Course; 150mm Class B4 recycled binder course
TB4 (240)	240mm Inlay: 40mm Dense Surface Course ; 200mm Class B4 recycled binder course
TSD	Minor Patching (up to 20% of the total area) + Surface Dressing
TSC	40mm Dense Surface Course Replacement
TAC20 (190)	190mm Inlay: 40mm Dense Surface Course; 150mm Hot Mix Binder Course (Control)
TAC20 (240)	240mm Inlay: 40mm Dense Surface Course ; 200mm Hot Mix Binder Course (Control)

Table 1 Treatment Types used in the Study

1.11. The Whole Life Cost exercise indicates that, based on the many assumptions made in the main body of this report, there appear to be savings associated with the use of ex situ CRBM in comparison with new Hot Mix Asphalt as shown in Figure 1 below.

20 Year Design Traffic (million std axles)	Depth of Treatment (mm)	Whole Life Costing 20 years (£'000)			Whole Life Costing Savings 20 years (£'000)	
		CBRM Class B3 TB3	CBRM Class B4 TB4	AC20 Dense binder course TAC20	CRBM Class 3 vs. AC20 Δ B3	CRBM Class 4 vs. AC20 Δ B4
2.5	140		420	597		177
5	190	448	366	448	0	82
10	240	406	336	443	37	107

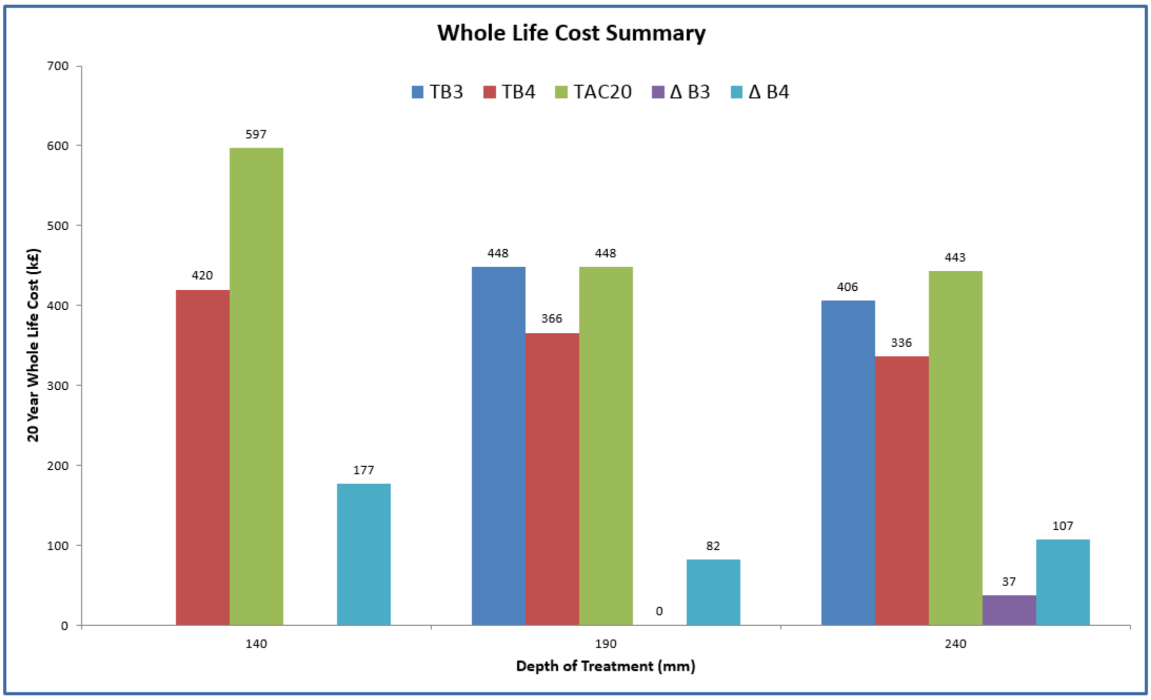


Figure 1 Whole Life Costing Summary

1.12. The difference in Whole Life Cost appear greatest when comparing the cost of Class B4 CRBM with the Hot Mix asphalt control. This difference appears to be evident over the range of design thickness and traffic loadings assessed.

1.13. The Whole Life Costing comparisons shown in Figure 1 are based on several assumptions relating to the service life of the various mixtures, maintenance profiles and project specific cost estimates. It is recommended that these assumptions and estimations, particularly the pavement modelling and stiffness variations are validated. This could be achieved by installation of a series of carefully designed full scale instrumented trials to assess long-term performance and to confirm the indicated whole life costing benefits.

1.14. Notwithstanding the assumptions made, it does appear that there are cost benefits associated with the use of ex-situ recycled materials within the treatment layers in comparison with hot mix asphalt. These benefits appear to be realised across the range of traffic loadings and treatment depths considered in this report. It must not be assumed that the performance of ex-situ CRBM is superior to that of in-situ treatment, or indeed inlay or overlay with conventional material. It must be reiterated that carefully designed full scale instrumented trials to assess long-term performance and to confirm whole life costing benefits would be needed to progress this study further.

2. Introduction

2.1. There are several ways of managing reclaimed asphalt that contains tar binder and these are covered in the ADEPT Guide to Managing Reclaimed Asphalt. It would be preferable to effect a design whereby the tar bound material is left in-situ and strengthening is carried out by means of applying an overlay. In many cases, however, this is impractical due to constraints such as existing kerb heights and thresholds. In situations where inlay is designed it can be costly to simply remove any tar bound material to the depth required and dispose of it as hazardous waste. Two main alternatives are available, firstly in-situ stabilisation as described in section 5.1 of ADEPT Guide to Managing Reclaimed Asphalt and MCHW Specification for Highway Works (SHW) Clause 947 *In-Situ Cold Recycled Bound Material*. Secondly, SHW Clause 948 describes *Ex-Situ Cold Recycled Bound Material*.

2.2. One of the aspects of using either In-Situ or Ex-situ Cold-recycled Bound Material (CRBM) is whether these processes are cost effective, both in terms of initial installation, as well as over the service life of the road construction where the treatment has been applied. There are many variables that could influence the durability and hence service life of the material. For in-situ CRBM, these include the grade of material produced, the treatment depth and method, volume of commercial traffic and the condition of the receiving layer below the treated layer comprising CRBM.

2.3. In the case of using Ex-situ CRBM its cost effectiveness depends on the variables described for in situ CRBM, including the cost of disposal of any tar-bound arisings, as well as over the service life of the road construction where the material has been used. There are many variables that could influence the durability and hence service life of the material. For ex-situ CRBM, these include the grade of material used, the layer thickness, installation method, volume of commercial traffic and the condition of the receiving layer onto which the CRBM is laid.

2.4. Ideally, it would be beneficial to compare whole life costs associated with both in-situ and ex-situ CRBM with those associated with use of conventional hot mix asphalt inlays or overlays. Due to limited resources available, however, this report is limited to an overview of the service life of a road section treated using an ex-situ cold recycled bound material (henceforth referred to as CRBM) in order to assess the effect of using different treatments in comparison with conventional construction comprising hot mix asphalt. It must not be assumed that whole life costs attributed to ex-situ CRBM material and conventional materials would translate into similar costs for in-situ CRBM material as the process is different. A similar exercise to that reported below would be required to justify this. Furthermore it must not be assumed that use of ex-situ CRBM is the best / most cost effective solution. This is not necessarily the case and the study reported below needs to be widened to include in-situ stabilisation as well as inlay and overlay with conventional hot mix asphalt.

2.5. The comparison in performance between the ex-situ CRBM material and conventional hot mix asphalt comprises a whole life costing exercise. The definition of Whole life Costing in the Design Manual for Roads and Bridges Volume 7 HD26/06 Pavement Design examines the costs of a project from inception to disposal, including the direct costs of constructing and maintaining a highway and the indirect costs imposed on society and the environment by its use and operation (e.g. traffic delay, accidents at roadworks, skidding accidents, fuel consumption and tyre wear). Integrating these principles in highway design can include reusing in situ materials to minimise resource consumption, waste disposal and emissions resulting from material haulage.

2.6. Due to the complexity of variables and absence of trial information on medium to long-term performance of CRBM in-service, a number of assumptions have been made to simplify the analysis. This has resulted in the comparison between CRBM and conventional materials being theoretical.

2.7. It must be borne in mind that any site-specific conditions and constraints, as well as particular asset management strategies used by different Local Authorities, may well produce different whole life costs and consequently different treatment strategies from those modelled in this document, as described below.

2.8. CRBM considered in this report is in accordance with Manual of Contract Documents for Highway Works (MCHW), Specification for Highways Works (SHW) Clause 948. This defines CRBM as *base and binder course mixtures produced in a fixed or mobile mixing plant from graded aggregate processed from arisings from the excavation of roads and similar sources, blended if necessary with other aggregate and bound with cementitious, hydraulic or bituminous binders, separately or in combination*.

2.9. SHW Clause 948 covers four generic material families: Quick Hydraulic (QH), Slow Hydraulic (SH), Quick Visco-Elastic (QVE) and Slow Visco-Elastic (SVE). The material considered in this whole life cost exercise is QVE, containing minimum 3% bituminous binder as the main component but also including a minimum of 1% of Portland Cement (CEM1), with Pulverised Fuel Ash (PFA) being added as filler if required. Two grades are considered: QVE Class B3 and Class B4. Class B3 material is less stiff, with a Mean Stiffness of 3100MPa, whereas the stiffer Class B4 mixture has a mean stiffness of 4700MPa.

2.10. Conventional Pavement Designs and analytical software programs are based on either fully flexible, flexible composite or rigid structures. TRL 615 *Development of a more versatile approach to flexible and flexible-composite pavement design* provides a ‘versatile’ approach to using a combination of different structural course materials. The CRBM considered in this report is a material that exhibits performance behaviour of a hybrid of bituminous bound and hydraulic bound material. Therefore, the rheology and hence performance characteristics of the hybrid CRBM must be combined to provide realistic estimations of its performance though time, and hence its service life.

2.11. The Whole Life Costing comparison between CRBM (QVE) and conventional asphalt is intended for Local Authority Roads, where relatively thin pavement construction and traffic loading up to 10 million standard axles is encountered. On this type of site, typically Local Authority Hierarchy 2-4 roads, it is considered likely that inlay treatments and reconstruction will encounter older materials containing tar binder.

3. Assumptions

3.1. There is a lack of sufficient data on performance of pavements rehabilitated using ex-situ CRBM. It is therefore impractical to predict the long term development of stiffness in CRBM material based on case studies, so assumptions have been made. These are based on TRL611 *A guide to the use and specification of cold recycled materials for the maintenance of road pavements.* Assumptions made are related to foundation conditions, traffic loading, material properties and resulting treatments.

3.2. Materials Selected - Surface Course

3.2.1. All of the CRBM materials are assumed to be surfaced with conventional Asphalt Concrete surface course. Whilst it is likely that some Local Authorities have policies that require use of different surface course materials such as Hot Rolled Asphalt or Thin Surface Course Systems. AC10 Dense surface course laid 40mm thick is considered to be a realistic surface course that might typically be used for this class of road / type of treatment to provide a durable skid resistant surface. Assumptions regarding in-situ performance of AC10 surface course, including layer stiffness, can be reliably made, as the material is compliant with the requirements of BSEN 13108-1.

3.2.2. The AC10 Dense surface course is assumed not to contain more than 10% Recycled Asphalt Product (RAP). RAP contents exceeding 10% are not currently in use. One of the main reasons is that the Polished Stone Value (PSV) of a mixture containing RAP could not be guaranteed due to its inherent variability. The presence of different aggregate types, possibly with lower PSV may have an adverse effect on the skid resistance of the surface and hence its safety.

3.2.3. Design Stiffness for AC10 surface course is based on Design Manual for Roads and Bridges Volume 7 HD26/06 *Pavement Design* and TRL Report 615 *Development of a more versatile approach to flexible and flexible-composite pavement design*. A Design Stiffness of 2500MPa has been assumed; this is a typical value for this type of mixture. The 2500MPa stiffness value was selected to ensure no overemphasis of any structural contribution of the surface course to the pavement structure

3.2.4. The assumption is that the surface course layer would be installed concurrently with the CRBM layers. Thinner surface treatment such as Surface Dressing or Microasphalt are not considered for the year zero treatment in the Whole Life Costing model.

3.3. Materials Selected - Binder Course (Control Material)

3.3.1. A control material is needed for comparison with the CRBM binder course materials. A conventional hot-mix AC20 Dense Binder Course material (recipe mixture) complying with SHW Clause 906 / BS EN13108-1 / PD9961 has been selected for this comparison.

3.3.2. A Design Stiffness of 4700MPa has been assumed for AC20 Dense Binder Course based on this value quoted in HD26/06 and TRL Report 615.

3.3.3. AC20 Dense Binder Course can be laid at layer thicknesses between 50mm and 100mm as appropriate for design. In thick pavements, installation of two layers of AC20 Dense Binder Course is assumed, rather than use of a different base material containing coarser material such as AC32 Dense Base.

3.4. Materials Selected - Surface Treatments

3.4.1. Surface treatments considered in the Whole Life Costing section of this report can be applied to construction containing either hot mix AC 20 Binder course or CRBM layers. Surface treatments such as Surface Dressing or Microasphalt have no structural contribution.

3.4.2. Minor patching is considered to be up to a maximum of 20% of the total surface area of the site, using new asphalt.

3.5. Materials Selected - Cold Recycled Bituminous material (CRBM) Binder Course

3.5.1. Two CRBM binder course materials have been considered, as described in SHW Clause 948 and TRL Report 611 *A guide to the use and specification of cold recycled materials for the maintenance of road pavements.*

- Class B3 (3100MPa stiffness) when installed
- Class B4 (4700MPa stiffness) when installed (Clause 948 Class B4 CRBM was not available at the time TRL611 was written).

Note 1 SHW Clause 948 (05/18) Table 9/27 indicates that CRBM stiffness values relate to measured stiffness (ITSM) (20^{o}C 2Hz). The corresponding Design Stiffness (20^{o}C 5Hz) used in the calculation will be higher, as measurements are at a higher frequency. To be conservative it is assumed that the design stiffness for Class B3 and B4 used in the calculation is equivalent to the measured stiffness (ITSM).

Note 2 It is difficult to predict the long term development of stiffness in CRBM material due to lack of available data, so assumptions have been made. These have been based on TRL611 Page 45 Table B2.3 Summary of test results obtained on in situ foammix. Cores extracted from selected sites and on data derived from Falling Weight Deflectometer literature on continuously graded mixtures with a thickness range 50-150mm in a long-term stiff, dry condition. (South African Mechanistic Pavement Design Method Table 3).

3.5.2. **CRBM Class B3:** Based on the assumptions above, the Design Stiffness for CRBM Class B3 material when installed is 3100MPa. The long term stiffness corresponding to a stiff / aged condition is 6000MPa. This increase is assumed to have resulted from curing of the CRBM over a period in service. The loss of fatigue resistance properties as the hydraulic binder cures and becomes stiffer has been accounted for by reducing the value of K_{Flex} in the transfer function described in TRL615 (see Section 5.12 below). Full scale trials would be needed to confirm the assumption made in this report.

3.5.3. **CRBM Class B4:** Based on the assumptions above, the Design Stiffness for Class B4 material when installed is 4700MPa (equivalent to standard hot mix AC20 Dense binder course). The long term stiffness corresponding to a stiff / aged condition is 9000MPa. This increase is assumed to have resulted from curing of the CRBM over a period in service. The loss of fatigue resistance properties as the hydraulic binder cures and becomes stiffer has been accounted for by reducing the value of K_{Flex} in the transfer function described in TRL615 (see Section 6.12 below). A further reduction to 8000MPa has been considered in the long term to account for mechanical deterioration of the material, particularly in the 5msa and 10msa models. Full scale trials would be needed to confirm the assumptions made in this report, as there remains debate about CRBM materials, particularly around being able to consistently produce Class B4.

3.5.4. In thick pavement options the use of two layers of CRBM or AC20 binder course is assumed, rather than selection of a different base mixture containing larger sized aggregate.

4. Foundation Class

4.1. A Class 2 foundation, with long term stiffness of 150MPa was selected for consistency of design. A typical Class 2 foundation could comprise one of the following construction types:

- Type 1 Granular Mixture (sub base)
- 150mm layer of Type 1 overlying capping layer
- Combination of these with geogrid
- Use of sacrificial asphalt layers.

Note 3 Foundations containing geogrids or including sacrificial asphalt layers have an equivalent Surface Modulus calculated using methodology described on Page 12 of TRL Report PPR127 Road Foundation Design for Major UK Highways

4.2. For the purpose of the Whole Life Costing Model, the condition of the foundation is assumed to be consistent, maintaining its original 150MPa stiffness. This assumes that the pavement foundation is not affected by drainage issues.

5. Design Parameters

5.1. The combinations of traffic loading and pavement thickness considered in this report are summarised in Table 2. The two types of ex-situ recycled material considered, CRBM Class B3 and the stiffer CRBM Class B4, have been assigned to road types carrying different volumes of commercial traffic. Whole Life costing profiles have been developed as shown in Table 2.

5.2. Three pavement thicknesses have been considered, each one related to a specific level of design traffic, reflecting pavement construction on a typical Local Authority network:

- ‘Thin’ pavement 140mm (40mm surface course and 100mm recycled binder course)
- ‘Intermediate’ pavement 190mm (40mm surface course and 150mm recycled binder course)
- ‘Thick pavement’ which is considered to be 240mm (40mm surface course and 200mm recycled binder course).

Traffic loading (million standard axles)	Total Thickness (mm) (CRBM thickness + 40mm Surface Course)		
	140 (100+40)	190 (150+40)	240 (200+40)
≤2.5	Class B4 & AC20		
2.6 -5		Class B3, Class B4 & AC20	
6 -10			Class B3, Class B4 & AC20

Table 2 Modelling Options

5.3. Analytical pavement design is very sensitive to traffic loading by commercial vehicles and it is therefore considered more appropriate to use discrete million standard axles (msa) values in the calculations, rather than the bandings described in TRL 611. Traffic loading values selected are 2.5 msa, 5 msa and 10 msa, and typical corresponding number of commercial vehicles is shown in Table 3. Traffic loading less than 2.5 msa will not be sufficient to significantly damage the road structure in a 20 year design period, and 10msa seems a reasonable upper limit for this whole life costing exercise. Where the design traffic is up to 2.5msa, both CRBM Class B3 and B4 can be used, provided that a Class 2 foundation is in place.

Traffic Loading (Million Standard Axles) (20 year design life)	Typical Number of Commercial vehicles (> 3.5T) per lane per day
2.5 msa	180
5 msa	350
10 msa	700

Table 3 Traffic loading and corresponding number of commercial vehicles

5.4. The failure modes in the three pavement thicknesses are likely to be different, with more rapid cracking developing in the thinnest pavement.

6. Design Methodology

6.1. Conventional pavement design uses design charts based on linear elastic modelling based on reference documents including TRL Report LR1132 *The structural design of bituminous roads* (1984) and TRL Report 615 *Development of a more versatile approach to flexible and flexible-composite pavement design* (2004). Use of design charts alone does not readily allow the properties of specific materials to be taken into account. An analytical pavement design approach provides a means of customising a pavement to locally available materials and/or construction methods and layer thicknesses, in an attempt to maximize the whole life value. However, it is essential that the material properties assumed in the design are actually achieved in situ.

6.2. Analytical pavement design methods have been used to assess the structural contribution of CRBM in comparison with conventional AC20 as a control. Software previously used for analytical pavement design in the UK was a program known as Genstress. This has not been available for many years and the Shell BISAR program was subsequently used to replicate the properties of Genstress. BISAR is no longer supported by Shell, so the software used for this report was Alize LCPC, Pavement design software produced by the French Laboratoire Central des Ponts et Chaussees Pavement Materials and Structures division. The Alize software enables parameters to be modified and these were set to UK design parameters in line with TRL Report LR1132 and TRL Report 615. Pavement modelling is based upon a representation of the structure by means of multilayer structure having an isotropic, linear elastic behaviour. Alize is a probabilistic model that enables the life expectancy of the pavement to be linked to the level of service specified for the pavement. This probabilistic methodology also takes into account the statistical distribution of material performance and soil bearing capacity, as well as fatigue performance and soil bearing capacity.

6.3. Use of pavement design software such as Alize routinely enables analysis of fully flexible, flexible composite and rigid pavement structures, however it is considered not to be entirely suitable for a hybrid material such as CRBM that contains hydraulic binder (a combination of cement and PFA) as well as foamed bitumen. An alternative design methodology is therefore proposed to determine design life for the hybrid CRBM material made with foamed bitumen and cement.

6.4. The Alternative Design Methodology selected is to use Alize software to calculate tensile strains in the pavement model using the various combinations of traffic loading, pavement thickness and material types described above. The tensile strain values derived from Alize were then used in Equation 8 of TRL 615 *Development of a More Versatile Approach to Flexible and Flexible-composite Pavement Design* (on Page 9) to calculate the design life.

6.5. A material-specific flexural factor, K_{Flex}, is included in the design criterion described in TRL Report 611. This factor, K_{Flex}, depends upon the design stiffness of the asphalt material. The use of this factor enables modelling of different fatigue performance of pavements having stiffer asphalt base mixtures. Stiffer materials do not perform so well in response to high flexural stresses as would be the case with less stiff, and thus more flexible materials.

$$\varepsilon_r = K_{Flex}.K_{Safety}.201\times10^{-6}\left(N/10^6\right)^{-0.24}$$

or,

$$N/10^6 = \left(\varepsilon_r/\left(K_{Flex}.K_{Safety}.201\times10^{-6}\right)\right)^{-(1/0.24)}$$

6.6. Parameter K_{Flex} in the equations above decreases with increasing stiffness. As higher stiffness values will be needed than those shown in TRL615 Table 7, the K_{Flex} values in TRL615 Table 7 have been extrapolated assuming a linear relationship between Design Stiffness and K_{Flex}. This is shown in Table 4 below.

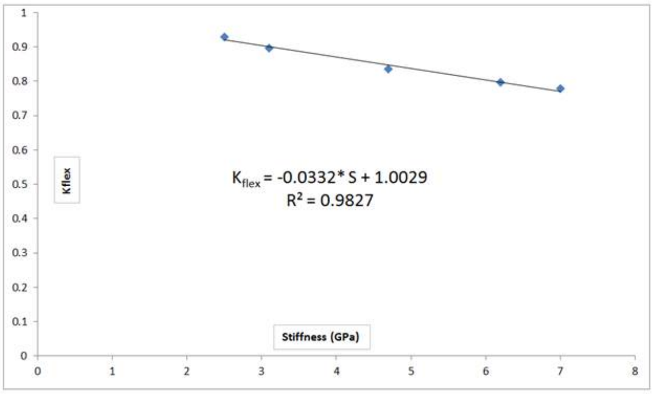


Table 4 Extrapolated relationship between K_{Flex} and Design Stiffness

6.7. Although the linear correlation is not as accurate as the polynomial relationship stated in TRL615 (equation 9 on Page 10) for low values of design stiffness, it does enable the K_{Flex} values to be extrapolated to higher values. These may be needed in order to reflect the characteristics of CRBM Class B4 material after several years of curing in-service. In order to limit the risk of misrepresentation of materials with excessive stiffness within a multilayered elastic model, an assumption has been made not to consider long term stiffness values exceeding 10,000 MPa. This will therefore be used as a limiting value.

7. Recycled Materials containing Foamed Bitumen and Hydraulic Binder

7.1. In a CRBM mixture, the effect of the hydraulic binder (cement or cement and PFA) will cause a significant stiffness increase as the cement cures. Consequently there will be an increase in stiffness and hence mechanical performance. The CRBM will not be as stiff as hot mix immediately after installation, due to its lower bitumen content, but it will become stiffer as the hydraulic binder cures. There may also be benefits in reducing early life wheelpath deformation.

7.2. An appropriate level of flexibility will be maintained in the CRBM due to presence of the bitumen in the recycled mixture. The effect of the hydraulic binder causing reduction in flexibility of the CRBM as hydration and curing takes place is modelled by applying a reduction in K_{Flex}. The proposed stiffness values and changes through time are shown in Table 5. For simplicity, no consideration is given to stiffness increase of these materials after year 12. It is assumed that any deterioration, characterised by stiffness reduction, of the material will be offset by stiffness increase due to the continuing curing of the hydraulic binder. It is also assumed that the fatigue life of the material will progressively reduce and this is modelled by progressive reductions in K_{Flex} values throughout the design life of the pavement.

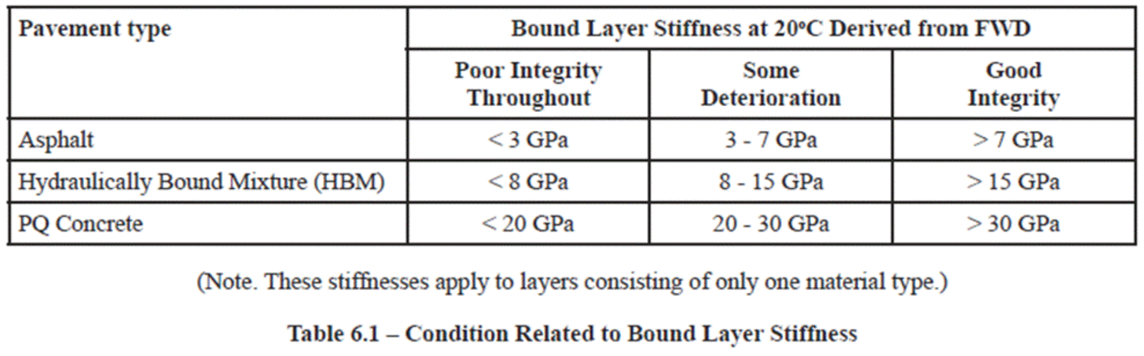
7.3. It should be noted that the service life of 20 years assigned to the CRBM is relatively unproven and further full scale trial work would be needed to validate this assumption.

	CRBM Class B3		CRBM Class B4		Comments
Year	Stiffness	K_{Flex}	Stiffness	K_{Flex}	
Year 0	3100	0.90	4700	0.85	Ref: TRL 615
Medium term (Year 5 onwards)	6000	0.68	9000	0.59	Reduction in KFlex to account for limited fatigue life of CRBM due to effect of Hydraulic binder and traffic damage
Long Term (Year 10 onwards)	6000	0.64	8000	0.53	Reduction in KFlex to account for further reduction in fatigue life of CRBM due to effect of Hydraulic binder and traffic damage. Stiffness reduction in Class B4 due to load induced cracking and possible shrinkage (Class B4 has higher cement content than Class B3)

Table 5 Stiffness/ Time relationship for CRBM Class B3 and B4 Mixtures

8. Conventional Asphalt Materials used as a Control

8.1. In the case of 'conventional' hot mix asphalt mixtures containing penetration grade bitumen without hydraulic binders, the anticipated bitumen / mixture ageing due to mixing and laying will take place and an increase in mixture stiffness will be developed. This will not be significantly different from the design stiffness. Once in service, the mechanical resistance of this material is considered to reduce with age. In a binder course not exposed at the surface, however, further oxidisation of the bitumen will be significantly reduced by the overlying surface course. Consequently, stiffness increase due to ageing will be limited, but it will nevertheless occur. Stiffness variation within a fully flexible pavement is described in HD30/08 Maintenance Assessment Procedure Table 6/1, based on Falling Weight Deflectometer measurements.



Pavement type	Bound Layer Stiffness at 20°C Derived from FWD		
	Poor Integrity Throughout	Some Deterioration	Good Integrity
Asphalt	< 3 GPa	3 - 7 GPa	> 7 GPa
Hydraulically Bound Mixture (HBM)	< 8 GPa	8 - 15 GPa	> 15 GPa
PQ Concrete	< 20 GPa	20 - 30 GPa	> 30 GPa

(Note. These stiffnesses apply to layers consisting of only one material type.)

Table 6.1 – Condition Related to Bound Layer Stiffness

Table 6 HD30/08 Table 6/1 Condition related to bound layers

8.2. A value of 5500MPa (5.5 GPa) is used in the model, based on an assumption that a stiffness decrease due to mechanical deterioration in the relatively thin pavements modelled is offset by limited oxidisation in the binder course material, resulting in asphalt with some deterioration. The corresponding K_{Flex} values are derived from TRL615 for the increase in stiffness. These are summarised in Table 7

	AC20 Dense Bin 40/60		Comments
Year	Stiffness	K_{Flex}	
Year 0	4700	0.85	Ref: TRL 615
Medium term (Year 5 onwards)	5500	0.80	Reduction in K_{Flex} to account for reduced fatigue life of AC20 due to aging of bituminous material and traffic damage
Long Term (Year 10 onwards)	5500	0.77	

Table 7 Stiffness/ Time relationship for AC 20 Dense Binder Course Mixtures

9. Whole Life Costing

9.1. Based on the assumptions described above, three Whole Life Costing (WLC) scenarios over a design period of 40 years with a break at 20 years have been considered. These are summarised in Table 8. Inlay thicknesses include 40mm of surface course on the CRBMC4 / CRBMC3 / AC20 binder course types.

Inlay Thickness (mm)	Design Traffic (msa)	CRBM Class	Control material
140	2.5	C4	AC20 Dense BC
190	5	C3 & C4	
240	10	C3 & C4	

Table 8 Whole Life Cost Scenarios

9.2. Treatment types used in the WLC calculations are described in Table 9.

Treatment Reference	Description
TB4 (140)	140mm Inlay: 40mm Dense Surface Course ; 100mm Class B4 Recycled Material
TB3 (190)	190mm Inlay: 40mm Dense Surface Course; 150mm Class B3 Recycled Material
TB3 (240)	240mm Inlay: 40mm Dense Surface Course; 200mm Class B3 Recycled Material
TAC20 (140)	140mm Inlay: 40mm Dense Surface Course ; 100mm AC 20 Binder Course
TB4 (190)	190mm Inlay : 40mm Dense Surface Course; 150mm Class B4 Recycled Material
TB4 (240)	240mm Inlay: 40mm Dense Surface Course ; 200mm Class B4 Recycled Material
TSD	Minor Patching (up to 20% of the total area) + Surface Dressing
TSC	40mm Surface Course Replacement
TAC20 (190)	190mm Inlay: 40mm Dense Surface Course; 150mm AC20 Binder
TAC20 (240)	240mm Inlay: 40mm Dense Surface Course ; 200mm AC20 Binder

Table 9 WLC Treatment Types

9.3. WLC calculations are based on consistent scheme areas. The area selected for the calculations is 3500m^2, representing a site that is nominally 500m in length, and 7m wide. Treatment costs used in the model presented in Appendix A are based on figures provided by Cambridgeshire / Peterborough Highways based on recent experience. The generic figures used were not project specific, but nevertheless reflect relative treatment costs.

9.4. A Class 2 level of bearing capacity is assumed to be in place prior to installation of the pavement construction on top of it. It is also assumed that this level of support will be maintained for the duration of the 20 year design life.

9.5. The WLC model assumes the presence of tar bound material in the existing pavement to be remediated. The cost of disposal of tar bound arisings as hazardous waste in a scenario where control AC20 is to be used, as opposed to use of the arisings as a feedstock for the recycled mixture, is included in the appropriate WLC models.

9.6. It is assumed that the both the conventional and recycled pavements will have a structural life at least as long as the overlying surface course or surface treatment.

9.7. Cracking caused by any differential movement in the underlying foundation is excluded in all of the whole life cost scenarios.

9.8. Minor patching is considered to be up to a maximum of 20% of the total area.

9.9. No account has been taken of cost inflation over the lifetime of the pavement.

9.10. The assumptions above have been used in summary sheets presented in Appendix A. These present various combinations and sequencing of the treatments described above over the duration of the WLC period.

9.11. WLC analysis of the various treatment options have been assessed and savings made have been considered after a period of 20 years for ease of comparison. It is recognised that hot mix asphalt may have a service life exceeding 20 years, however this would be affected by various factors including the support offered by the material below, layer thickness.

10. Whole Life Costing Findings

10.1. The Charts presented in Appendix A indicate that, based on the assumptions made in this report, there are savings. These are summarised in Figure 2

20Y Design Traffic (msa)	Depth of Treatment (mm)	WLC 20 years (k£)			WLC Savings 20 years (k£)	
		TB3	TB4	TAC20	Δ B3	Δ B4
2.5	**140**		420	597		177
5	**190**	448	366	448	0	82
10	**240**	406	336	443	37	107

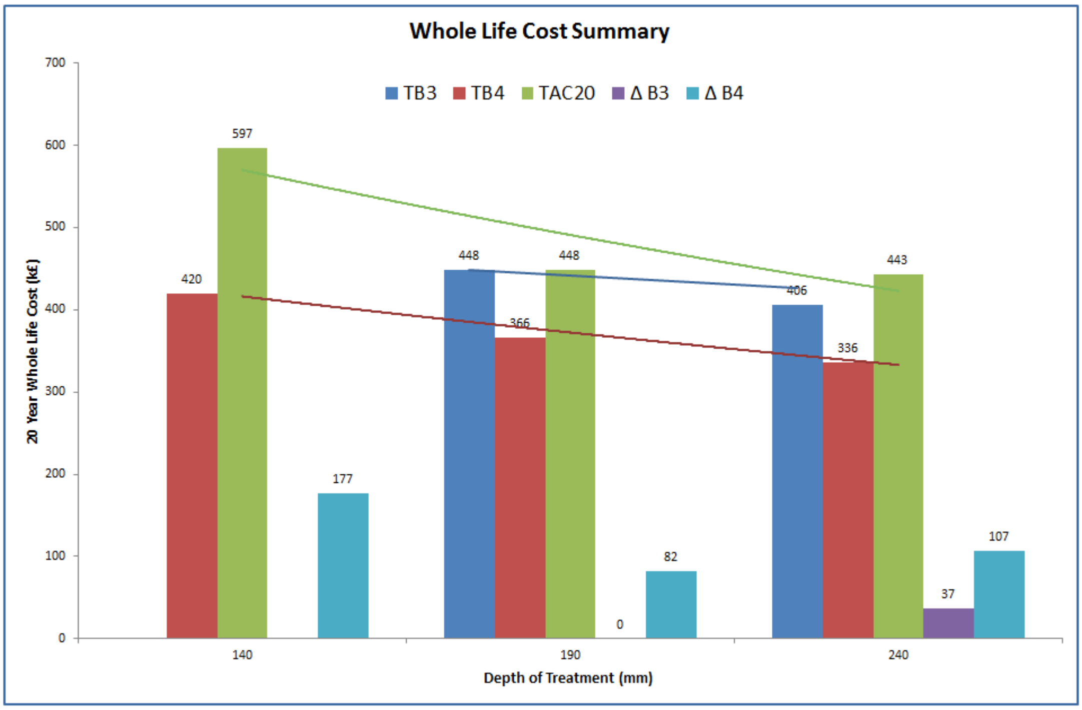


Figure 2 Whole Life Costing Summary

10.2. The WLC analysis indicates that there are cost benefits associated with the use of recycled materials within the treatment layers.

10.3. In particular, the savings appear maximised by use of CRBM Class B4 over the spectrum of design thickness and the three traffic levels selected.

10.4. It is noted that the WLC associated with the 140mm treatment is relatively high. This is due to the greater number of interventions within the first 20 years. These are required simply due to the thin pavement construction.

10.5. The trend lines showing the relationship between treatment depth and 20 year whole life cost indicate that the recycled materials, particularly the CRBM Class B4, can maximise the whole life costing across the various treatment depths.

11. Conclusions

11.1. The Whole Life Costing findings above are based on several assumptions relating to maintenance profiles and project specific cost estimates. It is recommended that these assumptions and estimations, particularly the pavement modelling and stiffness variations are validated. This could be achieved by installation of trial schemes, with subsequent monitoring.

11.2. Notwithstanding the assumptions made, it does appear that there are cost benefits associated with the use of ex-situ CRBM within the treatment layers. These benefits appear to be realised across the range of traffic loadings and treatment depths considered in this report.

11.3. Although there appear to be cost benefits to using ex-situ CRBM, these cannot be assumed for alternative methodologies for dealing with tar bound asphalt that are not included in the scope of this report. These include use of in-situ recycling and overlay treatments leaving the tar bound material undisturbed.

12. Acknowledgements

12.1. Thanks are due to Skanska (UK) plc for preparing this report jointly with Oxfordshire County Council / Oxfordshire Highways. Thanks are also due to Cambridgeshire Highways and Peterborough Highways for providing costing information to enable the Whole Life Costings to be calculated, based on recent experience.

140mm Inlay - Design Traffic = 2.5msa

Whole Lifetime Costing

Class B4 Recycled Material versus AC20 Dense Binder

Comparison Table

Year	Class B4 Recycled Material		AC20 Dense Binder	
	Action	**Direct Cost (£)**	**Action**	**Direct Cost (£)**
0	TB4 (140)	£180,600.00	TAC20 (140)	£227,500.00
1				
2				
3				
4				
5	TSD	£32,900.00	TSD	£32,900.00
6				
7				
8				
9			TSC	£86,800.00
10	TSC	£86,800.00		
11				
12				
13				
14			TAC20(140)	£227,500.00
15	TSD	£32,900.00		
16				
17				
18			TSD	£32,900.00
19				
20	TSC	£86,800.00		
	Residual Life	5 years	Residual Life	1 years
	20 year life cost	£420,000.00	20 year life cost	£596,633.33
	Total (£)	£420,000.00	Total (£)	£607,600.00
21			TSC	£86,800.00
22				
23				
24				
25	TB4(140)	£180,600.00		
26				
27				
28				
29				
30				
31				
32				
33				
34				
35				
36				
37				
38				
39				
40				
	40 year life cost		40 year life cost	
	Total (£)		Total (£)	

KEY

TB4(140)	140mm Inlay : 40mm Dense Surface Course ; 100mm Class B4 Recycled Material ; Class 2 Foundation
TAC20 (140)	140mm Inlay : 40mm Dense Surface Course ; 100mm AC 20 Binder Course; Class 2 Foundation
TSD	40mm Surface Course Replacement
TSC	Minor Patching (up to 20% of the total area) + Surface Dressing

190mm Inlay - Design Traffic = 5msa

Whole Lifetime Costing

Class B3 and B4 Recycled Material versus AC20 Dense Binder

Comparison Table

Year	Class B3 Recycled Material		Class B4 Recycled Material		AC20 Dense Binder	
	Action	Direct Cost (£)	Action	Direct Cost (£)	Action	Direct Cost (£)
0	TB3 (190)	£241,850.00	TB4 (190)	£246,400.00	TAC20 (190)	£328,300.00
1						
2						
3						
4						
5	TSC	£86,800.00				
6						
7						
8						
9						
10			TSC	£86,800.00	TSC	£86,800.00
11						
12						
13	TSD	£32,900.00				
14						
15						
16						
17						
18						
19						
20	TSC	£86,800.00	TSD	£32,900.00	TSD	£32,900.00
	Residual Life	5 years	Residual Life	6years	Residual Life	6years
	20 year life cost	£448,350.00	20 year life cost	£366,100.00	20 year life cost	£448,000.00
	Total (£)	£448,350.00	Total (£)	£366,100.00	Total (£)	£448,000.00
21						
22						
23						
24						
25	TB3 (190)	£241,850.00				
26			TSC	£86,800.00	TSC	£86,800.00
27						
28						
29						
30						
31						
32						
33						
34						
35						
36						
37						
38						
39						
40						
	40 year life cost		40 year life cost		40 year life cost	
	Total (£)		Total (£)		Total (£)	

KEY

TB3 (190)	190mm Inlay : 40mm Dense Surface Course ; 150mm Class B3 Recycled Material ; Class 2 Foundation
TB4 (190)	190mm Inlay : 40mm Dense Surface Course ; 150mm Class B4 Recycled Material ; Class 2 Foundation
TAC20 (190)	190mm Inlay : 40mm Dense Surface Course ; 1500mm AC20 Binder ; Class 2 Foundation
TSC	40mm Surface Course Replacement
TSD	Minor Patching (up to 20% of the total area) + Surface Dressing

240mm Inlay - Design Traffic = 10msa

Whole Lifetime Costing

Class B3 and B4 Recycled Material versus AC20 Dense Binder

Comparison Table

Year	Class B3 Recycled Material		Class B4 Recycled Material		AC20 Dense Binder	
	Action	Direct Cost (£)	Action	Direct Cost (£)	Action	Direct Cost (£)
0	TB3 (240)	£286,650.00	TB4 (240)	£292,950.00	TAC20 (240)	£399,350.00
1						
2						
3						
4						
5						
6						
7						
8						
9						
10	TSC	86,800.00				
11						
12						
13						
14						
15			TSC	86,800.00	TSC	86,800.00
16						
17						
18						
19						
20	TSD	£32,900.00				
	Residual Life	7 years	Residual Life	5 years	Residual Life	5 years
	20 year life cost	£406,350.00	20 year life cost	£336,350.00	20 year life cost	£442,750.00
	Total (£)	£406,350.00	Total (£)	£379,750.00	Total (£)	£486,150.00
21						
22						
23						
24						
25			TSC	£86,800.00	TSC	86,800.00
26						
27	TB3 (240)	£286,650.00				
28						
29						
30						
31						
32						
33						
34						
35						
36						
37						
38						
39						
40						
	40 year life cost		40 year life cost		40 year life cost	
	Total (£)		Total (£)		Total (£)	

KEY

TB3 (240)	240mm Inlay : 40mm Dense Surface Course ; 200mm Class B3 Recycled Material ; Class 2 Foundation
TB4 (240)	240mm Inlay : 40mm Dense Surface Course ; 200mm Class B4 Recycled Material ; Class 2 Foundation
TAC20 (240)	240mm Inlay : 40mm Dense Surface Course ; 200mm AC20 Binder ; Class 2 Foundation
TSC	40mm Surface Course Replacement
TSD	Minor Patching (up to 20% of the total area) + Surface Dressing