Cumbria County Council

LIVE LAB: PLASTIC ADDITIVES IN ASPHALT

70066681-REP2 R6
NOVEMBER 2021

PUBLIC

Cumbria County Council

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TYPE OF DOCUMENT (VERSION) PUBLIC

PROJECT NO. 70066681

OUR REF. NO. 70066681-REP2 R6

DATE: NOVEMBER 2021

WSP

Amber Court
William Armstrong Drive
Newcastle upon Tyne
NE4 7YQ

Phone: +44 191 226 2000

Fax: +44 191 226 2104

WSP.com

QUALITY CONTROL

Issue/revision	First issue	Revision 1	Revision 4	Revision 5	Revision 6
Remarks	DRAFT – CUMBRIA COUNTY COUNCIL USE ONLY	DRAFT – CCC AND MACREBUR INTERNAL USE ONLY	DRAFT – CCC AND MACREBUR INTERNAL USE ONLY	DRAFT – CCC AND MACREBUR INTERNAL USE ONLY	DRAFT – CCC AND MACREBUR INTERNAL USE ONLY
Date	20/10/2021	29/11/2021	30/06/2022	18/07/2022	22/07/2022
Prepared by	Donna James, Michael McHale, Tim Danson & Kirsten Holden	Donna James, Michael McHale, Tim Danson & Kirsten Holden	Donna James, Michael McHale, Tim Danson & Kirsten Holden	Donna James, Michael McHale, Tim Danson & Kirsten Holden	Donna James, Michael McHale, Tim Danson & Kirsten Holden
Signature					McHale, Michael (UKMJM012) Digitally signed by McHale, Michael (UKMJM012) DN: cn=McHale, Michael (UKMJM012), ou=Active, email=Michael.McHale@wsp.com Reason: I am the author of this document Date: 2022.08.16 16:55:13 +01'00'
Checked by	Dermott Doyle	Dermott Doyle	Dermott Doyle	Dermott Doyle	Dermott Doyle
Signature					Doyle, Dermott (UKDXD005) Digitally signed by Doyle, Dermott (UKDXD005) DN: cn=Doyle, Dermott (UKDXD005), ou=Active, email=Dermott.Doyle@wsp.com Date: 2022.08.16 17:05:10 +01'00'
Authorised by	Orlando Walters	Orlando Walters	Orlando Walters	Orlando Walters	Orlando Walters
Signature					Walters, Orlando (WaltersO) Digitally signed by Walters, Orlando (WaltersO) DN: cn=Walters, Orlando (WaltersO), ou=Active, email=Orlando.Walters@wsp.com Date: 2022.07.22 18:11:32 +01'00'
Project number	70066681				
Report number	70066681-REP2				
File reference					

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APPENDICES

Glossary

Term	Definition	Term	Definition
ADEPT	Association of Directors of Environment, Economy, Planning and Transport	**MBT**	Mechanical Biological Treatment
AC	Asphalt Concrete	**MPA**	Mineral Products Association
BBR	Bending Beam Rheometer	**MRF**	Material Recovery Facility
CCC	Cumbria County Council	**msa**	million standard axles
CTOD	critical tip opening displacement	**MSCR**	Multiple Stress Creep and Recovery
DCP	Dynamic Cone Penetrometer	**MSDS**	Material Safety Data Sheet
DENT	Double-Edge Notched Tension	**NTEC**	Nottingham Transportation Engineering Centre
DFID	Department for International Development	**NWHAUC**	North-West Highway Authorities & Utilities Committee
DfT	Department for Transport	**PACT**	Penrith Action for Community Transition
DSR	Dynamic Shear Rheometer	**PET**	Polyethylene Terephthalate
EMF	Ellen Macarthur Foundation	**PG**	Performance Grade
EVA	Ethylene Vinyl Acetate	**PP**	Polypropylene
FWD	Falling Weight Deflectometer	**PQC**	Pavement Quality Concrete
HDPE	High-Density Polyethylene	**PRD**	Percentage Refusal Density
HGV	Heavy Goods Vehicle	**PS**	Polystyrene
HRA	Hot Rolled Asphalt	**PVA**	Poly Vinyl Acetate
HWRC	Household Waste Recycling Centres	**RAP**	Recycled Asphalt Planing
ITFT	Indirect Tensile Fatigue Test	**SATS**	Saturated Ageing Tensile Stiffness
ITSM-CY	Indirect tensile stiffness modulus	**SBS**	Styrene Butadiene Styrene
ITSR	Indirect tensile strength ratio	**SMA**	Stone Mastic Asphalt
KPI	Key Performance Indicators	**SMDS**	Soils & Materials Design & Specification
LAS	Linear Amplitude Sweep	**SPI**	Society of the Plastics Industry
LCA	Lifecycle Assessment	**TTSP**	Time-temperature superposition
LDPE	Low-Density Polyethylene	**UV**	Ultraviolet

EXECUTIVE SUMMARY

In recent times, there has been increasing public interest in reducing the amount of plastic waste that is destined for landfill. One initiative is that some of this waste plastics could be used to replace part of the bitumen in an asphalt mix and in some instances improve the performance of roads. If proven, it could provide a sustainable solution for the future. However, it is essential that the influence of plastic additives is fully understood to ensure it does not adversely affect the long-term performance of road materials, release microplastics into the environment, and it is safe to use for plant and construction operators.

This report describes a project that involves investigating the suitability and sustainability of using waste plastic as an additive to asphalt mixtures used in road construction. The project forms part of the national Live Labs project, sponsored by the Association of Directors of Environment, Economy, Planning and Transport (ADEPT) and the Department for Transport (DfT). The idea is to utilise waste plastic, that cannot be recycled and is destined for landfill or incineration, as an additive that sometimes has the potential to enhance the performance of asphalt mixtures and provide a cost saving alternative by replacing part of the bitumen. The overall aim is to reduce the carbon footprint in the highway industry and provide a more resilient road network.

In January 2019, Cumbria County Council (CCC) and partners MacRebur were successful in securing funding from the ADEPT Smart Places Live Labs project. Funds were made available to cover research, full-scale installation trials, monitoring and publicity on the use of plastic additives in road construction. The project initially focussed on recycled plastic additive products that won sponsorship through the Virgin Media Business Voom national competition in 2016. These products are added as a dry flake or pellet when the asphalt is mixed at the asphalt plant, which is known as the dry process.

Information provided by MacRebur suggests that some recycled plastic additives can increase material stiffness and deformation resistance, without compromising flexibility. During the lifetime of the project, an additional recycled plastic product became available that uses the wet process, where the additive is pre-blended with the bitumen. In this case, the waste plastic has been subjected to a depolymerisation process to produce a wax. The effect of the wax additive on asphalt materials is generally to reduce the temperature that they are mixed and laid at. Known generically as Warm Mix Asphalt (WMA), the asphalt requires less energy during manufacture and CO2 emissions are reduced. Following consultation with the Client, it was agreed that two different additives (Additive 1, Additive 2) using the dry process and one additive using the wet process (Additive 4) would be incorporated into the full-scale Live Lab trials.

The report has been structured with the aim of addressing the original project brief as follows:

- Literature Review (Chapter 4)
- Circular Economy Assessment (Chapter 5)
- Design of Live Lab trials (Chapter 6)
- Live Lab Trial sites (Chapter 7)
- Mixture Testing (Chapter 8)
- Rheological Testing (Chapter 9)
- Conclusions and recommendations (Chapter 10)

Literature review

The literature review highlighted that the scientific and engineering understanding of using recycled plastic is still at an early stage and more research is required. In general, the literature review demonstrated that most research is laboratory based, with insufficient technical information from studies that take samples from in-service pavements. Information gathered as part of the literature review identified some gaps in knowledge, in particular the need to:

- Establish a method of determining the properties and consistency of the waste plastic feedstock to ensure reliable performance.
- Provide guidance on fume generation to confirm suitable workplace exposure limits.
- Examine the low temperature properties of bitumen incorporating waste plastic and the durability of adhesion to aggregate in asphalt mixes.
- Verification of the dispersion and digestion of waste plastic polymers, particularly when using the dry process.

Circular economy

Based on a review of available information provided by CCC, Chapter 5 provides guidance that could be adopted by local government authorities seeking to make progress on circular economy activity. Key recommendations are provided under the headings of Policy, Council Activity and Context, and Data management. Chapter 6 describes the key features that were considered in selecting the trial sites from the CCC road network, and the outlined approach could be adopted by other authorities.

Road trials

A description of the Live Lab trials is provided in Chapter 7, including an overview of the trial locations, material suppliers, material types and additives used, and any observations made while construction took place. The Live Lab quarry trials provided an early opportunity to make comparisons between the in situ properties of mixtures that contain a range of plastic additives and more conventional control mixtures. Chapter 8 presents findings from the mixture testing that demonstrate that binder course materials containing Additive 1 show an average increase of around 12% in stiffness, although a wider spread in results is observed when compared to the control mixture. Stiffness results from a range of combined surface course types indicate a 14% increase in stiffness with the addition of Additive 1. A more modest increase of 9% is observed with Additive 2. In addition, other material properties are reviewed and compared, including binder contents, air voids, wheel tracking and water sensitivity.

A total of ten asphalt mixture samples were taken during laying operations at the trial sites and supplied to NTEC at the University of Nottingham. The bitumen and plastic additive components of the 10 different asphalt mixtures were recovered and subjected to a series of rheological and binder performance tests to determine their relative rheological properties and performance. Based on the results of the recovered binder testing, Chapter 9 presents findings and key conclusions. Results from binder testing do not explain the increased mixture stiffness observed in the trials. However, the results do show that the recycled plastics appear to change the rheology of the binder, which can be separated into three groups. The behaviour and performance of these groups of binders are described. One of the key conclusions is that they do not exhibit the behaviour traditionally seen for a bitumen that has been polymerically modified.

Key conclusions and recommendations

Chapter 10 summarises all the report findings and conclusions to date and makes a series of recommendations. Based on the mixture testing carried out to date, mixtures comprising waste-derived plastic additives using the dry process are broadly comparable with the control mixtures. The notable difference is an increase in mixture stiffness, albeit there is typically an increased spread in results. The latter raises some concerns about the quality control or reproducibility of the dry mixing process. Increased stiffness in binder course materials is seen as beneficial owing to improved load spreading properties. However, unexplained increases in surface course stiffness should be treated with some caution.

Results from binder rheological testing did not explain the increased mixture stiffness and there still remains a question or uncertainty as to what is causing the increased stiffness observed. It is possible that some of the plastic does not achieve full dispersion in the bitumen and acts as a filler within the mixture. Achieving adequate dispersion and digestion of the waste plastic in bitumen may be a critical factor in achieving reliable results from asphalt mixtures in the future. Other potential reasons for the observed increase in stiffness could be related to production issues, dosage variations and binder recovery conditions.

Recommendations include additional testing to assess the degree of dispersion and digestion that has occurred after asphalt mixing. A recently developed approach to assess the release of microplastics from plastic-modified asphalt through applying abrasion to asphalt samples in a controlled environment is recommended. The procedure has been shown to successfully separate microplastics from bitumen and aggregate residues and their size distribution can be validated by fluorescence microscopy analysis.

As the Live Lab road trials have been in service between 11 and 26 months, it is important that the performance be assessed on a regular basis as subtle changes in the early-life performance could provide an indication of longer-term performance. Annual visual assessments are recommended utilising an established inspection and marking system that ranks the performance of the control sections and those that include additives.

Contact name Orlando Walters

Contact details 0191 226 2628 | orlando.walters@wsp.com

1

INTRODUCTION

1 INTRODUCTION

1.1 LOCAL ROADS THAT ARE FIT FOR THE FUTURE

This project involves investigating the suitability and sustainability of using waste plastic as an additive to asphalt mixtures that are used in road construction. The project forms part of the national Live Labs project, sponsored by the Association of Directors of Environment, Economy, Planning and Transport (ADEPT) and the Department for Transport (DfT). The idea is to utilise waste plastic that cannot be recycled and is destined for landfill or incineration, as an additive to replace part of the bitumen and sometimes enhance the performance of asphalt mixtures. However, it is important to establish that there are no detrimental effects to the performance of asphalt mixtures. The overall aim is to reduce the carbon footprint in the highway industry and provide a more resilient road network.

1.2 BACKGROUND

In September 2018, Cumbria County Council (CCC) submitted an expression of interest for funding from the ADEPT Smart Places Live Labs project. With partners MacRebur, the proposal was to develop the use of plastic additives to reduce waste and carbon emissions, with the potential additional benefit of constructing asphalt roads with improved performance. In January 2019, CCC were notified that they had been successful in their bid and funding was secured to cover research, full-scale installation trials, monitoring and publicity on the use of plastic additives in road construction. The Live Labs project runs over two years, 2019/20 and 2020/21.

There is currently a huge global focus on the ‘plastic epidemic’. Recent scientific studies and documentary exposés such as David Attenborough’s ‘Blue Planet’, have revealed just how detrimental plastics and packaging can be to the environment and to human health. Consequently, there has been extensive press and media attention around the innovative approach of using waste plastics in road construction materials.

Plastic waste can be incorporated into asphalt mixtures by one of the following methods: the wet process and the dry process. In the wet process, the waste plastic is added and mixed with bitumen at a high shear milling plant to create a homogenous binder. The ‘modified binder’ is then mixed with the aggregates in the coating plant. In the dry process, the waste plastic is added either directly to the heated aggregate or added at the same time the bitumen is added to the aggregate in the plant’s mixing drum.

Advantages of the dry process are that it does not normally require modification to the asphalt plant or pre blending at a specialist plant. In the dry process, the plastics are stored dry and do not require to be stored at an elevated temperature. Experience has shown that a benefit of the wet process is that polymers, such as SBS, are better dispersed within the bitumen. However, the latter may require specialist handling and storage techniques (e.g. agitation) to prevent separation.

The project initially focussed on recycled plastic additive products that won sponsorship through the Virgin Media Business Voom national competition in 2016. The MacRebur products are made from 100% waste materials and are used to replace part of the bitumen in any asphalt mix. It is added as a dry flake when the asphalt is mixed at the plant using the dry process.

The additive product is not plastic that would otherwise enter the recycling stream but uses end of life plastic that is destined for landfill or incineration. Between 1kg to 5kg of waste plastics are used in every tonne of asphalt depending on the road design. It should be noted that although often labelled as 'plastic roads', the total volume of plastic in the finished asphalt is typically very small at around 3kg per tonne or 0.3%.

The additive products are used as binder modifiers to reduce the volume of bitumen required in an asphalt mix. Initial testing information provided by the producer indicated that the products increase the stiffness and deformation resistance of asphalt.

The supplier provided two different waste plastic products that came as mixed granulated particles (see Figure 1-1 below).

Figure 1-1 - Dry process product samples

Additive 1 comes in the form of fine shredding which replaces part of the bitumen and can be used in any asphalt mix, e.g. Asphalt Concrete (AC), Stone Mastic Asphalt (SMA), Hot Rolled Asphalt (HRA), etc. Information provided by the manufacturer suggests that the A1 product should be selected to increase stiffness and deformation resistance, without compromising flexibility. The recommended use is for surfacing high stressed areas of the highway such as intersections, roundabouts and heavy, slow-moving traffic areas.

Additive 2 also comes in the form of shreddings and is designed as an extension/replacement of the bitumen. Information provided to date has shown that the product would be selected to maximise environmental and economic benefits, in that there is no adverse impact of performance, suggested use is low trafficked areas, car parks, driveways and local roads.

During the lifetime of the project, an additional product (Additive 4) became available from another supplier, the product contains a wax additive which has been derived from waste plastic. The wax product shown in Figure 1-2 is pre-blended with bitumen using the wet process; the additive is derived from waste plastic that has been subjected to a depolymerisation process.

The effect of the product on asphalt materials is to allow a reduction in the temperature that they are mixed at, known as Warm Mix Asphalt (WMA). Production temperatures are around 30°C lower when compared to traditional hot mix asphalt. WMA typically offers around 15-25% reduction in energy usage at batching and consequently provides carbon savings.

Following consultation with the Client it was decided that Additive 1, Additive 2 and Additive 4 would be incorporated into the full-scale Live Lab trials. It should be noted that laboratory test results for asphalts containing Additive 4 were not available at the time of writing.

Figure 1-2 - Additive 4 sample before blending with bitumen using the wet process

2

OBJECTIVES

2 OBJECTIVES

2.1 CCC LIVE LAB OBJECTIVES

At the commencement of the research study, the objectives of the CCC Live Lab project were:

- To investigate the possibility of improving the design life of road pavements by using plastic additives, by looking at the potential to produce new pavement designs that increase durability, whilst reducing cost.
- Determine the optimum pavement design configurations and material specifications when waste plastic additive is used.
- Determine what financial benefits there are to highways authorities when adopting roads with plastic additives as a standard design principle, including looking at how much of Cumbria's waste plastic could be used if roads with plastic additive were introduced as a new standard.
- If feasible, produce a business model for authorities to adopt that create a circular economy of waste and construction, as a "local waste for local roads ethos".
- Consider the future supply of plastic waste, with respect to any proposed relevant government legislation, producer controls and changes in product packaging, e.g. industry change from plastic to paper packaging.
- Ensure that the use of recycled waste plastic in road surfacing does not pose a risk to the environment or people during manufacture, laying, when in situ or at end of service life.
- Work with communications and engagement teams to understand the political and public view and perception of the innovative approach to highways maintenance and waste management.
- Develop partnerships across other highways authorities in the UK where 'plastic roads' have been used and with authorities seeking advice on its use.

2.2 PROJECT OBJECTIVES

The following specific tasks were to be undertaken as part of this report:

- Review existing information available where plastic additive has been used in road construction and identify areas where additional work is required. Devise a series of pavement designs and specifications that test the inclusion of plastic additive to determine the optimum material properties whilst challenging current highway design and specifications, including but not limited to durability, volume of raw materials and construction depths. Determine the optimum pavement design / specification when waste plastic additive is used.
- Evaluate the viability of non-standard design options to improve environmental and economic performance.
- Produce detailed design and specification documentation for test schemes and control sites.
- Provide professional advice relating to the technical surveys and testing which may be required to achieve the project objectives.
- Coordination and procurement of additional specialist site testing, laboratory testing and academic services from universities.
- Produce guidelines for use of plastic additives in asphalt.
- Undertake baseline assessment of the council waste disposal procedures. Including but not limited to collating information on quantities and form of waste plastic produced and from what

source; the current mechanism for disposal. Map out the process of kerbside to final disposal and understanding economic and environmental costs of this process.

- Undertake a baseline assessment of the quantities of asphalt currently used by the authority annually and in what form, i.e. base, binder, surface course and what kind of material.
- Utilise the baseline assessments to summarise the potential revenue savings or revenue generating opportunities for the council as waste disposal authority by utilising 'local waste for local roads'.
- Utilise the baseline assessments to summarise what the environmental benefits are for adopting 'plastic roads' as a standard design principle when considering waste disposal and the improved lifecycle of the highways network.
- A workshop with key stakeholders to confirm objectives and opportunities for the key partners.
- Summary of all environmental and economic benefits and dis-benefits associated with the Live Labs trials.
- A business case model for the circular economy potential for the authority in respect of using local waste on local roads. This model should seek to be transferable to other local authorities.

3

METHODOLOGY

3 METHODOLOGY

The aim of the study is to investigate the sustainability and suitability of using additives derived from waste plastics as part of highway surfacing. The adopted approach to achieve this aim was to split the study into several sections that addressed specific parts of the project brief as follows:

- Literature Review (Section 4)
  - An overview of the current state of knowledge of using waste plastic additives, including published papers and reports, and laboratory tests on asphalt mixtures and binders incorporating plastic additives.
  - An analysis of the information collected to provide trends in performance and inform the Live Lab testing programme, e.g. any additional testing required.
- Circular Economy Assessment (Section 5)
  - Based on information made available, this section contains two assessments: a circular economy assessment and a lifecycle assessment.
  - This chapter discusses the findings and makes recommendations relating to policy, council activity and context, and data management.
- Design of Live Lab trials
  - Summary of the key features that were considered in selecting trial sites from the CCC road network. The outlined approach could be adopted by other authorities.
- Live Lab Trial sites
  - Description of the existing trials established as part of Cumbria County Council's Live Lab including an overview of the trial locations, material suppliers, material types and additives used, and any observations made while construction took place.
- Mixture Testing
  - Summary of the results of testing data that has been carried out to date, including relative stiffness values and other mixture properties.
- Rheological Testing
  - Summary and findings of rheological and binder performance tests on ten recovered binders to determine their relative rheological properties and performance.
- Conclusions and recommendations
  - Summary of the initial Live Lab findings including recommendations on future monitoring of the trial sites and any additional testing that may be required.

In addition to the above, presentations were given to key stakeholders during the course of the project to disseminate the project objectives and enable constructive feedback. Owing to Covid-19 restrictions, on-line presentations were given to the Mineral Products Association (MPA), the Soils & Materials Design & Specification (SMDS) Group of ADEPT, and the North-West Highway Authorities & Utilities Committee (NWHAUC).

4

LITERATURE REVIEW

4 LITERATURE REVIEW

The literature review was broadly split into two parts: a general search for articles and papers on the use of plastic waste in roads; and a review of documents provided by MacRebur and CCC, including an analysis of the testing data provided.

Sasidharan, Torbaghan and Burrow[1] from the University of Birmingham carried out a literature review on use of waste plastic in roads that was published in May 2019, on behalf of the Department for International Development (DFID). The review collated experience from India, UK, Ghana, Ethiopia and the Netherlands where waste plastics have been used in road construction. The report provided an excellent source of further papers to consider for review. It should be noted that not all research into the use of waste plastic in roads is relevant to this project (e.g. use of plastic prefabricated blocks in the Netherlands).

4.1 RESEARCH ON THE USE OF WASTE PLASTIC IN ROADS

4.1.1 DRY PROCESS USING PLASTIC ADDITIVES

Vasudevan *et al*[2,3,4,5] has co-authored numerous papers of the use of waste plastic in asphalt mixes in India. The process involves adding shredded mixed plastic waste to hot aggregate before mixing with bitumen. The plastic forms a film around the coarse aggregate particles which are then coated with bitumen in the normal asphalt production process. Vasudevan does not report any issues with specific higher melt point plastics such as polyethylene terephthalate (PET). In addition, polypropylene (PP), poly vinyl acetate (PVA), polystyrene (PS), low-density polyethylene (LDPE) and high-density polyethylene (HDPE) are all listed as suitable. In India, testing is carried out to determine the melt flow value of waste plastic combined sources and limit values have been set by the Indian Road Congress. The testing is undertaken in accordance with the American Standard ASTM D 1238[6] with the following permissible values:

- LDPE 0.14-58 gm/10 min
- HDPE 0.02-9.0 gm/10 min

The Centre for Innovations in Public Systems[7] report that plastic waste has been used widely in road construction in India since 2003. Critical success factors to its use are that the aggregate must

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[1] Manu Sasidharan, Dr Mehran Eskandari Torbaghan & Dr Michael Burrow (2019). *Use of waste plastic in road construction*.[link]
[2] Vasudevan, R. (2004). *Use of plastic waste in construction of tar road*. Environmental information system), Indian Centre for Plastics in the Environment 2: 1-4.
[3] Vasudevan, R. and S. Rajasekaran (2006). *Study on the construction of flexible road using plastic coated aggregate*. Global Plastics Environmental Conference, Atlanta, USA.
[4] Vasudevan, R., A. Ramalinga Chandra Sekar, B. Sundarakannan and R. Velkennedy (2012). *A technique to dispose waste plastics in an ecofriendly way – Application in construction of flexible pavements*. Construction and Building Materials 28(1): 311-320.
[5] Vasudevan, R.N.S.K., R. Velkennedy, A.R.C. Sekar and B. Sundarakannan (2010). *Utilization of waste polymers for flexible pavement and easy disposal of waste polymers*. International Journal of Pavement Research and Technology 3(1): 34-42.
[6] ASTM D1238 *Standard Test Method for Melt Flow Rates of Thermoplastics by Extrusion Plastometer.*
[7] Center for Innovations in Public Systems (2014). *Use of Plastics in Road Construction – Implementation of Technology and Roll Out*. Hyderabad, India.

become well coated to improve water resistance. Several laboratory tests are cited as methods for determining the effect of the waste plastic additive including:

- Stripping test (IS:6241, BS EN 12697-11) – a visual assessment of soaked specimens used for determining the adhesion of aggregates to binders.
- Marshall stability test (BS EN 12697-34, ASTM D 6927 and others) – improvement in Marshall stability when compared to a comparable mix that does not contain plastic waste.
- Water absorption test (BS EN 1097-6 or similar mass by difference) – on uncoated and plastic coated coarse aggregate.

Brasileiro *et al* [8] provide a comprehensive review on the use of a variety of reclaimed polymers for use as bitumen modifiers. It is noted that different waste plastic polymers can require a range of time to complete digestion at a range of mixing speeds. This may prove an important aspect to research further, as the method currently proposed for the trials uses the dry process, where the mixing time may be less than that required to achieve digestion. Further work should be considered to assess the degree of dispersion and digestion that has occurred after asphalt mixing. The paper also highlights the importance of compatibility of the base bitumen with the added plastic waste. The authors suggest a detailed rheological assessment of the bitumen before the addition of the plastic waste, after addition and then comparison with a commercially available polymer modified binder with a comparable performance enhancement objective (i.e. elastomeric or plastomeric).

A significant number of road trials have been laid across India (including Tamil Nadu, Karnataka, Jharkhand). Although case studies exist[7], there does not appear to be any detailed testing information available. A national specification for the use of waste plastic in hot bituminous mixes using the dry process was published in 2013[9].

4.1.2 ALTERNATIVE WET PROCESS USING PLASTIC ADDITIVES

As previously stated in Chapter 1, there are two approaches of incorporating recycled plastics in asphalt pavements: the wet process and the dry process. The dry process is attractive as it does not require specialist mixing facilities but there is some concern regarding the lack of consistency in the quality of the produced mixtures[10]. Although the international literature review above indicates India has over 15 years of experience with the dry process, the studies are laboratory based in the main and they lack the confidence that is provided through robust in-service performance data.

In the wet process, the plastic additive and bitumen are mixed to ensure the additive has homogeneous distribution and completely dissolves in the bitumen. For other polymers this is typically achieved through the use of high shear mixers that are applied to ensure particle size reduction of the polymer. Sugar cubes and granules provide a good analogy, i.e. it takes longer to dissolve sugar cubes in a cup of tea than granules. If low shear mixing equipment is used then milled versions of the polymer can be used[11].

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[8] Brasileiro, L, Moreno-Navarro F, Tauste-Martínez R, Matos, J, Rubio-Gámez M (2019). *Reclaimed Polymers as Asphalt Binder Modifiers for More Sustainable Roads: A Review*. Sustainability Online Journal.
[9] Indian Roads Congress (2013). *IRC:SP:98-2013 Guidelines for the use of waste plastic in hot bituminous mixes (dry process) in wearing courses*. Delhi, India.
[10] National Center for Asphalt Technology (2019). *Discussion on the Use of Recycled Plastics in Asphalt [Link]*
[11] Kraton [Link]

However, it has been reported[12] that the wet process also has limitations due to the poor storage stability of plastic modified binders, i.e. the recycled plastic has a tendency to separate from the bitumen binder due to differences in density and viscosity between the two components.

One method could be to use an ultraviolet (UV) light microscope as it can be a powerful tool to visualize the polymeric network in asphalt binders[13]. The microscope makes it possible to gain insight into the polymer and asphalt binder's compatibility or the blend preparation process's effectiveness.

4.1.3 FUME AND MICROPLASTIC GENERATION

4.1.3.1 Fumes

As noted in the Shell Bitumen Handbook[14], bitumens consist of a complex mixture of hydrocarbons with no well-defined boiling point. Emissions start to develop at approximately 150ºC, and double for every 10 to 12ºC increase. For bitumen, these fumes generally compose of hydrocarbons and smaller quantities of hydrogen sulphide, which raises health and safety concerns and should be managed.

Considering the varying plastic types available[15], PVC (3) is toxic as it releases hydrogen chloride gas and dioxins during degradation or burning, LDPE (4) and PP (5) may contain harmful additives, and PS (6) can release styrene when burning, but are not dangerous to use when not burning. Generally, it is essential not to burn the plastic to prevent releasing harmful fumes.

According to White[16], during the testing of MacRebur additives, the hazardous fumes from the mixture were from the bitumen and not from the addition of plastics. However, the authors note that if the composition of MacRebur additives are altered in the future, then further verification of their safety should be carried out. An extract of MacRebur's Material Safety Data Sheet (MSDS) is reproduced below:

> *3.0 Hazards Identification*
>
> *Some dust may be generated when handling. Moreover, some vapours may be released upon heating. The end-user must take the necessary precautions (mechanical ventilation, respiratory protection, etc.) to protect employees from exposure (dust or vapour exposure).*
>
> *8.0 Exposure Controls and Personal Protection*
>
> *Engineering Controls:*
>
> *If user operations generate dust or fumes ventilation measures should be used to keep the concentrations of airborne contaminates below the workplace exposure limits.*
>
> *Respiratory Protection:*
>
> *A suitable respirator required when dust is generated, or fumes are produced*

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[12]Plastic Industry Association [Link]
[13] Kraton [Link]
[14] Shell Bitumen Hand Book [Link].
[15] Precious Plastic Academy [Link].
[16] White, G (2019). *Evaluating recycled waste plastic modification and extension of bituminous binder for asphalt.* 18th Annual International Conference on Pavement Engineering, Asphalt Technology and Infrastructure. Liverpool, UK [Link]

Eye Protection:

Wear suitable eye protection to protect from dust. In case where the product is heated eye protection against fumes may be required

The MSDS does not provide any definitive guidance on fume and it is recommended that this aspect of the product is further raised with MacRebur and possibly assessed by a specialist in the Control of Substances Hazardous to Health to establish suitable workplace exposure limits. Consideration also needs to be given to any other additive that is mixed with the recycled plastic.

There are various types of plastics, which can be identified by their SPI (Society of the Plastics Industry) code as seen in Table 4-1. The melting points in the table are only indicative, as there are a number of types of plastics which can fit into these categories which have a range of melting points; more detailed information can be provided by the British Plastics Federation[17]. In order for the plastics to meet the recommended mixing temperatures of approximately 170ºC, the plastics would preferably fit into the SPI 3 category. It should be noted that MacRebur's MSDS states that the softening temperature for MR6 is > 120ºC.

Generally, different types of plastic should not be melted together, due to their varying melting points. If melted together some may burn while others melt which may release harmful chemicals.

Table 4-1 - SPI Plastic Types

Code and abbreviation	Name	General use example	Recycled	Melting Point (ºC)[18]
1 – PETE	Polyethylene Terepthalate	Shampoo bottles, food trays, water bottles	Commonly	260-280
2 – HDPE	High Density Polyethlene	Detergents, milk bottles, toys, garden furniture, refuse bins	Commonly	210-270
3 – PVC	Polyvinyl Chloride	Credit cards, window frames, pipes, wire and cable sheathing, synthetic leather	sometimes	160-210
4 – LDPE	Low Density Polyethylene	Bubble wrap, thick shopping bags, wire and cable applications, irrigation pipes	sometimes	180-240
5 – PP	Polypropylene	Yogurt containers, ketchup bottles, fabric fibres, drinking straws	Occasionally	200-290
6 – PS	Polystyrene or Styrofoam	Low cost toys, egg boxes, coat hangers	Not generally	Variable (170-280)
7 – Other	Other (incl Plycarbonate and Polyacitide)	Nylon, layered or multi-material mixed polymers, DVDs	Difficult to recycle	220-290

[17] British Plastics Federation [link]
[18] https://www.plastikcity.co.uk/useful-stuff/material-melt-mould-temperatures

4.1.3.2 Microplastics

As noted by the National Ocean Service "Plastic is the most prevalent type of marine debris found in our ocean and Great Lakes. Plastic debris can come in all shapes and sizes, but those that are less than five millimetres in length (or about the size of a sesame seed) are called 'microplastics'."[19]

The organisation does mention that there are standardised methods for collecting sediment or surface water which, after testing, will tell us the amount of microplastics in the material.

Microplastics have multiple sources such as clothes fibres and fragments from tyres or packaging breaking down. Primary microplastics are manufactured as such, like microbeads and fibres. Secondary microplastics is from larger plastics breaking down due to various factors such as UV[20].

During finalisation of this report, a new methodology was developed[21] in Australia to assess the release of microplastics from plastic-modified asphalt by providing abrasion to asphalt samples in a controlled environment followed by a microplastic extraction and characterisation procedure. It is possible that this methodology could be adopted to assess differences between standard mixes and those containing plastic additives, and conventional PMBs.

Photomicrographs can be used to qualitatively assess the dispersion of standard polymer additives. The test is performed using a microscope after illuminating the samples with ultraviolet light and utilises the phenomenon of differential fluorescent induction of the material components. If the plastic additive is fully dispersed it may be reasonable to assume that it would not become available as a solid microparticle due to asphalt wear when in use.

Microplastics are discussed further under **Section 5.8**.

4.2 MACREBUR PRODUCTS

Nearly 200 documents were provided by MacRebur and CCC by the end of February 2020. These documents were uploaded onto a collaborative workspace and have been indexed with a brief description added to enable rapid assessment of the information to be undertaken. The list includes a small number of papers and reports: five published technical papers and nine case study reports. The remaining documents are results from a range of laboratory tests on asphalt mixtures and binders incorporating plastic that have been recovered from asphalt mixtures.

Three published research papers and one presentation were provided by MacRebur in the early stages of the project. The papers are by White and Reid[16,22,23]. These papers identify the key features of the waste plastic additive process proposed for use in the trials to be undertaken by Cumbria County Council, namely:

- A specific source of waste plastic is added directly to the asphalt production plant (i.e. uses a 'dry process').

[19] National Ocean Service [Link]
[20] University of Southampton [Link]
[21] Austroads Research Report AP-R663-2: Use of Road-grade Recycled Plastics for Sustainable Asphalt Pavements
[22] White and Reid (2019). *Recycled waste plastic modification of bituminous binder.* 7th International Conference on Bituminous Mixtures and Pavements, Thessaloniki, Greece, 2019.
[23] White, G (2019). *Evaluating recycled waste plastic modification and extension of bituminous binder for asphalt.* 18th Annual International Conference on Pavement Engineering, Asphalt Technology and Infrastructure. Liverpool, UK.

- The waste plastic acts as either a partial bitumen replacement (extender) or to enhance certain properties of the binder (modifier).
- The type of waste plastic used has specific low melt point properties to allow it to disperse during the mixing process.

According to White and Reid[22], the main sources of waste plastic in the environment are:

- Plastic drink bottles manufactured from PET with a melting point of around 260°C.
- Single-use plastic bags manufactured from HDPE with a melting point of up to 270°C.

Typical UK asphalt mix production temperatures are 150°C to 190°C. Consequently, White reports that PET and HDPE are generally not suitable as binder extenders and modifiers but that these materials may be used as a filler in asphalt mixtures or as an aggregate replacement. It should be noted that some HDPE has a melting point of less than 270°C and therefore may be suitable for use directly in asphalt mixes.

White and Reid report on three different commercially available waste plastic additives:

- MR6 – designed to increase asphalt stiffness.
- MR8 – designed to reduce bitumen content without performance enhancement.
- MR10 – designed to increase crack resistance.

The MR6 product aims to replicate the properties of an ethylene vinyl acetate (EVA) polymer modified binder i.e. is plastomeric. The MR10 product aims to replicate the properties of a styrene butadiene styrene (SBS) polymer modified binder i.e. is elastomeric.

The papers report on mixtures using the additives that have been tested, including a 10 mm Stone Mastic Asphalt 40/60 (BS EN 13108-5) and a 20 mm Asphalt Concrete dense base 40/60 (BS EN 13108-1).

The mixtures included for testing are summarised in Table 4-2.

Table 4-2 – Mixture testing in published papers

Mixture	Base binder	Additive
AC20 dense base	40/60	None
AC20 dense base	40/60	6% MR6
SMA10 surf	40/60	None
SMA10 surf	40/60	6% MR6 6% MR8 6% MR10

The results from the testing carried out on the laboratory prepared mixtures are summarised in Table 4-3 and the reference mixtures shown in bold. Testing was undertaken to UK standards using the following tests:

- Indirect tensile stiffness modulus (ITSM – CY) BS EN 12697-26
- Indirect tensile strength ratio (ITSR) BS EN 12697-12
- Indirect Tensile Fatigue Test (ITFT) BS EN 12697-24

- Wheel tracking (depth and rate)[24] BS EN 12697-22
- Crack propagation by semi-circular bending test BS EN 12697-44

Table 4-3 – Summary results from mixture tests

Mixture	Stiffness Modulus (MPa)	Water Sensitivity (ITSR %)	Wheel Track Rut Depth (mm)	Wheel Track Rate ($mm/10^3$ cycles)	Fracture Toughness (N/mm^2)
AC20 dense base	**7,827**	**95.6**	**1.8**	**0.046**	**n/a**
AC20 dense base + 6% MR6	11,600	>100	1.5	0.039	n/a
SMA10 surf	**1,823**	**94.8**	**3.1**	**0.11**	**23.8**
SMA10 surf + 6% MR6	5,438	>100	1.3	0.03	29.1
SMA10 surf + 6% MR8	4,032	85.0	2.6	0.07	25.8
SMA10 surf + 6% MR10	6,451	86.0	2.0	0.05	27.6

It should be noted that for the results provided, all values comply with the current requirements in UK asphalt mixture standards where they exist, including the unmodified mixtures. The reported data shows that the stiffness can vary from around a 50% increase for AC20 with MR6, to more than a 250% increase for SMA10 with MR10. The paper[23] notes that further work is required to examine the practical effects of increased stiffness modulus in terms of pavement design life. In general, the test data demonstrates that the addition of plastic waste delivers an improvement in performance as measured by the other laboratory tests. Fatigue data was also available from ITFT, but it was not possible to draw any firm conclusions from the data at this stage.

It should be noted that the vast majority of specimens appear to have been produced in the laboratory and that the additive was introduced using a quasi-wet process. It is not always clear from the papers how the specimens were prepared and what compaction method was used prior to stiffness testing. Previous research[25] has shown that consideration should be given to the laboratory compaction method when specifying values for mechanical properties of asphalt mixtures. Caution should therefore be applied when interpreting the data as some of the high values may be due the method of specimen preparation. These high values are unlikely to be replicated when the asphalt and additive is produced at a plant using the dry process and then compacted using conventional compaction plant. However, it is possible that the laboratory results may correlate to those found from specimens (cores) taken from the mat. This is discussed further under section 4.3.4.

[24] Assumed to be small device procedure B in air

[25] Allpress C, Artamendi I, Allen B & Phillips P (2017). *Effect of Laboratory Compaction Method on the Mechanical Properties of Bituminous Materials.* 16th Annual International Conference on Pavement Engineering, Asphalt Technology and Infrastructure. Liverpool, UK

4.2.1 BITUMEN RHEOLOGY

The rheology of bitumen is associated with conducting tests and measurements that describe the flow and deformation characteristics of bitumen. White and Reid[22] report rheological properties for plastic waste modified bitumen and unmodified bitumen: penetration value; softening point; force ductility; and dynamic shear rheometer (DSR) testing, which includes complex modulus, phase angle, multiple stress creep and recovery (MSCR) test and performance grade (PG) rating assessment. Only testing at high temperatures were reported.

Force ductility testing was carried out at 25°C rather than the more common UK test temperatures of 5°C or 10°C. The base bitumen was either a 100/150 or 50/70 pen grade. This was then modified by the addition of either 4%, 6% or 8% by mass of bitumen of the MR6 or MR10 additives. The base bitumen was heated to 170°C and the appropriate mass of waste plastic added to a laboratory high shear mixer for 30 seconds (i.e. a small-scale wet process).

The main part of the work examined the effect of the plastic waste additive on the PG of the binder under the Superpave test regime and the MSCR test. These tests are considered as indicators of binder properties that improve in-service rut resistance. In general, the results showed that the addition of the plastic waste products increased the high temperature grade assessment under both protocols, i.e. mixes using these binders would potentially be able to withstand greater temperatures before permanent deformation occurred. It appeared that dosage rates higher than 6% did not necessarily give rise to further increases in the temperature grading.

4.2.2 CASE STUDIES

The MacRebur case studies mostly take the form of one to two-page overview sheets. One study carried out at Green Dragon Lane in Enfield, includes a more detailed description and a basic visual condition assessment after two years. The trail site incorporates asphalt material with three different MacRebur additives and a control section surfaced with a proprietary polymer modified asphalt surface course. A summary of the information provided is given in, including the study name; location; date laid; carriageway type; MacRebur product type trialled; and where known, which layer has been treated with an additive.

Table 4-4 – Case study summary

Project Description	Location	Date laid	Carriageway Type	Product	Layer
Ashton Rise Housing Estate	Bristol	Aug 2019	Estate road	MR6	Unknown
A709	Dumfries & Galloway	Oct 2017	A-road	MR10 pellet	HRA 30/14 surf
Hundeth Hill	Cumbria	Sept 2018	Unknown	MR8	SMA10 surf AC20 HDM bin
Tesco Car Park	Dumfries & Galloway	May 2018	Car Park	MR8	SMA10 surf
Truro Avenue Murton	Durham	June 2018	Estate road	MR8	AC10 surf
Waterworks Bridge, Olympic Park	London	June 2019	Cycleway (Bridge deck)	MR6 MR8	Unknown
Springfield Yard and housing estate	Unknown	July 2019	Estate road Yard	MR8	Unknown
Green Dragon Lane, Enfield	London	Sept 2017	Single CW bus route	MR6 MR8 MR10	HRA 35/14 surf

4.3 ANALYSIS OF MACREBUR DATA SHEETS

A significant amount of laboratory test data was provided by MacRebur. The data was collated into a single summary spreadsheet for analysis.

4.3.1 TYPES OF DATA

The test data falls into three main categories:

- laboratory mixtures
  - Tests on specimens that have been prepared in the laboratory.
  - Specimens are produced from aggregate, bitumen and additives that have been heated, mixed and compacted (typically roller compactor or impact hammer) to produce cylindrical samples.
- Binder tests
  - Laboratory tests carried out on bitumen with and without additives.
- Site samples
  - Loose bulk samples taken from the paver or delivery vehicle.
  - Cores taken from the laid and compacted mat.

4.3.2 LABORATORY TESTS

Based on the literature review and information received as part of the project, laboratory testing included:

- Resistance to permanent deformation - Wheel tracking test;
- Resistance to fatigue - Indirect Tensile Fatigue (ITFT) Test;
- Elastic stiffness - Indirect Tensile Stiffness Modulus (ITSM) test;
- Water sensitivity - Indirect Tensile Strength Ratio (ITSR);
- Crack propagation - Semi-circular Bending test;
- Marshall asphalt design properties;
- Air voids content and density;
- Grading - Particle Size Distribution;
- Binder penetration;
- Binder softening point;
- Rheological testing of binders - Dynamic Shear Rheometer, Bending Beam Rheometer, Multiple Stress Creep and Recovery test); and
- Superpave PG grading binder conformity testing.

4.3.3 MIXTURE TYPES

The mixtures tested can be categorised into the following types:

- 10 mm proprietary thin surface course
- 14 mm proprietary thin surface course
- 10 mm stone mastic asphalt surface course
- 20 mm dense asphalt concrete binder course
- 20 mm heavy duty asphalt concrete binder course
- 14 mm Marshall asphalt surface course

4.3.4 ADDITIONAL DATA ANALYSIS

The greatest part of data provided by MacRebur related to ITSM testing that measured the effect of various additive types on the stiffness of asphalt specimens. Using the same ITSM apparatus, data was also available on resistance to fatigue (ITFT) and water sensitivity (ITSR). This section provides some additional analysis of stiffness and fatigue data. Information on the indirect tensile strength ratio – a comparison of strength between dry and wet (soaked samples) – showed the mixtures containing additives were not water sensitive.

4.3.4.1 Stiffness results

Figure 4-1 shows the results of stiffness testing for samples of a binder course (AC 20) and surface course (10 mm SMA) with and without a range of plastic additives. There is clear trend showing that samples with additives produce higher stiffnesses than those without, AC20 control and SMA10 control. The exception to this was the three specimens containing a very high dose (20%) of MR8.

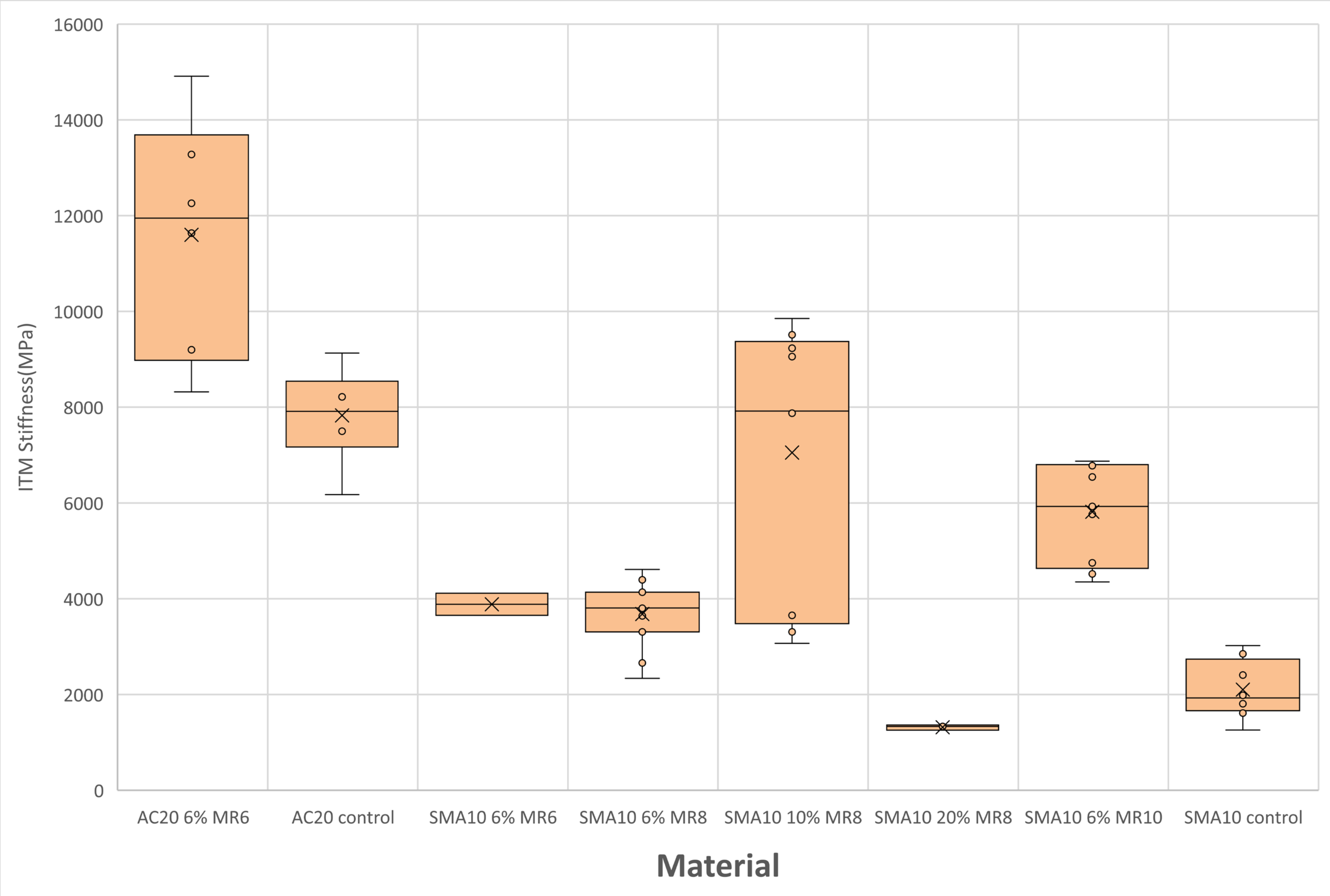

Figure 4-1 – Stiffness for laboratory prepared specimens containing different plastic additives

From an examination of the test certificates it can be seen that the majority of specimens were plant produced samples that were reheated and compacted in the laboratory. Test certificates show that 36 (66%) of the specimens were compacted using a mechanical roller compactor, whereupon 150 mm diameter cores were extracted and tested. Twelve (22%) were compacted used a Marshall Hammer which produced 100 mm cylindrical specimens which were then tested. Finally, six (11%) of the samples comprised 150 mm diameter cores which were extracted directly from a compacted pavement surface.

As stated earlier, results from laboratory prepared specimens can be different from those taken directly from an asphalt pavement. For example, the results produced for the AC 20 control are around two to three times the stiffness typically expected from a fresh binder course taken from a mat. However, where samples are prepared in the same way the results from mechanical tests can be compared. The AC 20 6% MR6 and AC20 control were both prepared using the roller compactor. The modified mixture clearly produces a higher stiffness. It is also clear that the modified mixture produces a greater range of results, i.e. the AC20 control results are lower but more consistent.

When the SMA10 control is compared to the modified SMAs, the latter produce higher stiffnesses, with the exception of SMA10 20% MR8. It can be seen that SMA10 6% MR8 produces a large spread of data compared to the other mixtures. A closer examination of the specimens containing SMA 6% MR8 shows that the results were based on specimens that were prepared in two different ways: 6 roller compactor and 3 Marshall Hammer. In this instance, the Marshall Hammer specimens produce around one third of the stiffnesses produced in the roller compactor and can explain the large spread in results.

4.3.4.2 Resistance to fatigue

Figure 4-2 shows the results from ITFT testing. In order to estimate the fatigue life of the specimen, the microstrain at 10^6 load cycles (value 6 on x-axis) is reported. The higher the microstrain at 10^6 cycles the higher the fatigue life. An examination of Figure 4-2 indicates that the AC 20 MR6 has slightly better fatigue life than the AC 20 control. The converse is true when the SMA control is compared to SMA MR8, with the control producing a higher fatigue life. However, there is considerable scatter in the data collected from the tests and it was not possible to draw any firm conclusions from the data at this stage.

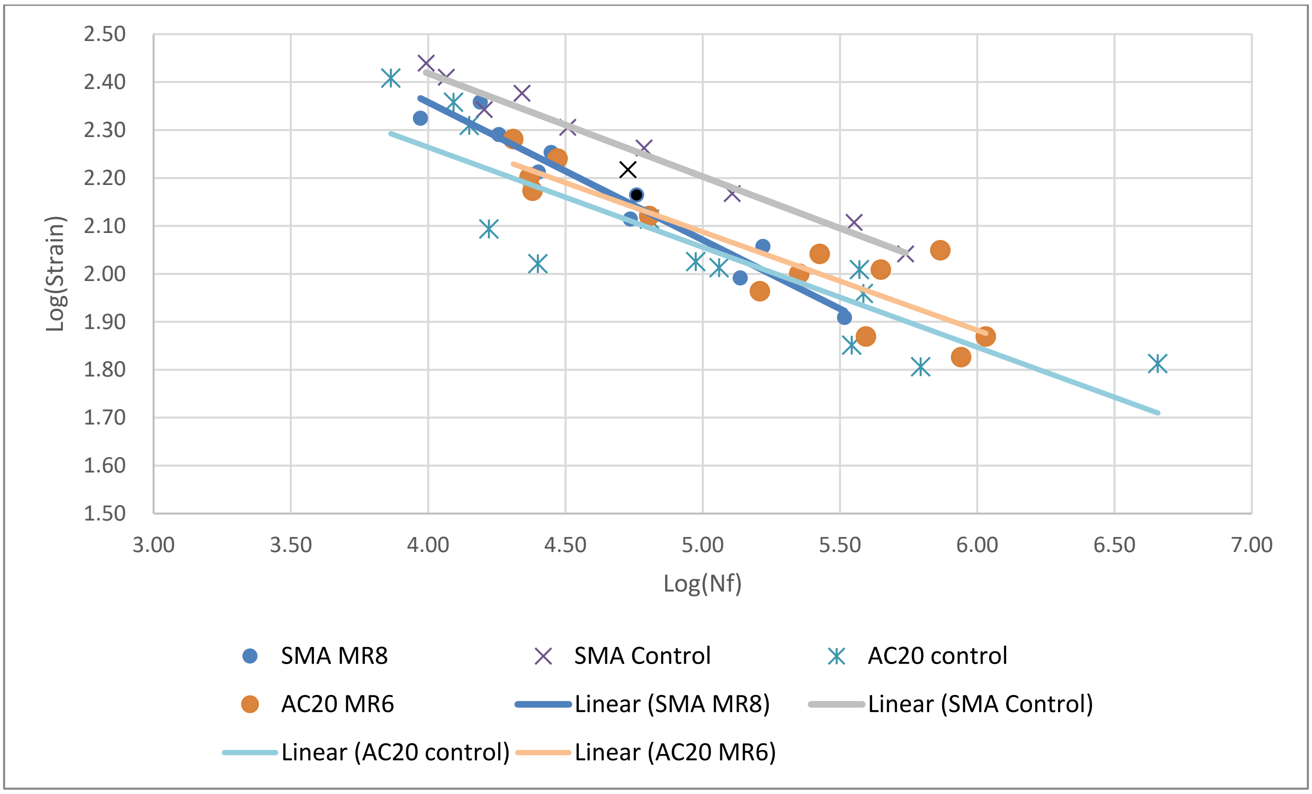

Figure 4-2 – Results of Indirect Tensile Fatigue (ITFT) Testing

4.4 DISCUSSION

A significant amount of laboratory-based research into using recycled plastic as a bitumen modifier has been undertaken worldwide. The types of recycled plastic used in such applications vary quite widely. However, they are broadly categorised as either plastomers or elastomers.

Some work has been undertaken to allow mixed waste plastic feedstock to be assessed for suitability. Having an accurate characterisation of any waste plastic will be extremely important in ensuring the consistent modification of binder and hence asphalt mix properties. This will be required to ensure that any testing undertaken during the full-scale trials remains valid for any wider scale introduction of these materials.

Achieving adequate dispersion and digestion of the waste plastic may be a critical factor in achieving reliable results from asphalt mixtures. Work undertaken to date does not appear to have assessed this. Further work should be considered to assess the degree of dispersion and digestion that has occurred after asphalt mixing, as the mixing time in the dry process may be less than that required to achieve digestion or dissolution.

The case study data does not provide any immediate opportunity to assess the long-term durability of asphalt materials containing plastic. The two oldest sites were laid in late 2017. Both these sites were surfaced with hot rolled asphalt material containing plastic. The site at Green Dragon Lane in Enfield is likely to provide the most useful data, as it is reasonably heavily trafficked and contains material incorporating MR6, MR8 and MR10, as well as a control site that is surfaced with HRA incorporating a commercially available polymer modified binder. The latest report from Green

Dragon Lane from February 2020 identifies that no underlying pavement condition data appears to have been collected for this case study trial site and it is therefore difficult to determine the cause of any defects which may now be visible.

On initial assessment of collected test data, it appears that a significant amount of laboratory testing has been undertaken. It appears that there has been no test data provided explicitly for Fraas breaking point or dynamic viscosity testing. Fraas breaking point provides information on the behaviour of the binder at low temperature, whilst, dynamic viscosity testing provides an estimate of the workability of the binder. However, both properties are covered to a degree by the rheological tests that have been undertaken.

It also appears that no Saturated Ageing Tensile Stiffness (SATS) testing data has been provided to date, although it is understood that this is available. This test was designed to measure the durability of adhesion between aggregates and binder, by simulating the ageing of asphalt base materials in the presence of water, with the application of increased pressure. Although not a fundamental property, it would provide a useful comparison of material performance under these demanding test conditions.

The case studies examined in the literature review highlighted the need for independent planned trials to scientifically examine any effects plastic additives may have on pavements, hence demonstrating the importance of the Live Labs Trials.

4.5 SUMMARY

The literature and test data reviewed in this chapter provides some evidence that adding recycled plastics can significantly increase binder stiffness and rutting resistance. Laboratory based studies suggest that the addition of plastic additives has the potential to produce asphalt mixtures that will extend the service lives of asphalt pavements. Any significant increase in asphalt mixture stiffness modulus must be treated with some caution, as previous experience in the UK has shown that focussing on increasing stiffness modulus without accounting for other mixture properties can lead to a decrease in overall pavement durability[26].

In general, the literature review has shown that there does not appear to be any significant technical studies of in-service performance of pavements incorporating waste plastic additive as a bitumen extender or enhancer. As such, the impact of plastic additives on the actual pavement performance is largely unknown and warrants further investigation.

The following conclusions and findings can be drawn from the literature and data review:

- There is a significant body of laboratory-based research on the use of recycled plastic added to asphalt mixtures as a bitumen extender or enhancer.
- To date, no large-scale road trial performance data has been identified.
- Road trials have been undertaken in India, but the assessment of performance has been largely qualitative.
- A method of determining the properties and consistency of the feedstock of waste plastic needs to be established to ensure consistency of performance in the future.

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[26] Stephen F. Brown (2013) *An introduction to asphalt pavement design in the UK*. ICE Transport Proceedings, Volume 166, Issue TR4. ICE Publishing.

- Guidance on fume is required by a specialist in the Control of Substances Hazardous to Health to establish suitable workplace exposure limits, and consideration also needs to be given to any other additive that is mixed with the recycled plastic.
- Some additional laboratory testing is likely to be required to examine low temperature properties of bitumen incorporating waste plastic and the durability of adhesion in asphalt mixes.
- Further work to establish the dispersion and digestion of waste plastic polymers under the dry process of addition should be undertaken.

5

CIRCULAR ECONOMY ASSESSMENT

5 CIRCULAR ECONOMY ASSESSMENT

5.1 INTRODUCTION

The principles of a circular economy challenge us to *systematically* and *systemically* look at the way we use resources across our value chains, and identify ways in which we can:

- Keep resources (energy, materials, waste and water) in use for as long as possible, extracting their maximum value;
- Design out waste and pollution; and
- Recover and regenerate products, materials and systems at the end of each service life.

In contrast to a linear economy, the circular economy seeks to reduce our reliance on the extraction and manufacture of primary resources; rather, it encourages 'loops' of resources where waste is minimised at every stage of an asset lifecycle.

But the circular economy does not just consider resources and waste in isolation. In particular, the Ellen Macarthur Foundation (EMF), in collaboration with Material Economics in their seminal paper 2019 'Completing the Picture' [27] reports that the role of the circular economy can be expected to contribute up to 45% [28] of the net zero challenge, as shown in Figure 5-1.

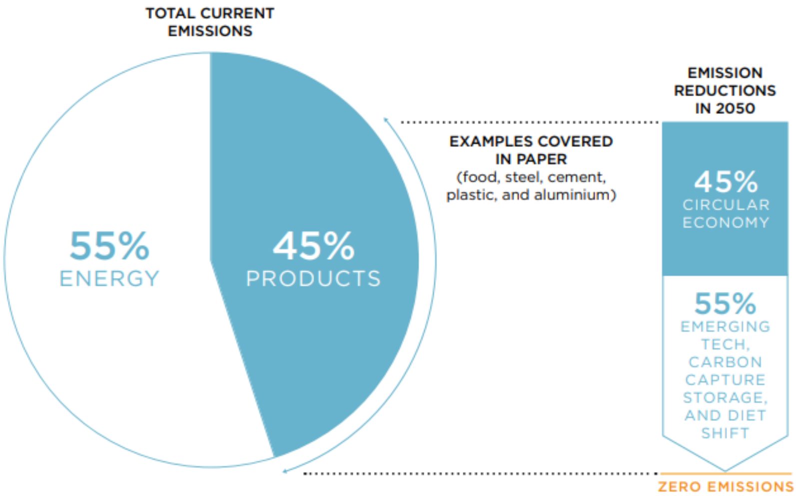


Figure 5-1 - The circular economy's role in achieving Net Zero (Credit: EMF, Material Economics)

In the context of CCC's commitments to carbon reduction (first encapsulated in its 2009 Carbon Reduction Plan) the role of the circular economy has a clear and critical role to play. This is particularly the case in the context of CCC cabinet's 'unanimously agreed' Carbon Management Strategy (November 2020), which incorporates a commitment to "*achieve a low/net zero carbon economy by 2050*".

[27] Ellen MacArthur Foundation, 2019, Completing the Picture [link]
[28] 39% reduction, according to the 2021 Circularity Gap Report (Circle Economy [link]

5.2 COMMISSION SCOPE

Two different but interrelated assessments were commissioned to provide a layer of technical analysis over and above that which has been prepared in the other chapters of this report, and in support of the overarching objective of the commission:

"To investigate the possibility of improving the design life of road pavements by using plastic additive, by looking at the potential to produce a new design of road that increases durability, whilst reducing cost."

These assessments are now described:

5.2.1 CIRCULAR ECONOMY ASSESSMENT

To build on the extensive research, partnerships and trialling that CCC continues to conduct in the arena of plastic roads, WSP was commissioned to undertake a circular economy assessment of the potential use of plastic additives in either wet or dry processes for asphalt. In particular, the assessment was commissioned to look at the system benefits (and any possible disbenefits) of including plastics in roads, particularly with regards to:

- Reducing reliance on technical (man-made) or biological materials;
- Recovery, reuse and open-loop recycling of waste;
- Landfill diversion;
- Embodied lifecycle impacts; and
- Rethinking product development to encourage durability, flexibility and environmental performance.

5.2.2 LIFECYCLE ASSESSMENT

In addition to the circular economy assessment, WSP was commissioned to conduct a Lifecycle Assessment (LCA) of the comparative plastic and non-plasticised surfacing products that were being investigated. The LCA was commissioned to look at environmental impacts across different product lifecycles, to compare the performance of each from cradle-to-grave.

5.3 RESEARCH PROGRESS: A SUMMARY

During the research programme conducted, and based on the information made available, it was agreed that neither a *full* circular economy statement, nor an LCA could be robustly undertaken.

This decision was made primarily in the absence of robust data from the surfacing supply chain, though this did not depreciate from CCC's ambition to generate clear and quantified data to support decision making. As stated in the recommendations within this chapter (Section 5.11) – an LCA should be pursued in the future when valid information is made available.

Instead of the full circular economy by assessment and LCA, it was agreed with CCC that WSP would evaluate the information provided, establish any key gaps, and identify areas in which the collection, analysis and interpretation of more granular or wider information would benefit CCC's ongoing commitments to sustainable resource management and the circular economy, as part of the wider Council ambition to achieve net zero by 2050. WSP was also asked to comment on current and future plastic policy, and (within this) contextualise the potential benefit of incorporating plastics in asphalt, should an 'ideal scenario' be possible.

The following sections describe the information reviewed as part of the circular economy assessment. Key conclusions and recommendations are set out in Sections 5.10 and 5.11.

5.4 KEY INFORMATION REQUESTED

To help complete the circular economy assessment for this commission, WSP requested a suite of information from CCC and its value chain partners, as described in Table 5-1.

The status of the initial information (at the time of writing this chapter) is shown in the right-hand column of the table; it has been used to help inform the findings of this chapter.

Table 5-1 - Circular economy information requested and its status

Product type and information request	Status of information
Plastics	
▪ Any Council policy, commitments, ambition, practice or achievements (other than the MacRebur venture) to drive circular practice on plastics (qual)	Received
▪ A breakdown of plastic waste generated within CCC's geographical remit, by type (qual) and volume (m3 or tonnes)	Received, though not by plastic type
▪ Local / regional resource and waste management facilities / processes designed to help maximise performance in accordance with the Waste Hierarchy / proximity principle (qual)	Received
▪ The high-level process undertaken for collecting household / other plastic waste, to the point of recovery or disposal (qual)	Received
▪ Annual costs associated with plastic collection / transportation / management, if known / discernible (£)	Information on recycling credits received [29]
▪ Plans for new or improving facilities to manage plastic waste in the region (qual)	(Not known)
Asphalt	
▪ The volume of asphalt deployed annually in the CCC region (m3 or tonnes)	Received (data from CCC's main surfacing contractor)
▪ Typical asphalt form (qualitative and/or %)	Received
▪ The methods adopted for laying asphalt (hot, cold, other) in Cumbria (qualitative and/or %)	Received
▪ The current typical recycled aggregate / other secondary content (%) content of asphalt laid	Received
▪ Typical lifetimes specified for asphalt (years)	Received
▪ Annual costs associated with asphalt laying (production, transportation, laying) (£)	Received
▪ Annual costs associated with asphalt maintenance / repair (£)	(Not known)

The following three sections (Sections 5.5 to 5.7) describe information acquired from CCC during the course of this research project.

[29] Information received confirmed that – as the Waste Disposal Authority – CCC issues a recycling credits (£76.51 per tonne) to all district, city and borough councils within the county, to incentivise landfill diversion. Credits are issued for all kerbside materials recycled, excluding electronic and electrical resources.

5.5 RESEARCH FINDINGS: WASTE MANAGEMENT IN CUMBRIA

5.5.1 BULKY WASTE

To provide additional context for this section of the report, the following financial data and policy ambitions on waste management in Cumbria were collected. The information demonstrates CCC's ongoing ambition to reduce waste generation and disposal, and to achieve cost savings and environmental benefits as a result.

Approximately 2,224 tonnes of bulky waste was collected from Cumbrian households and landfilled in 2019, costing CCC over £470,000 in disposal costs. CCC is committed to a reduction of 70% of this waste, which would lead to the following savings:

- £327,600 savings from disposal costs;
- £50,000 savings in shared administrative costs across the six Cumbrian district authorities; [30] and
- £25,000 saving to Cumbria County Council's Welfare Assistance Programme.

It is noted by CCC that the workstreams needed to achieve these savings could also generate sources of potential revenue (e.g. recyclate for sale), which would to be shared across the council's partnerships. This could, in future, apply to the recovery of plastics for use in asphalt, for example.

CCC noted that there are options for encouraging more recycling of bulky waste at Household Waste Recycling Centres (HWRC) - for example mattresses, carpet and hard plastic recycling - but success in this context is often dependent on the presence of a local or regional re-processor that can accept the resource. Haulage costs and logistics were also noted to influence the success with which such items can be recycled. This information is a particularly material consideration in the context of **5.10.3 (h)** in this chapter, which discusses the current state of material recovery and processing facilities near Cumbria.

[30] Noting that the value of these savings will eventually change, when unitary authority statuses are assigned across Cumbria

5.5.2 LOCAL PLASTIC WASTE MANAGEMENT

5.5.2.1 Overview

CCC is responsible for plastics deposited at its HWRCs. The plastic within HWRCs is collected and taken to the Hespin Wood Material Recovery Facility (MRF), to be baled and sold on for processing. Any non-conforming material is removed where offtake arrangements allow.

All district councils (with the exception of Barrow Borough Council) collect plastic as part of kerbside collections and at their 'bring sites' (bottle, clothing and paper banks location in public places e.g. supermarket car parks) and use transfer stations to deliver recyclate to Hespin Wood MRF. Various recycled plastic products are generated at the MRF, including granulated pellets.

Barrow Borough Council does not have a HWRC, but initially delivers any collected plastics to a recycling provider. The recycling provider then reprocesses any rigid plastics ready for granulation, regrind or extrusion. Any contaminated plastic from Barrow Borough Council is transported to MRFs outside Cumbria (increasing environmental and cost impacts from haulage); rejected recyclate is sent to the Barrow Mechanical Biological Treatment (MBT, for Solid Fuel Recovery) at Plant Southern Resource Park. There is currently understood to be a high rejection rate of recyclate collected across Barrow.

At the moment, management costs associated with individual waste streams (including plastic) are not split out from the overall cost of waste management. It is hence not possible to gain a clear picture of the cost impact of plastic waste management to CCC, or individual district / borough councils, therein.

Currently, there are no plans for developing new or improving facilities to manage plastic waste in the region.

5.5.2.2 Plastic waste data

In Cumbria, data for plastic waste recycling is collated on a financial year basis, to identify opportunities to divert from landfill.

The data in Table 5-2 describe the most recent information (from 2018 to 2020) available for the region: both for plastics that were recycled (direct) and an estimation of plastics extracted and managed from residual waste compositions. In all, 9,202 tonnes of plastic were recycled.

Estimations for the two years for which information is available are that each year nearly 4,500 tonnes of plastic was reported as recycled, and as much again unseparated from residual waste (9,000 tonnes in total, per annum).

Whilst hard plastic bulky items are collected at HWRCs, it is not yet known whether these offer a suitable source of material for incorporation in asphalt courses.

Table 5-2 - Plastic sorting, treating and recycling in Cumbria (2018/2020)

Plastics sent for recycling (kerbside collections, tonnes)	2018/2019	2019/2020
Allerdale Borough Council	877	758
Barrow-in-Furness Borough Council	151	137
Carlisle City Council	1,207	1,227
Copeland Borough Council	531	559
Eden District Council	331	339
South Lakeland District Council	875	914
Cumbria County Council	515*	544
Total for recycling	*4,488*	*4,478*

Plastics in residual waste sent for Mechanical Biological Treatment, MBT (tonnes) #	2018/2019	2019/2020
Plastics (general)	1,639	2,111
Pots, tubs and trays	3,075	2,805
Total to MBT	*4,714*	*4,915*

Estimated overall total recycled

* From HWRCs and includes over 300 tonnes of hard plastics

\# Includes plastic film, but does not include any estimates of plastics in HWRC residual waste, or Material Recovery Facility (MRF) rejects.

5.6 SURFACING DATA

5.6.1 ROAD SURFACING MATERIALS

CCC relies on its value chain to provide information on road surfacing materials. By way of an example, information on asphalt from CCC's core contracts (2018 to 2021) is provided in

Table 5-3.

Table 5-3 - Road surfacing materials in Cumbria (data from CCC core contracts, tonnages, 2018 - 2021)

Annual period	Base	Binder		Foam Mix	Surface Course					PCC	Annual totals
	AC32	AC20	AC14		AC14	AC10	AC6	SMA10	HRA		
April 2018 to Mar 2019	0	3,490	0	0	0	98	47	5,912	2,026	304	**11,877**
April 2019 to Mar 2020	393	10,370	0	0	126	608	800	16,749	3,040	456	**32,543**
April 2020 to Mar 2021	0	6,336	0	2,551	1,154	2,757	381	3,971	257	39	**17,445**
April 2021 to date	1,598	16,342	1,382	0	6,902	6,931	785	6,076	499	63	**40,577**

As described, trends for asphalt consumption vary significantly year on year, and depend on maintenance cycles, the construction of new on- and off-line assets, and – increasingly, it is expected – impacts from climate on highway condition.

As part of the research conducted, it was noted that none of CCC's suppliers use Recycled Asphalt Planing (RAP) in surfacing, as historically, failures have caused a lack of confidence in these products. Furthermore, all asphalt laid in Cumbria is currently via hot mix processes; whilst cold mix [31] is used for surface dressings, neither this nor any other asphalt consumption data were available for inclusion in

Table 5-3.

[31] Cold mix asphalt has the potential to significantly reduce the carbon impact of resource laying. A variety of studies exist in this context (e.g. *Lundberg, Jacobson, Redelius 3 , Östlund (2016) Production and durability of cold mix asphalt, 6th Eurasphalt & Eurobitume Congress [link]*), each citing different reductions under different conditions (more than 50% in some cases), but each also subject to highway performance criteria such as lifespan, durability and potential end-of-use recoverability.

5.7 INCENTIVISING BEST PRACTICE AT CCC

Whilst neither the CCC Joint Municipal Waste Management Strategy 2008 – 2020, nor the Minerals and Waste Local Plan (2017) specifically cover plastic as a topic, they do make references to plastics in terms of a component of household, construction, demolition and excavation wastes.

As these documents were produced prior to plastic waste management coming to the fore in mainstream media, it is expected that future iterations will incorporate a much more comprehensive set of policies.

Whilst CCC does not have a policy on plastics, it does take action through the following initiatives. It:

- develops model contracts that incentivise (among other environmental sustainability factors) low impact asphalt: CCC works with its supply chain to agree a retention fee on projects, and contractors can claim part or all of the retention fee back, subject to their framework environmental performance which is linked into a series of Key Performance Indicators (KPI). Information on contractor performance is held centrally, and subject to discussion at progress meetings and quarterly review with service lead undertaken but not reviewed;
- is part of the Plastic Clever Cumbria initiative, which is run by Penrith Action for Community Transition (PACT), with support from sustainability groups across Cumbria. The initiative encourages pledges from residents and business to reduce consumption and disposal of single use plastics.
- reports on % recycling achievements at its HWRCs, though this is not specific to plastic waste

In the context of this report, the above demonstrates CCC's growing ambition to reduce impacts from plastic across the region. These measures will be augmented through (for example) the implementation of new legislation, as discussed in Section 5.8.1.

5.8 THE MICROPLASTICS DEBATE

As introduced in Section 4.1.3.2, and in the wider context of this circular economy chapter, it is important to consider the subject (and potential impacts and effects) of microplastics, which has recently gained prominence through media attention.

5.8.1 UK POLICY ON PLASTICS

The UK Government has responded to concerns on plastics (in general) by increasing powers to reduce consumption and disposal: particularly through a greater responsibility for the packaging production and by incentivising consumers to recycle more. These measures will be implemented through (for example) the:

1) ban on microbeads, cutting the sale of plastic bags, and prohibiting the supply of plastic straws, stirrers and cotton buds;
2) emerging Environment Bill, which will lay down measures that encourage:
    - consumers to return drinks containers to retailers through a Deposit Return Scheme; and
    - manufacturers to absorb the full costs of recycling packaging waste that they produce (Extended Producer Responsibility), with financial penalties being drawn down where packaging is harder to reuse or recycle;
3) (future) introduction of consistent recycling collections for all households and businesses in England.

5.8.2 MICROPLASTICS FROM ROADS

As national coverage of the impacts of plastics grows, and proposals to incorporate waste (including plastics) in highway applications gain momentum, concerns within the public and media have emerged: in particular, the leaching or translocation of microplastics from highway surfaces into the natural environment.

At the time of publication, there is no research which conclusively shows that microplastics are transferred from highway surfaces to the natural environment. Engagement with highway engineers based on pilot studies conducted to date, suggest that due to the fact that as plastics are chemically bonded to the bituminous binder within highway surfaces, the risk of disassociation and pollution is actually far lower than the risk of (for example) tyre microparticles being released.

As results of research into microplastics impacts are not at this time definitive, further work will need to be conducted in this arena, particularly taking into consideration impacts from climate change and future technologies: effects on roads could (for example) be materially influenced by:

- increasing average and peak temperatures;
- more intense freeze-thaw effects;
- changes in the frequency and severity of precipitation events, as well as acidification; and
- changes to automobile weights and highway-tyre surface interactions, in the advent of electric and autonomous vehicles.

5.9 THE POTENTIAL BENEFIT

5.9.1 ASPHALT PRODUCTION AND SALES IN THE UK

According to the MPA [32,33] England, Wales and Scotland produce over 20M tonnes of asphalt every year, from nearly 300 manufacturing facilities located primarily in quarries, but also in local plants that serve regional markets. Some asphalt plants are temporarily installed on developmental construction sites, particularly for major infrastructure works.

As shown in Table 5-4, sales of asphalt in England exceeded 21M tonnes in 2019, with sales in the north west occupying over 10% of this.

Table 5-4 - Asphalt sold in the UK, million tonnes, 2019

East of England	East Midlands	North East	North West	South East & London	South East	South West	West Midlands	Yorkshire and the Humber	**England**	**England, Wales & Scotland**
2.5	2.8	0.8	2.4	4.6	1.9	2.2	2.0	2.1	**21.3**	**27.4**

5.9.2 REDUCING DISPOSAL OF PLASTICS

The UK government's statistics on waste [34] show that in 2020, 2.48M tonnes of plastic packaging waste was disposed of, with 47.4% recycled. Whilst the data provided do not represent the total tonnage of plastic waste (there will also be some plastics contributing to mixed waste streams e.g. black bags, that are categorised as 'household and similar wastes'), it can therefore be asserted that more than 52.6% of plastics (some 1.3M tonnes) is still sent to landfill or energy recovery each year.

Based on data provided by CCC which asserts that (on average) for every tonne of asphalt produced, 3kg (0.3%) plastic could be incorporated in its fabric, the extrapolations in Table 5-5 can be derived. Note that subject to the caveats set out in the previous paragraph on the availability and granularity of plastic waste information in the UK and at a regional level, these data should be treated with a commensurate level of caution, especially as they are high level and based on a relatively 'ideal / theoretical' scenario for waste recovery.

[32] Mineral Products Association (2021), Asphalt information page [link]
[33] Mineral Products Association (2021), Profile of the UK Mineral Products Industry, 2020 Edition [link]
[34] Defra, Government Statistical Services (2021), UK Statistics on Waste [link]

Table 5-5 - Potential for incorporating plastic waste in asphalt

Criterion	Metric	North West	England	England, Wales & Scotland
(1) Asphalt sales by region	Tonnes	2,400,000	21,300,000	27,400,000
(2) Plastics disposed of (not recycled) by region	Tonnes	113,869*	1,010,584*	1,300,000
(3) Plastic that could be accommodated in regional asphalt (1) (based on 0.3% contribution and subject to suitability)	Tonnes	7,200*+	63,900*	82,200
(4) National or regional disposal (2) that *could* be avoided if plastic resources (3) were maximally incorporated in *all* regional asphalt layers (1)	Percentage		6%	

* *Extrapolated from data from England, Wales and Scotland (final column), noting that data for plastic recyclate is subject to previously-stated caveats in 5.9.2.*

\+ *this may well be an underestimate, taking into account data for Cumbria as set out in*

Table 5-3.

5.9.3 POTENTIAL COST SAVINGS

CCC confirmed that it spends approximately £12M per annum through its core surfacing contractor; it is estimated that some £10M of this is spent on the laying of asphalts.

With the laying of asphalt costing between £90 and £130 per tonne (depending on material type), it is also currently estimated (using unverified data from CCC's supply chain) that adding plastic to this mix would add between £0 to £5 per tonne (therefore, between a 0% and 6% increase in cost).

Adopting an 'ideal scenario' (where cost impacts from plastics in roads are zero) and taking into account that plastic to landfill (presuming the application of the standard rate of landfill taxation) is £96.70 per tonne (from 2021, in England), diverting 7,200 tonnes of plastic from landfill across the north west could represent a direct cost saving of £696,240 per annum, excluding haulage costs and the wide range of environmental and socio-economic (employment) benefits that would also be derived. At a UK level, and presuming an optimal usage of plastics, the potential savings could reach £7.95M per annum. With landfill tax and regulation on plastics becoming more stringent each year, the benefits of incorporating 'otherwise waste' resources in asphalts, will become more prominent.

Note *In presenting this information and analysis, the data that have been used should be considered 'best estimates' which have also (for purposes of clarity) rounded to 0dp. It is* *also important to clarify that the findings of this report are based on assertions from CCC and its value chain, with caveats clearly stated. Therefore, it is reasonable to assert that additional costs could be attributed to materials being specified outside of existing framework contractor rate agreements and therefore attract an 'over and above' increase" to standard material costs. Hence, the use of data from other council regions may influence the outcomes indicated. Overall, however, the key message for this section is that where the use of plastic waste as an addition to asphalt layers can be proven viable, and the infrastructure and value chains are in place to respond to demand, there remains a significant potential to achieve financial savings at a council and national level, by reducing the transport and disposal of plastics to landfill.*

5.9.4 BALANCING THE EQUATION

Where plastics can be engineered to both chemically bind *and* extend the performance of bituminous binder in asphalt, the greatest possible benefit can be derived.

Plastics that can be used in this way adhere to the principles of circularity by:

- recovering and reusing otherwise discarded resources (which would be disposed of to landfill, potentially contributing to leachate that needs management);
- reducing the need for bitumen required asphalt production; and
- improving the performance (resistance to polishing, longevity, etc) of asphalt products.

To ensure any benefits achieved are truly sustainable, local government must factor in the following criteria:

- What surface life extension can be derived from incorporating plastics into asphalt? Under what conditions does this remain true?
- What are the actual direct costs and indirect environmental impacts of sorting, processing, transporting and incorporating plastic resources in roads (*noting this was an original ambition of this research study, subject to the provision of robust data*)?
- What effect does using different plastic products have on overall asphalt performance, in different highway applications?
- Under what conditions might the risk of microplastic pollution be exacerbated, and is it possible to compare this to current polymer modified bitumen usage?
- What impact does the incorporation of plastics in bituminous layers have on the potential for planing and recycling at end of service life?

5.10 CHAPTER CONCLUSIONS

The following conclusions have been drawn from the information acquired and reviewed in this study, and (as previously stated) relate to information accessed from CCC and its value chain (where available). Where possible, both the conclusions and – particularly – the recommendations in Section 5.11, have been framed in the context of the UK and highway authorities in general, to ensure that the outputs of the study are useful to as wide a range of councils as possible. It is noted that the conclusions drawn would likely need to be tailored to individual local authorities and their particular circumstances.

5.10.1 VIABILITY AND BENEFITS OF USING PLASTICS IN ROADS

a) At the time of writing this report chapter, and based on the information collected and reviewed, the viability and benefits of using plastics (or polymers, therein) in highways applications cannot be robustly asserted. Nevertheless, and subject to the future acquisition of successful trial data to validate these statements, the potential circular economy benefits of using plastics in highways has been proposed through extrapolation.

b) In summary, at a UK level, the following benefits could be expected to be derived:

- 82,200t of plastic waste diverted from landfill each year, and reused as part of a national circular economy; and
- £7.95M per annum saving on landfill tax (excluding savings from reduced haulage).

c) Presuming a worst case scenario of £5 per tonne cost to embed plastics in highways products (Section 5.9.3), the savings forecast could be used to fund the laying of nearly 1.6M tonnes of plasticised asphalt (some 17% of the asphalt sold per annum in the UK).

5.10.2 POLICY

d) Currently, national policy in the UK is tightening its grip on plastics, particularly those that are single use. Legislation such as the Environment Bill will increasingly mandate that organisations, both in the public and private sector, take responsibility for effective and more circular product / material management.

e) CCC does not have a firm policy on plastics. Furthermore, desk-based research suggests that this is a commonly-held position across many council bodies in the UK. The lack of clear ambition to reduce plastic consumption and disposal (as part of commitments laid down through climate / ecological emergency declarations, and through other circular activities), is a blocker to more effectively managing plastic wastes from corporate, household, business, construction, demolition and excavation sources.

5.10.3 COUNCIL GOVERNANCE AND MANAGEMENT

f) Experience of working with CCC, and with councils across the UK, confirms significant knowledge on, and ambitions for, improving the sustainability (including circular) performance of highway products, including asphalt – not least in terms of product specification, but in identifying innovation and efficiency in lifecycle asset maintenance and management. In many cases, delivering on these ambitions is made challenging by the complex structure of council bodies, and the contrasting experience of different value chain members. Overall, this does not promote an ideal environment from which to achieve a cohesive strategy for, and approach to, plastics and asphalt data acquisition, interrogation and decision making.

g) CCC encourages its supply chain to perform sustainably through the use of model contract conditions and financial benefits, though the specificity of the requirements, and the extent to which associated data are reviewed and compared across the region is not currently clear.

h) There are a number of asphalt processing plants near Cumbria. In general, however, it is reported that these facilities are ageing and it is not known as to whether process upgrades (for example, those that could accommodate plastics or RAP) are due to be installed.

5.10.4 DATA MANAGEMENT

a) As summarised in **Section 5.10.1 (a)**, at the time of publication, there is no interrogable data from CCC or its supply chain on the potential performance of plastics (or polymers) in asphalt layers.

b) Across Cumbria and its value chain, the granularity and robustness of data on the *availability* of plastics (or polymers, therein) and their use as either a 'bulk additive' and / or performance enhancer for bituminous layers in asphalt, is not sufficient to allow a detailed analysis or LCA of the relative benefits of different products. Similarly, data on the current cost of plastics management cannot be split out from general waste management workstreams, making analysis on potential savings difficult to specify.

c) Data on asphalt consumption across Cumbria is more complete and is supplied by key members of CCC's contracting (road surfacing) value chain. Financial data on asphalt laying is also available at a county, but not at a product, level.

d) In general, data quality, availability and access are largely dependent on individuals working for or on behalf of CCC, rather than being subject to a centralised system.

5.11 RECOMMENDATIONS AND NEXT STEPS

The following recommendations are made in response to the findings and conclusions of this chapter of the report. They respond directly to the information collected and analysed for CCC, but could equally be adopted by other local government authorities seeking to make progress on circular economy activity, either as a topic in its own right, or in support of net zero / carbon neural commitments.

5.11.1 POLICY

1) Local authorities should review and prepare integrated policies on plastic consumption (and other key material resources, as appropriate) and advance commitments such that they are set within the context of a circular economy, or sustainable resource and waste management best practice.

   Policy and commitments should be aligned to pending legislation, and links to net zero / carbon neutrality should be made in any documentation prepared. Links to existing and planned authority documents should be made.

   A clear and comprehensive policy on resource management (including plastics), as underpinned by other activities (examples herein) would provide a clear commitment to (and foundation for) action.

5.11.2 COUNCIL ACTIVITY AND CONTEXT

2) Local authorities should consider the formation of (or expansion of existing) council-wide working groups through which highways materials and waste can be centrally monitored and managed, and where opportunities and business decisions (such as integrating plastics in asphalt) can be discussed by consensus. Working groups should seek attendance from colleagues across council departments, to ensure that there is a standard suite of metrics and data collected and reviewed (that suits all parties' needs), and that economies of scale and opportunities for consistent sustainable approaches are adopted.
3) Councils should – across all procurement routes – review contract terms to identify opportunities to make more specific (granular and financial) information provision from waste management and highway value chain partners. Where information cannot currently be refined and collected, workstreams to resolve such situations should be agreed.

5.11.3 DATA MANAGEMENT

4) Local authorities should seek to standardise the collection and analysis of materials, waste and associated financial and environmental data, across all highway applications. Having a comprehensive and complete picture of materials, waste and associated financial data will allow risks and opportunities to be more effectively identified and managed. For example, understanding the volume and type of different plastics disposed of across a county, district or parish, and the costs (even extrapolated) from managing these would:

a) give authorities greater confidence in the identification and volume of (currently recycled or waste) plastic that may be viable for incorporating in asphalt, and;

b) identify more precisely the financial savings / gains that could be afforded.

5) At a time when robust value chain data on plastics (or polymers) in asphalt can be acquired within a council's boundary, a full LCA should be conducted on a variety of different asphalt products, under different conditions. Information should be shared across authority boundaries to build capacity and knowledge, and investigate the reasons for any variances in findings.

6

DESIGN OF ROAD TRIALS

6 DESIGN OF ROAD TRIALS

6.1 ROAD TRIALS

Road trials have proved to be an excellent way to evaluate the performance of new materials. It is essential to include a control section that incorporates a standard or established material of known performance. The trial materials can then be compared under the same environmental conditions and traffic loading. Care needs to be taken when selecting site locations and the construction of the road should be reasonably uniform along all the test sections, including the control. The initial condition should be measured and recorded so that any variations in performance can be noted as the trial progresses. Ideally, environmental conditions should be uniform, e.g. the site should avoid crossing major junctions which attract different trafficking movements that make it difficult to make fair comparisons.

It is also important to consider how performance will be assessed, including the type and frequency of monitoring which should be greater than that required for general maintenance. Subtle changes in the early-life performance could provide an indication of longer-term performance. Typically, the frequency of monitoring can be relaxed as the trial progresses, but it is essential that good records and maintained and updated, particularly in the event of possible staff changes.

6.2 SITE SELECTION

This section summarises the key features that were considered in selecting trial sites from the CCC road network. Although this approach was used to select sites from CCC's highway maintenance programme, it could be adopted by other authorities.

6.2.1 SITE FACTORS

The following parameters were considered to be important when selecting trial sites:

- Low speed/High speed;
- Urban/Rural;
- Exposed/Sheltered (environmental conditions);
- Heavily trafficked/Lightly trafficked; and
- Mainline/Junctions.

In addition, the following factors also need to be accounted for in the overall trial programme:

- Plastic additive type (Additive 1, Additive 2…);
- Surface course type (Stone Mastic Asphalt, Thin Surface Course System [e.g. Tufflex HD], Hot Rolled Asphalt, other specialist proprietary surfacing [e.g. Countyfalt]); and
- Binder course type (e.g. AC20 HDM bin 40/60).

In an ideal scenario, the trials could be carried out as part of new construction or major maintenance work. However, it was considered unlikely that the opportunities for using these materials in a completely new pavement construction would be limited within the lifetime of the CCC project.

Wherever a trial material was installed, an equivalent control section using the same bitumen source, but without plastic additive, was installed. Ideally, the minimum length of all trial sections and control sections should be 100m, to minimise start and end of load effects. It was deemed impractical to trial all the site permutations including additives and material types, as listed above. It was therefore recommended that two surfacing types which were commonly used in Cumbria be selected and used in the main trials. Table 6-1 shows the types of site, in priority order, that are expected to yield the most useful data for trialling the plastic additive products.

Table 6-1 - Trial Site Parameters

Priority	Speed	Traffic	Location	Environment	Layout
1	High	Heavy	Rural or Urban	Exposed or Sheltered	Mainline
2	Low	Heavy	Urban	Exposed or Sheltered	Mainline
3	High or Low	Light	Rural	Exposed	Mainline
4	Low	Heavy	Urban	Exposed or Sheltered	Junction
5	High or Low	Light	Rural	Sheltered	Mainline
6	Low	Light	Urban	Exposed or Sheltered	Junction
7	Low	Light	Urban	Exposed or Sheltered	Mainline

Following consultation with CCC it was agreed to trial three plastic additives (Additive 1, Additive 2 and additive 4). It was recommended that at least two sites of each description should be included over the life of the Live Lab project.

Early discussions indicated that the most heavily trafficked sites available for the project, would have a design traffic of around 10 million standard axles (msa). It was highlighted that owing to the nature of experimental trials, there was a risk that some premature material failures could occur at some of the sites.

6.3 PRODUCT MIX TRIAL

Product mix trials provide the opportunity to see the designed mixtures with additives being produced, laid and permits an assessment of material behaviour during laying and compaction in a controlled environment. For the CCC Live Lab project, three product mix trials were carried out at suppliers' quarries. These trials were undertaken to enable the collection of important information on the laid and compacted material such as binder content, gradings, density and air voids content. The latter information can be used to reduce the amount destructive testing (road cores) undertaken on the live road trials and permit correlations to be developed for non-destructive testing devices. The quarry trials also allow the supplier to become familiar with the material when produced with additives and provides the opportunity to extract samples from the compacted mat that can be tested for performance properties, e.g. stiffness, fatigue and water sensitivity.

7

CCC LIVE LAB TRIAL SITES

7 CCC LIVE LAB TRIAL SITES

This chapter provides information on the ten trials established as part of Cumbria County Council's Live Lab. It provides an overview of the trial locations, material suppliers and then presents more detailed information about the individual sites, material types and additives used, and any observations made while construction took place. In addition, data on material testing carried out is provided in Appendix A, which is discussed in Chapter 8.

It should be noted that owing to the ongoing nature of the Live Lab trials some information on trial sites was not available when preparing the report, i.e. some sites currently contain more information than others.

7.1 TRIAL LOCATIONS

Six live road trials and four quarry trials are located within or near the Cumbria County Council area. Figure 7-1 shows the location of the current trials in progress. Live road trials are coloured in red and quarry trials in blue.

Figure 7-1 – Live Lab Trial Locations

7.2 SUPPLIERS AND ADDITIVES

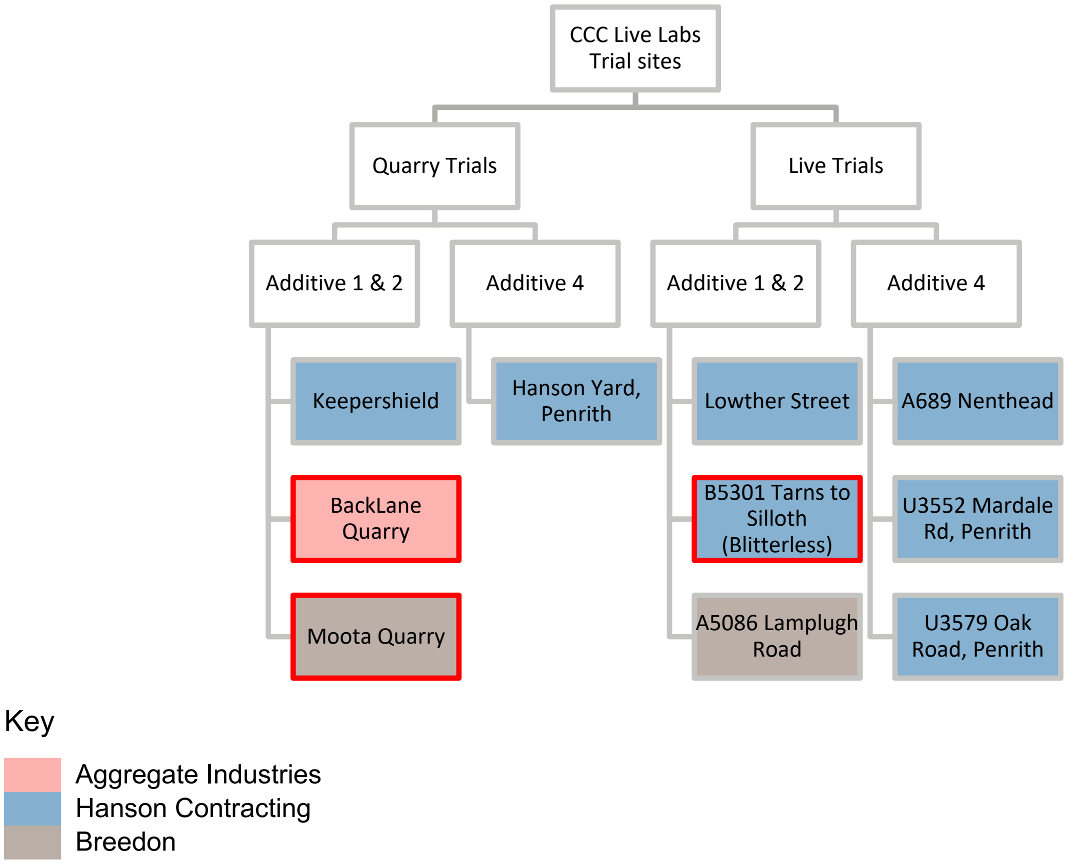


Figure 7-2 - Live Lab trial sites, suppliers and additives

Figure 7-2 shows the relationship between the Live Lab trial sites, suppliers and additives used. The diagram indicates which trials were conducted at suppliers' quarries, and which suppliers provided material for the live road trials. The red outlined boxes indicate where samples were taken for specialist rheological testing at Nottingham University, which is presented in Chapter 9.

7.3 TRIAL SITES

7.3.1 KEEPERSHIELD QUARRY

The site is located at Hanson's Keepershield Quarry, near Hexham in Northumberland. A schematic of the materials laid is shown in Figure 7-3. As seen in the schematic, the trial is located at the entrance to the quarry in a one-way section. Therefore, all vehicles including heavy goods vehicles (HGV) entering the site, use this route.

7.3.1.1 Materials laid

Various materials were laid at this quarry trial site between the 16 and 17 March 2020, namely:

- Binder Course
  - AC 20 HDM bin 40/60 des
  - SMA 10 bin 40/60 – 10 mm SMA with fibres
- Surface Course

- Tufflex D 10 – proprietary 10 mm SMA with PMB
- Countyfalt 14 – proprietary 14 mm asphalt concrete that can be laid as a single layer/binder course
- Tufflex 14 – proprietary 14mm SMA with PMB
- HRA 35/14 surf

Figure 7-3 shows that the mixtures were laid with Additive1, Additive 2 and without an additive to provide control sections that could be compared. The aggregate used in the mixtures was primarily a Basalt sourced from Keepershield Quarry. The Tufflex D mixture contained a Gritstone aggregate.

Bulk samples and cores were taken for testing which included binder contents; densities; air voids; ITSM testing, including water sensitivity and stiffness; wheel tracking and Percentage refusal density (PRD)s. A summary of the results on testing from the Keepershield trial is shown Appendix A.1-Appendix A.2 and the initial findings are discussed in Chapter 8.

Figure 7-3 – Keepershield trial location

7.3.2 A7 LOWTHER STREET

The site is located on Lowther Street, Carlisle, Cumbria. A diagram of the scheme layout is shown in Figure 7-4. The site is situated in a city centre environment, along the main Carlisle shopping area bus stop route and is expected to take approximately 20 million standard axles (msa).

7.3.2.1 Existing condition and pavement design

The original pavement surface prior to treatment consisted of a combination of HRA surface course, 14mm SMA surface course and some microsurfacing. All extracted cores were in a good condition and showed the pavement construction as flexible composite. In general, the pavement makeup comprised around 240 mm of Pavement Quality Concrete (PQC) overlaid with bituminous materials that varied between 100 to 200 mm in thickness.

CCC design intent statement included for a 40 year design life with associated traffic estimate of 18.6 msa. In general, the scheme allowed for an inlay which comprised 60mm Binder Course and 40mm for Surface Course.

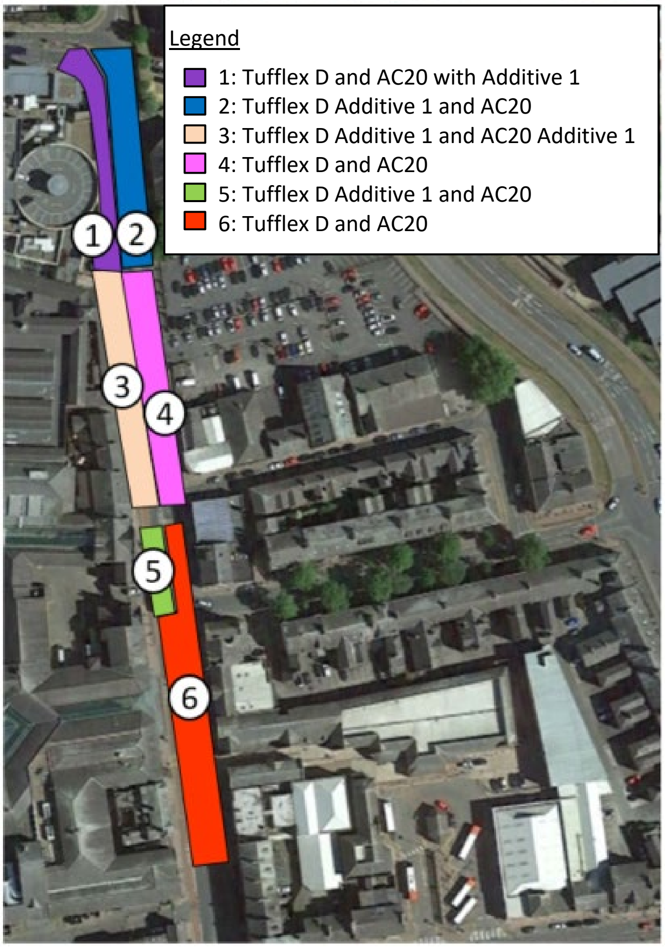


Figure 7-4 – Lowther Street trial location

7.3.2.2 Materials laid

The trial took place on 14 July 2020. Additive 1 material was alternatively mixed in with Tufflex D and AC20 material.

Prior to the trials being laid at Lowther Street, some mixing issues were reported as a result of the moisture content of the Additive 1 mixture. The moisture content was reported to be 8.6%, with a target of 6%. It was also reported that when introducing Additive 2, a blockage occurred which resulted in some equipment damage.

Most of the surface course material was laid in dry conditions and air temperatures ranging between 11 and 20ºC. The laying records indicate that when laying some of the Tufflex D material, the team was caught in heavy rain and paving was suspended for a time. The binder course was laid during a period of showers. However, the road was recorded as being dry before laying recommenced. The surfacing records indicate the bond coat was tracked wet and the rolling temperature at the start was 138ºC. When laying the AC20 material, there was a delay in supply due to “mixing issues”.

Testing was done on site which included compositional analysis, in situ density tests, macrotexture tests and surface profile testing. Test data is summarised in Appendix A.3.

7.3.3 BACK LANE QUARRY

The site is located at Aggregate Industries' Back Lane Quarry, Carnforth, Lancashire, and trials were laid on 17 February 2021. A diagram of the scheme layout is shown in Figure 7-5. As the diagram suggests, the site is the access road to the quarry and therefore carries all HGVs entering and exiting the quarry.

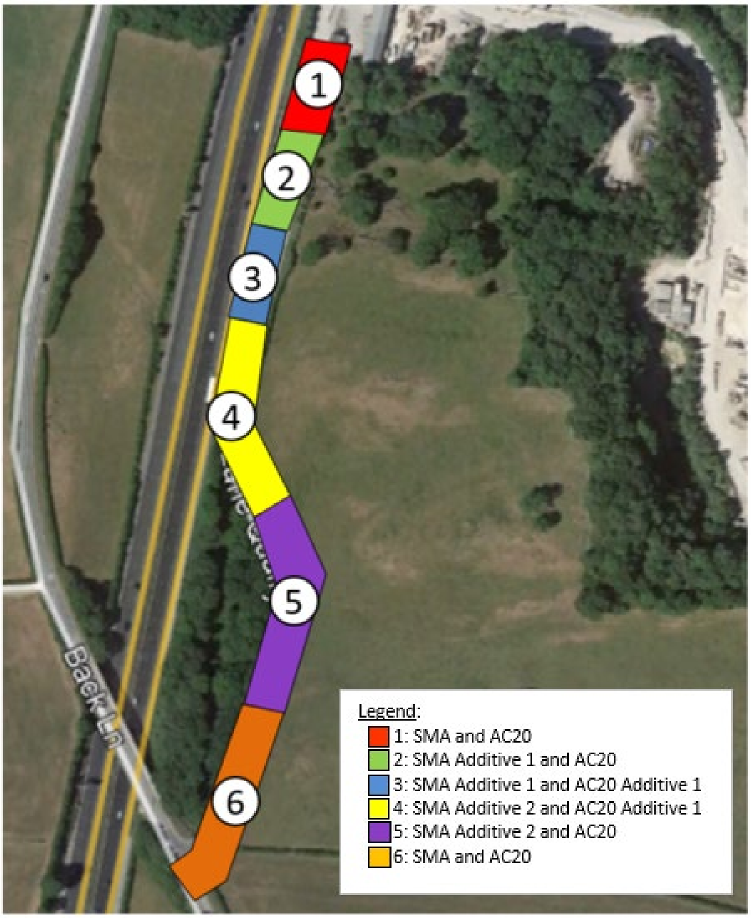


Figure 7-5 – Back Lane Quarry trial location

7.3.3.1 Materials laid

Six sections were laid at the Back Lane Quarry trial. Both Additive 1 and 2 were used at a dosage of 6% of the binder. The intent was to keep the mix as similar as possible to the production of an SMA with fibres. Sections 1 to 3 were laid with 40 mm SMA and 60 mm AC 20, and trial sections 4 to 6 were laid with 25 mm SMA and 50 mm AC 20.

When laying the AC20 Dense Bin 40/60 material the minimum delivery temperature was 162ºC and minimum rolling temperature was 134 ºC. Similarly, when laying the surface course material, the delivery temperature was not less than 164 ºC and the minimum average rolling temperature was 134 ºC.

Testing similar to that at Lowther Street was performed, including texture depths, surface irregularities, as well as in situ densities. In addition, cores were taken to determine in situ stiffness. Collected data is summarised in Appendix A.4.

7.3.4 MOOTA QUARRY

Breedon's Moota Quarry is located near Cockermouth in Cumbria. The trial at Moota Quarry was laid on 4 January 2021. A diagram of the scheme layout is shown in Figure 7-6. The site is situated within the quarry boundaries and can be expected to take HGVs. However, the volume of HGVs is not known.

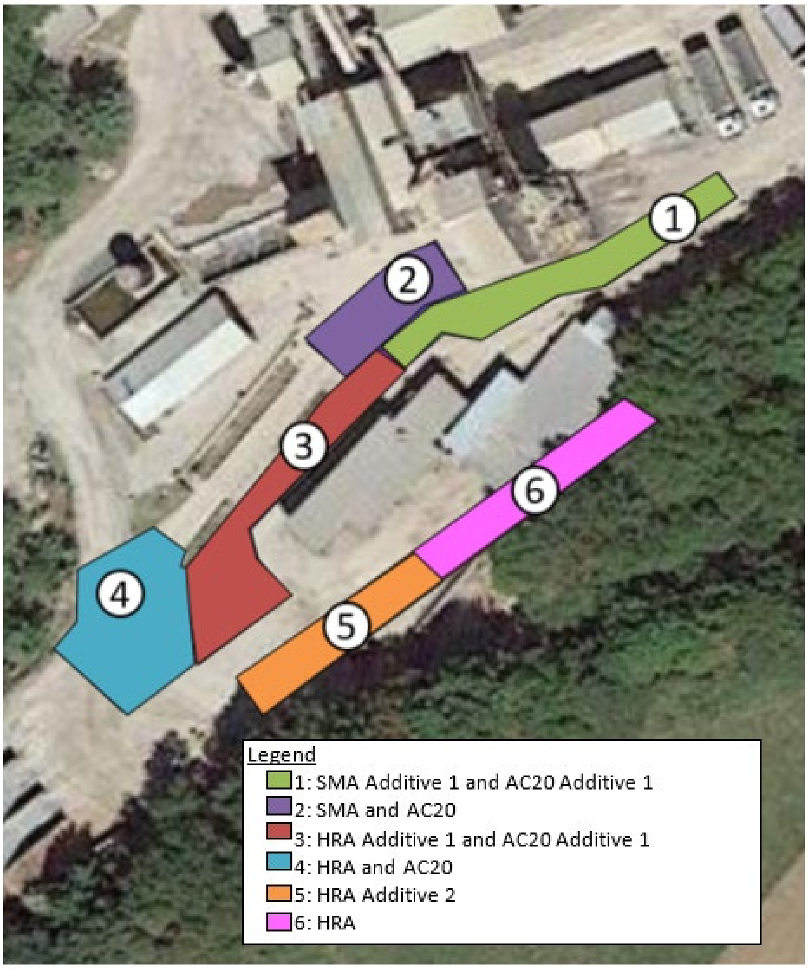


Figure 7-6 - Moota Quarry schematic

7.3.4.1 Materials laid

The materials laid at the quarry contained Additive 1 in an AC20 Binder DBM 40/60 and an SMA 40/60. Figure 7-7 shows some images that were taken during the laying trial. Testing carried out at Moota quarry included wheel tracking, densities and stiffness testing on cores. Test data is summarised in Appendix A.5.

Figure 7-7 – Moota Quarry laying trial

7.3.5 B5301 TARNS TO SILLOTH (BLITTERLESS)

The trial site is located on the B5301 near Tarns, Cumbria. The trials were carried out on 2 November 2020. A diagram of the scheme layout is shown in Figure 7-8. The site is characteristic of a country lane and is not expected to carry large volumes of vehicles. The estimated standard axles is below 1 msa.

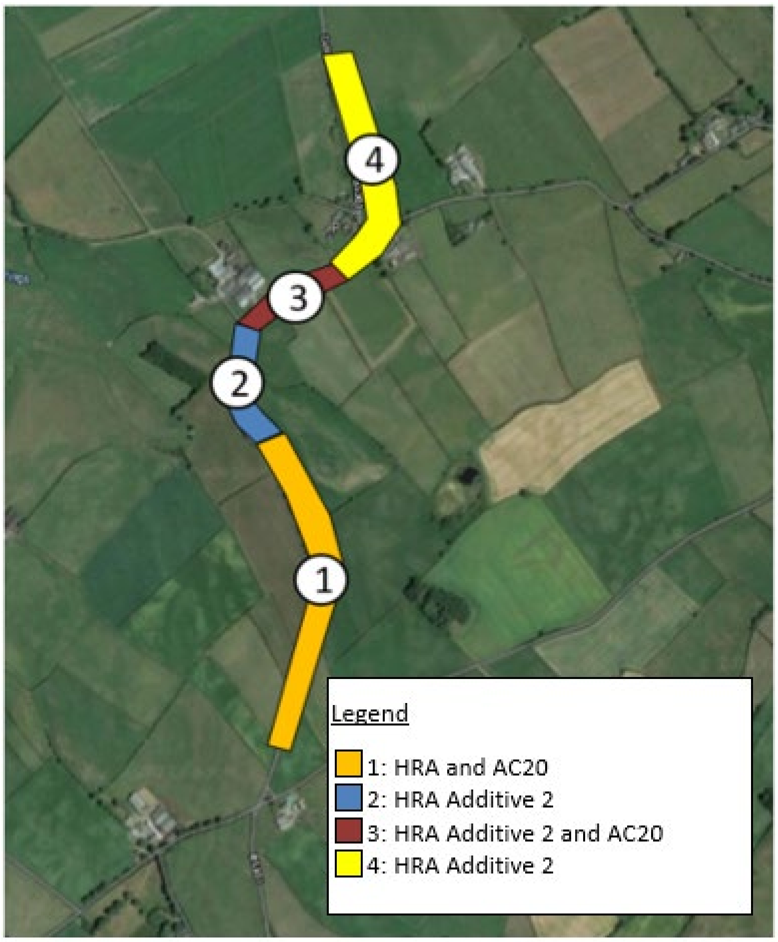


Figure 7-8 – B5301 Tarns to Silloth (Blitterless) trial location

7.3.5.1 Existing condition and pavement design

The majority of the section is surfaced with a thin surface course system with a 10 mm aggregate. A pre-trial site investigation was carried out on behalf of CCC comprising coring and Dynamic Cone Penetrometer (DCP) testing. The investigation concluded that the pavement is of fully flexible construction throughout, with an average asphalt thickness of 90 mm. Some cracking was observed on the southbound lane. The DCP-CBRs indicated that the upper foundation (to a depth of approximately 400mm) was above 41%, with the majority of the section indicating a foundation of >100% CBR. The lower foundation minimum DCP-CBR was calculated to be 12% at more than 571 mm depth.

CCC design intent statement includes for a 20 year design life with an associated traffic estimate of 0.5 msa. In general, the scheme allowed for a 50 mm inlay of HRA 35/14 to Cl911 for section 1, 2 and 4. Section 3 was fully reconstructed and comprised 50 mm HRA 35/14 to Cl911, 50 mm AC 20, 150 mm AC 32 and 225mm Type 1 sub-base.

7.3.6 A5086 LAMPLUGH ROAD

The trial is located in Cockermouth, Cumbria and was laid on 15 February 2021. A diagram of the scheme layout is shown in Figure 7-9. The site is located within a predominantly suburban area, with one lane in each direction. The estimated standard axles is 1.6 msa.

Figure 7-9 – A5086 Lamplugh Road trial location

7.3.6.1 Existing condition and pavement design

A pre-trial site investigation was carried out on behalf of CCC comprising a Falling Weight Deflectometer (FWD) survey, coring and DCP testing. The investigation concluded that the pavement construction is fully flexible with an average depth of 165 mm (ranging from 140 mm and 195 mm) including a Hot Rolled Asphalt surface course. The pavement is in a good condition with a minimum DCP-CBR of 45%. The pre-trial site investigation noted in their design statement that the pavement did not show signs of structural failures. However, there were areas where the surface course was failing.

CCC design intent statement includes for a 20 year design life with associated traffic estimate of 1.6 msa. In general, the scheme includes a 50 mm inlay of HRA 35/14 to Cl911 and 50 mm AC 20 HDM bin 40/60. Sections 1 and 2 contain Additive 1 in the surface course and sections 3 and 4 are controls, i.e. without additives.

7.3.7 A689 NENTHEAD

The trial is located on the A689 in Nenthead, Cumbria and was laid on 24 May 2021. A diagram of the scheme layout is shown in Figure 7-10. Section 2 consisted of an SMA control and Section 1 an SMA with Additive 4. The site runs through the village of Nenthead, with one lane carriageway in either direction and a 30 mph speed limit. This site was selected on the basis of its extreme winter weather conditions.

Figure 7-10 – A689 Nenthead road trial location

No significant problems were reported on site. The only note was that some fatty areas were evident on the finished surface where Additive 4 had been laid.

7.3.8 U3552 MARDALE RD, PENRITH

The site is located on the U3552 Mardale Road, Penrith, as indicated in Figure 7-11. The trial took place on 7 June 2021 and comprised an HRA control material and an HRA material with an additive. The site is situated in an industrial area and passes the entrance to a Truck Stop and therefore can be expected to carry HGVs.

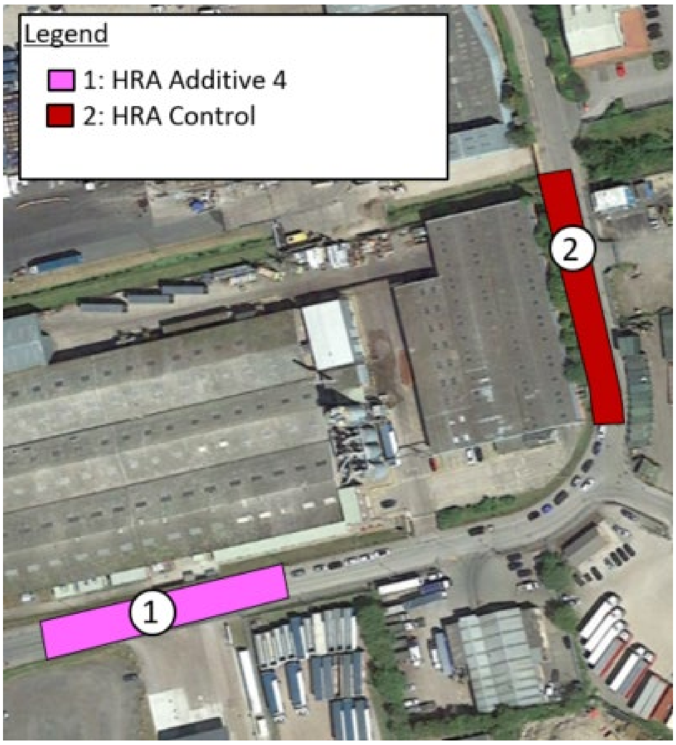


Figure 7-11 - Mardale Road Schematic

7.3.8.1 Existing condition and pavement design

A pre-trial site investigation was carried out by others on behalf of CCC, comprising an FWD survey, coring and DCP testing. The investigation concluded that the pavement is of fully flexible construction throughout. The pavement was determined to have a Class 2 foundation. A GPR survey was carried out which indicates the bituminous layers for the most part of the carriageway were between 250 and 280 mm. The design traffic was estimated to be 12 msa. A pavement design in accordance with CD 226 would require 285 mm of asphaltic concrete.

No significant problems were reported on site during laying although some fatty areas were evident on the finished surface of Section 1 which included Additive 4.

7.3.9 U3579 OAK ROAD, PENRITH

The trial was undertaken on 6 April 2021 and comprised a 10 mm SMA product with Additive 4 and a control. A schematic of the site is shown in Figure 7-12. The site is situated in a suburban area with one lane in either direction and a 20 mph speed limit.

Figure 7-12 - U3579 Oak Road trial location

7.3.10 HANSON YARD

A trial area was established Hanson Contracting’s yard, Coleridge House, Penrith on 25 May 2021. Figure 7-13 shows the location of the yard and general location of material. The materials were laid with the Additive 4, as well as areas of unmodified materials were laid to provide a control.

The material laid in the Hanson Yard enabled an easy and safe option for taking cores required for asphalt testing. Cores were extracted to determine density, air voids content, wheel tracking and water sensitivity.

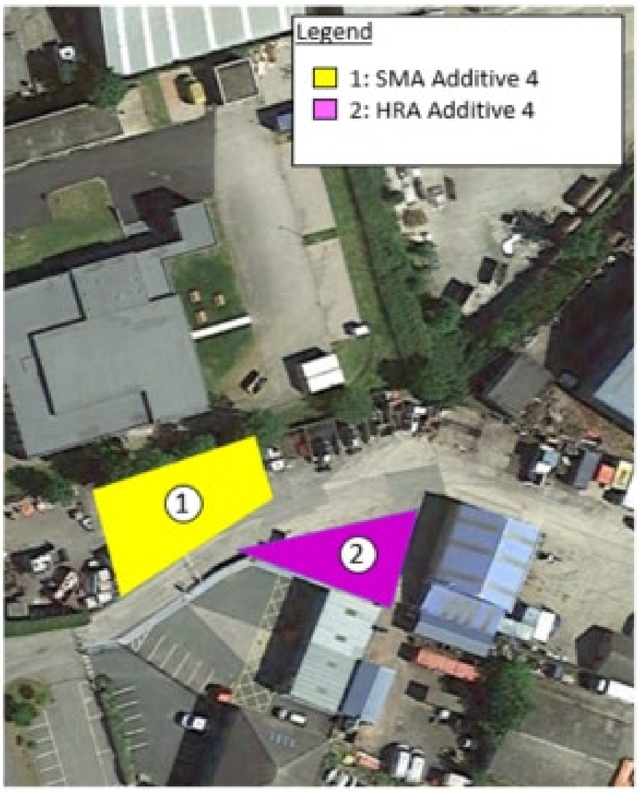


Figure 7-13 - Hanson Yard

8

LIVE LAB MIXTURE TESTING

PUBLIC

8 LIVE LAB MIXTURE TESTING

8.1 INTRODUCTION

This chapter summarises the results of testing data that has been collected from the quarry trial sites described in Chapter 7. Owing to the nature of the Live Labs trial, more information will become available and be reported at a later date. As such, the findings represent the measured properties of the mixtures at an early stage of the trials, but provide an opportunity to make comparisons between mixtures that contain plastic additives with more conventional control mixtures.

Testing results on recovered binders are discussed and summarised in Chapter 9.

8.2 STIFFNESS RESULTS

Indirect Tensile Stiffness Modulus (ITSM) values were determined from specimens that were derived from bulk samples and cores taken from the quarry trials described in Chapter 7. The stiffnesses have been reported according to the additive used, as well as the specimen preparation method used prior to testing. The stiffnesses were split up in this manner so that a more accurate comparison could be made. A selection of some of the results is provided below.

8.2.1 TUFFLEX D

The Tufflex D surface course material is a proprietary 10 mm SMA with PMB which was laid at the Keepershield Quarry. Figure 8-1 shows the results for cores extracted from the mat and bulk samples that were reheated and compacted in the Marshall Hammer.

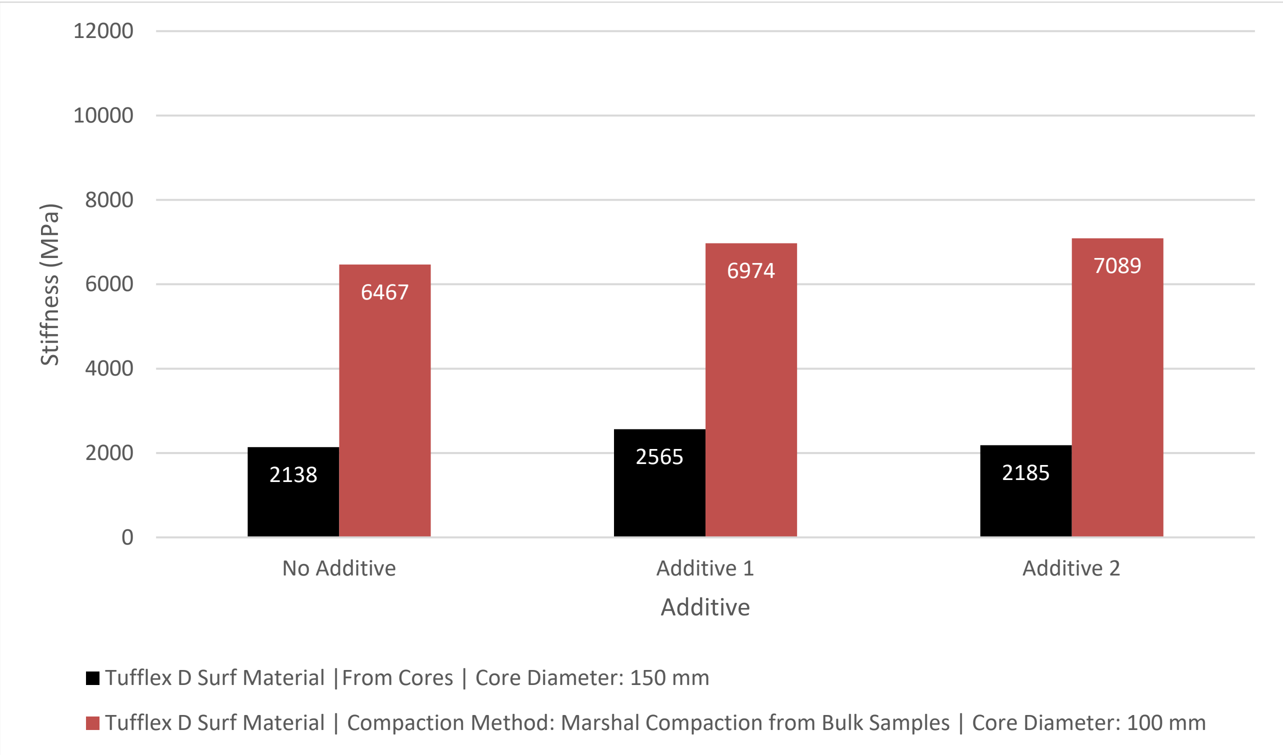


Figure 8-1 - ITSM values for Tufflex D Surf material

8.2.2 COUNTYFALT

Countyfalt 14 is described as a proprietary 14 mm asphalt concrete that can be laid as a single layer/binder course. Figure 8-2 shows the results for cores extracted from the mat and bulk samples that were taken at the Keepershield Quarry trial.

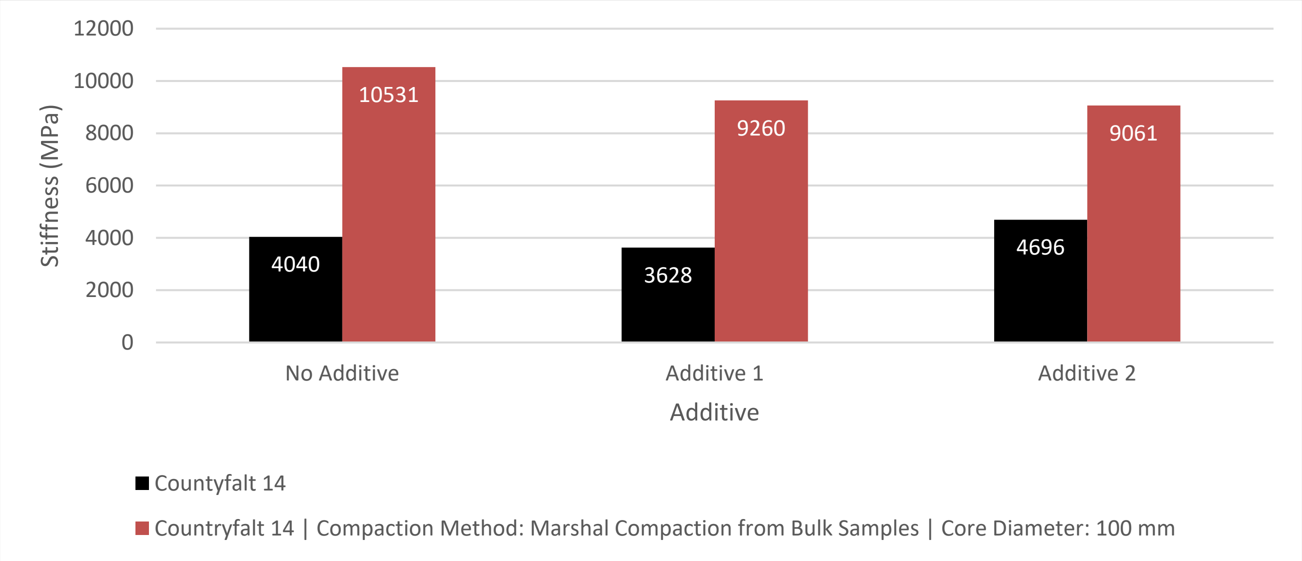


Figure 8-2 - ITSM values for Countyfalt 14 material

8.2.3 AC 20 HDM

The 'AC20 HDM bin 40/60 des.' was used as a binder course material in two of the quarry trials. Figure 8-3 shows the average stiffness of 18 cores taken from the Moota Quarry: 6 with no additive and 12 with Additive 1. The reconstituted bulk samples (dark blue) compacted with a Marshall hammer are from Keepershield Quarry.

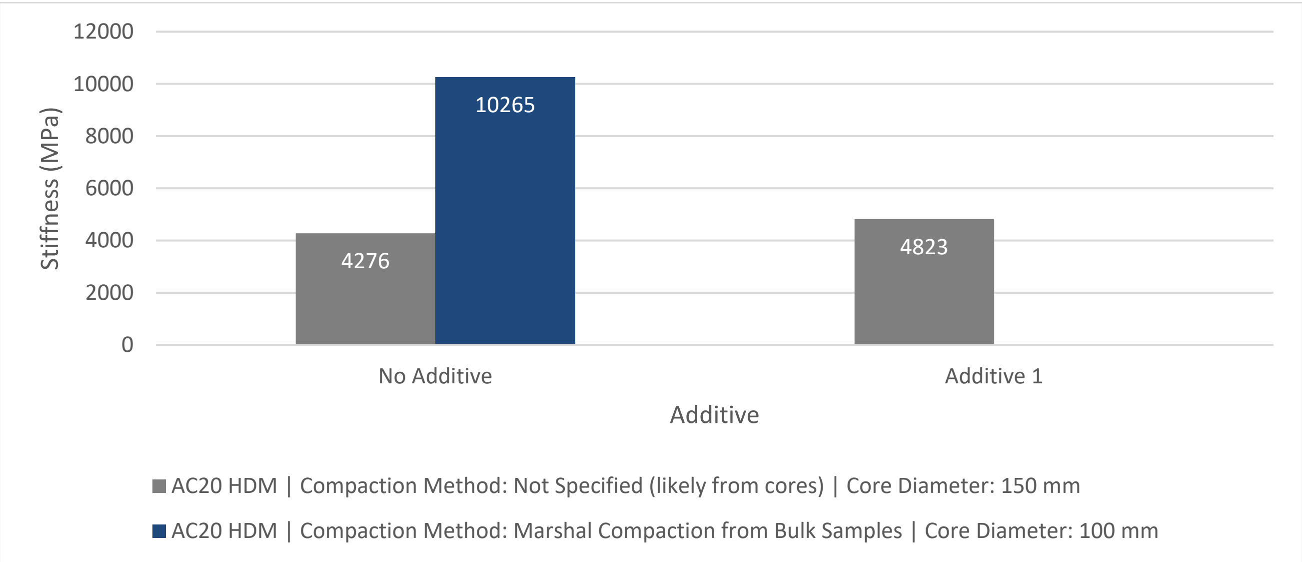


Figure 8-3 – Average ITSM values for AC20 HDM material

Owing to the number of cores taken at Moota Quarry, it was possible to take a closer look at the results. Figure 8-4 includes the average results shown in Figure 8-3 which represents around a 12% increase in stiffness on using additive 1. However, the figure also shows that there is considerable spread in the data and indicates that the increase in stiffness is variable.

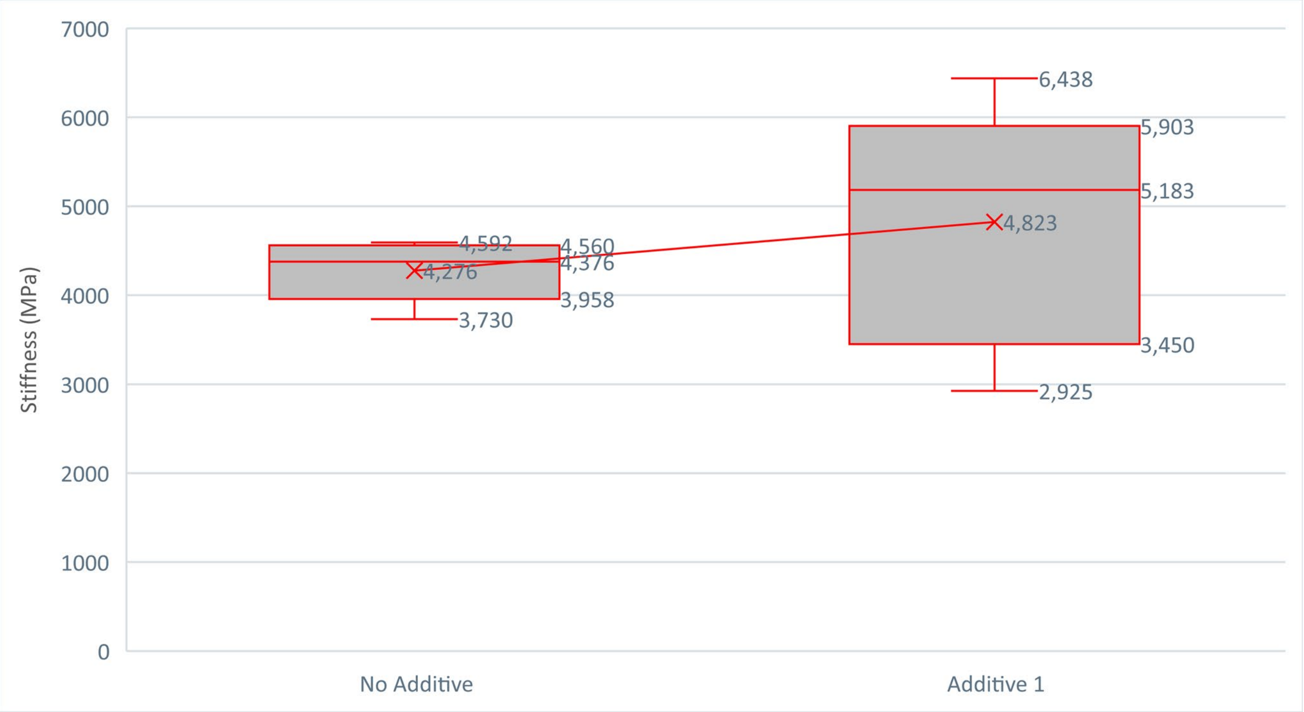


Figure 8-4 - ITSM values for AC 20 HDM cores

8.2.4 SURFACE COURSE STIFFNESS TREND

An analysis was undertaken to establish whether a general trend exists for plastic additives to increase or decrease the stiffness of surface courses. As two of the surface course mixtures already contained a PMB, namely Tufflex 10 & 14 mm, these were not included in the analysis. The results from cores samples taken on two surface courses laid at the Keepershield Quarry and one from Back Lane Quarry were compared against each other. Figure 8-5 shows the range of ITSM values from the core samples.

Results show that tests on cores indicate a 14% increase in stiffness with the addition of Additive 1. The addition of Additive 2 produces a more modest increase of 9%, with a slight increase in the spread of results.

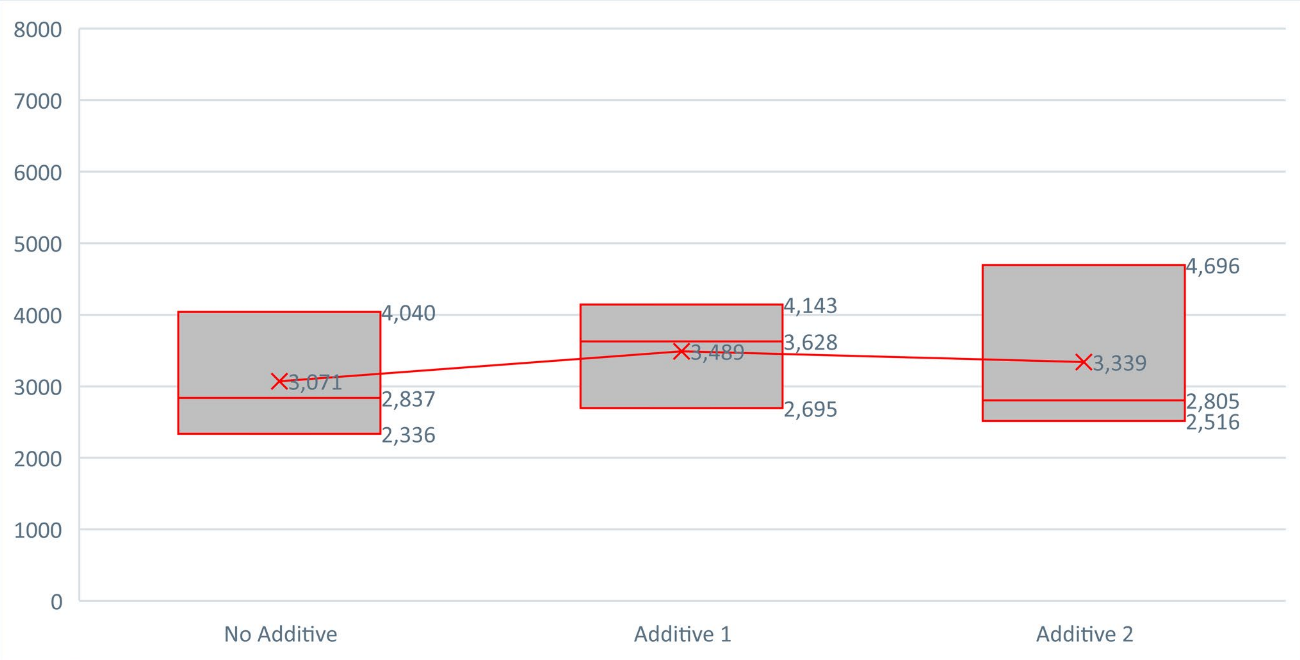


Figure 8-5 - ITSM values for cores of various surfacing types

8.3 OTHER PROPERTIES

The Keepershield Quarry trial provided a significant amount of data following testing of bulk and core samples, including binder contents, densities, voids, water sensitivity and wheel tracking. Line graphs comparing these properties for the control samples and samples containing Additive 1 and Additive 2 are provided in Appendix A.6. Some of the observed differences are summarised below.

8.3.1 BINDER CONTENTS

When any bitumen replacement additive is used in a mix, it should be noted that the term “Target Binder Content” comprises both bitumen and additive. Whereas, when no bitumen is replaced (i.e. control mixes), the binder content is the same as the bitumen content.

The average recovered binder content from the Keepershield quarry was found to be marginally lower in mixtures that contained Additive 1 and Additive 2 when compared to the control mixtures by around 0.3%. Although the variation in binder content could possibly be explained by the working tolerance of the plant, the reduced binder contents for the modified mixtures could be due to the fact that the plastic has not always dissolved completely in the bitumen. However, it should be noted that visual signs of ‘un-digested’ plastic were not reported, as part of the rheological testing (binder recovery) carried out in Chapter 9.

It should be noted that the overall reduced binder contents could contribute to observed increases stiffness. Similarly, low binder contents could reduce mixture workability which may increase air voids content.

8.3.1.1 Additional testing

Achieving adequate dispersion and digestion of the waste plastic in bitumen may be a critical factor in achieving reliable results from asphalt mixtures. Work undertaken to date does not appear to have assessed this. Further work should be considered to assess the degree of dispersion and digestion that has occurred after asphalt mixing, as the mixing time in the dry process may be less than that required to achieve digestion or dissolution of the recycled plastic.

Photomicrographs of the modified binder using ultra-violet or other technique could be used to indicate the presence of the additive in the bitumen but should not be used as an indicator of performance. Guidance on the interpretation of photomicrographs is given in BS EN 13632 Visualisation of polymer dispersion in polymer modified bitumen.

8.3.2 AIR VOIDS CONTENT

In general, the voids content in mixtures containing Additive 2 are slightly higher than the control and Additive 1 mixtures. This suggests that mixtures with Additive 2 could possibly be less compactible. Percentage refusal density of cores also indicates that the control and Additive 1 show improved compaction over Additive 2. The extent to which this poses a problem should be further investigated and monitored during the trials.

8.3.3 WHEEL TRACKING & WATER SENSITIVITY

Wheel tracking results are improved with the addition of plastic additives, although all results are acceptable. Water sensitivity assessed using the ITSR test showed that all results were above the standard specification of 80%.

8.4 WARM MIX – ADDITIVE 4

Asphalt mixtures containing Additive 4 have been laid alongside control sections containing a 40/60 paving grade bitumen as described in Chapter 7. All materials containing Additive 4 were mixed and laid at lower temperatures and no issues with workability have been reported when laying material supplied at 30^{0}C lower than conventional temperatures. Observations and feedback from the paving crews has been generally positive. No significant problems have been reported on the sites during laying although some fatty areas were evident on sections that included the warm mix (Additive 4).

The material laid in the Hanson Yard trial has been cored to determine density, air voids content, wheel tracking and water sensitivity.

Bitumen samples were taken at the bitumen manufacturing unit and bulk asphalt samples were taken as part of an agreed sampling plan. Binder and asphalt have been sent for laboratory testing. Further coring will be arranged in early 2022 to enable further testing of aged material. It should be noted that laboratory test results for asphalts containing Additive 4 were not available at the time of writing.

9

LIVE LAB RHEOLOGICAL TESTING

9 LIVE LAB RHEOLOGICAL TESTING

9.1 INTRODUCTION

In addition to the mixture testing described in Section 8, the Nottingham Transportation Engineering Centre (NTEC) were commissioned to assess the rheological properties of some of the modified binders used in the Live Lab trials. A total of ten asphalt mixture samples were taken during laying operations at the trial sites and supplied to NTEC at the University of Nottingham. The bitumen and plastic additive components of the 10 different asphalt mixtures were recovered and subjected to a series of rheological and binder performance tests to determine their relative rheological properties and performance. This section is an abridged version of the NTEC report which describes the tests carried out and summarises the results and findings.

9.2 TESTING PROGRAMME

The rheological and binder performance was assessed using the following tests:

- Empirical binder property tests consisting of standardised needle penetration, softening point and Brookfield (rotational) viscosity.
- Standard rheological assessment (Dynamic Shear Rheometer (DSR) oscillatory frequency sweep testing).
- High temperature flow properties (Multiple Stress Creep Recovery (MSCR) Test).
- Intermediate temperature fatigue (damage) properties (Linear Amplitude Sweep (LAS)).
- Intermediate temperature fracture strength and cracking resistance (Double-Edge Notched Tension (DENT)).
- Low temperature stiffness, stress relaxation and cracking resistance (Bending Beam Rheometer (BBR)).

A description of each test including some background on how they are used to characterise the rheology of the binder is provided in Appendix B.

9.2.1 MATERIALS TESTED

All testing at NTEC was undertaken "blind", i.e. bulk asphalt samples were delivered with unique reference numbers, but no information was provided to NTEC on material descriptions and the type of additive present. Once the bitumen and plastic modifier components of the different asphalt mixtures were recovered, they were assigned NTEC numbering. Table 9-1 shows the NTEC laboratory sample numbers for the recovered binders. The table also provides information that was not provided to NTEC, including a description of the type of asphalt and additive used. It should be noted that NTEC 21-1354 (shown in bold) was provided as a control and the supplied mixture contained a straight-run penetration grade 40/60 bitumen, i.e. it did not contain a plastic additive.

It is likely that the sources of bitumen used in the trial were from different suppliers and are likely to have slightly different compositions. However, it is regarded that the differences would have been small and within British Standard tolerances.

Table 9-1 – Material sample details

Recovered Binder	Material Designation	Plastic Modifier
NTEC 21-1351	SMA 10 surf 40/60	Additive 1
NTEC 21-1352	SMA 10 surf 40/60	Additive 2
NTEC 21-1353	AC 20 dense bin 40/60	Additive 1
NTEC 21-1354	**AC 20 dense bin 40/60**	None
NTEC 21-1355	HRA 35/14 surf	Additive 2
NTEC 21-1361	AC 20 dense bin 40/60	Additive 2
NTEC 21-1362	SMA 10 surf 40/60	Additive 1
NTEC 21-1363	AC 20 dense bin 40/60	Additive 1
NTEC 21-1364	HRA 35/14 surf	Additive 2
NTEC 21-1365	HRA 55/14 surf	Additive 1

9.2.2 BINDER RECOVERY

The bitumen and plastic modifier components of the different asphalt mixtures were recovered using a modified and enhanced version of BS EN 12697-4:2015. The method was deemed to be the most appropriate method to produce a recovered plastic modified binder for each asphalt mixture. The modified version used in this study consisted of multiple soakings of the asphalt material in dichloromethane to ensure that all the bitumen and plastic modifier was recovered. Figure 9-1 shows pictures of two examples of asphalt mixture material as delivered (and prior to binder recovery) and two examples of remaining (clean) aggregate and filler after binder recovery.

Asphalt mixture prior to soaking

Clean aggregate

Asphalt mixture prior to soaking

Clean aggregate

Figure 9-1 - Asphalt mixtures as supplied and clean aggregate after binder recovery

9.3 EMPIRICAL BINDER PROPERTIES

9.3.1 PENETRATION & SOFTENING POINT

The needle penetration (BS EN 1426) was measured for the ten recovered binders with the penetration values presented in Figure 9-2. The results show that five of the binders (NTEC 21-1351, 21-1354, 21-1355, 21-1363 and 21-1364) can be considered to be ‘harder’ than the other binders with an average penetration of about 25 dmm. NTEC 21-1353 and 21-1362 can be considered to be slightly ‘softer’ with an average penetration of about 35 dmm with two of the binders (NTEC 21-1361 and 21-1365) being even ‘softer’ (penetration values of approximately 45 dmm) with NTEC 21-1352 being the ‘softest’ binder with a penetration value of almost 60 dmm.

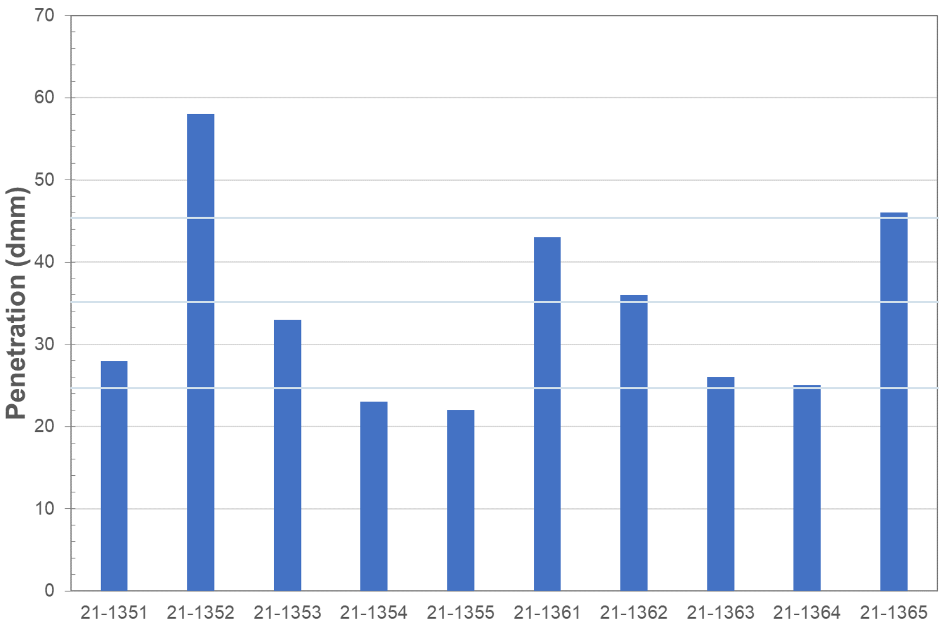


Figure 9-2 - Penetration values for recovered binders

The softening point temperature (BS EN 1427) was measured on the ten recovered binders with the softening point values presented in Figure 9-3. The results support the findings seen for the penetration test in Figure 9-2 with binders NTEC 21-1351, 21-1354, 21-1355 and 21-1364 having the highest softening point temperatures ('hardest' binders) with an average value of about 61°C. As seen from the penetration values, binders NTEC 21-1353, 21-1362 and 21-1363 are slightly 'softer' with an average softening point of about 56°C with binders NTEC 21-1352, 21-1361 and 21-1365 being the 'softest' of the ten recovered binders with an average softening point of approximately 51°C.

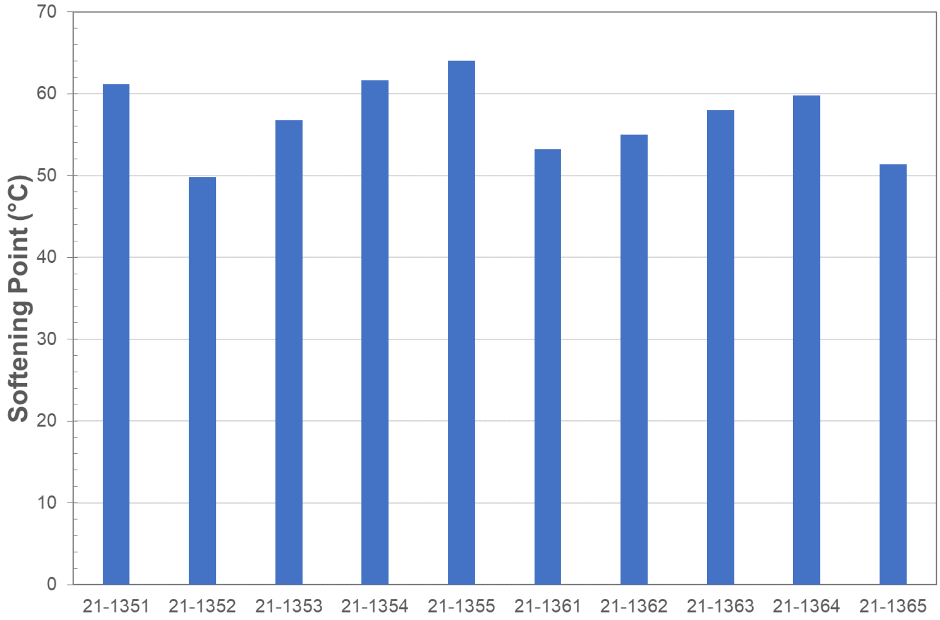


Figure 9-3 - Softening point temperatures for recovered binders

9.3.2 BROOKFIELD VISCOSITY

The viscosity results at three temperatures (120°C, 150°C and 180°C) are shown in Figure 9-4 for the ten recovered binders. Four of the binders (NTEC 21-1351, 21-1354, 21-1355 and 21-1364) show higher viscosity over the tested temperature range with NTEC 21-1351 having the highest viscosity. This fits with the lower penetration and higher softening points found for these binders in Section 9.3.1. Three of the binders (NTEC 21-1353, 21-1362, and 21-1363) show intermediate viscosities. The final three binders (NTEC 21-1352, 21-1361 and 21-1365) have the lowest viscosities indicating that they are the 'softest' binders of the set, similar to what was established from the penetration and softening point results.

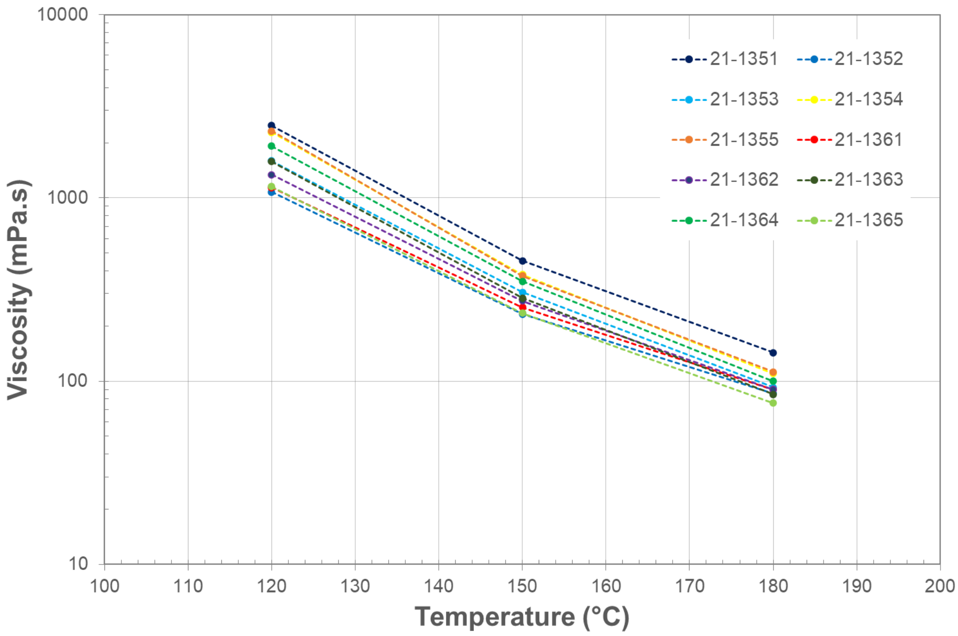


Figure 9-4 – Brookfield viscosity versus temperature relationship for recovered binders

9.4 LINEAR VISCOELASTIC RHEOLOGICAL CHARACTERISATION

9.4.1 DSR OSCILLATORY RHEOLOGY

The linear viscoelastic rheological properties from small strain oscillatory testing using a DSR were undertaken on the ten recovered binders. The ten binders were subjected to small strain oscillatory DSR testing, using both 8mm and 25mm parallel plate geometries, over a range of temperatures and frequencies. The rheological data (complex modulus and phase angle) was then subjected to time-temperature superposition (TTSP) to produce rheological master curves at a reference temperature of 25°C as shown in Figure 9-5 and Figure 9-6.

9.4.1.1 Master Curves

The complex modulus master curves for the ten binders are shown in Figure 9-5. The results show that over the entire frequency range of the master curves, NTEC 21-1355 has the highest complex modulus (G*) values ('hardest' binder) followed by a group consisting of NTEC 21-1351, 21-1354, 21-1363 and 21-1364 with very similar G* master curves and then a slightly lower stiffness group consisting of NTEC 21-1353 and 21-1362. The three 'softest' binders, as represented by the lower stiffness G* master curves, are NTEC 21-1352, 21-1361 and NTEC 21-1365. The results and deduction from the master curves coincide with the observations on these binders from the empirical tests in Section 9.3.

In addition to the G* master curves, the phase angle master curves for the ten binders have been produced and presented in Figure 9-6.

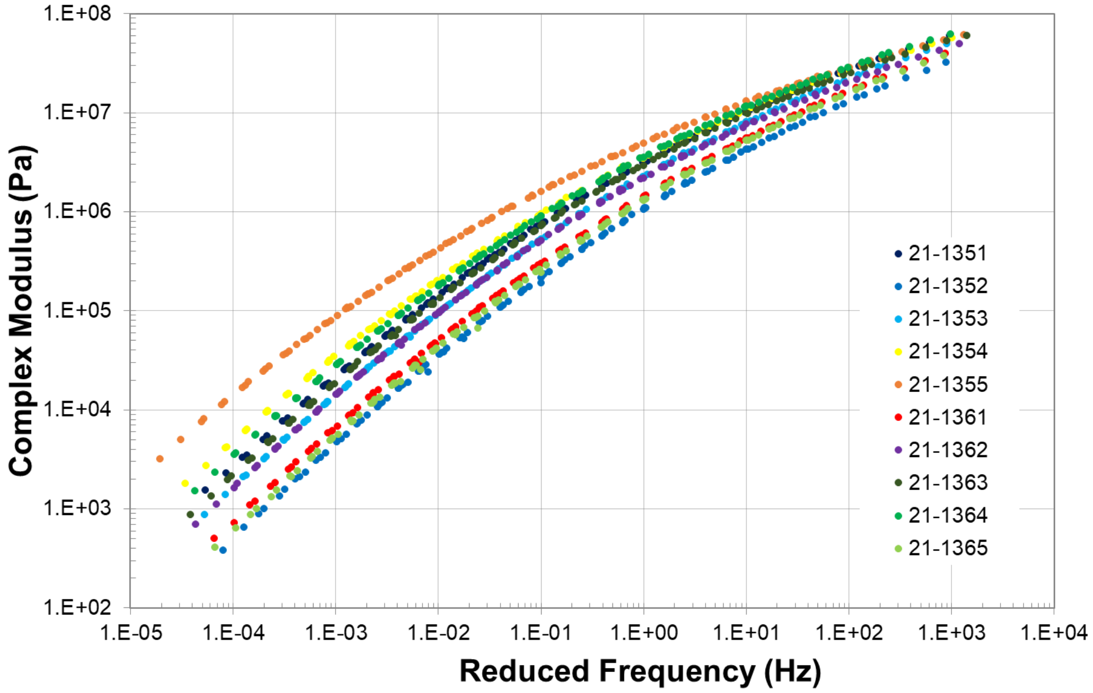


Figure 9-5 - Complex modulus master curves for recovered binders at 25°C

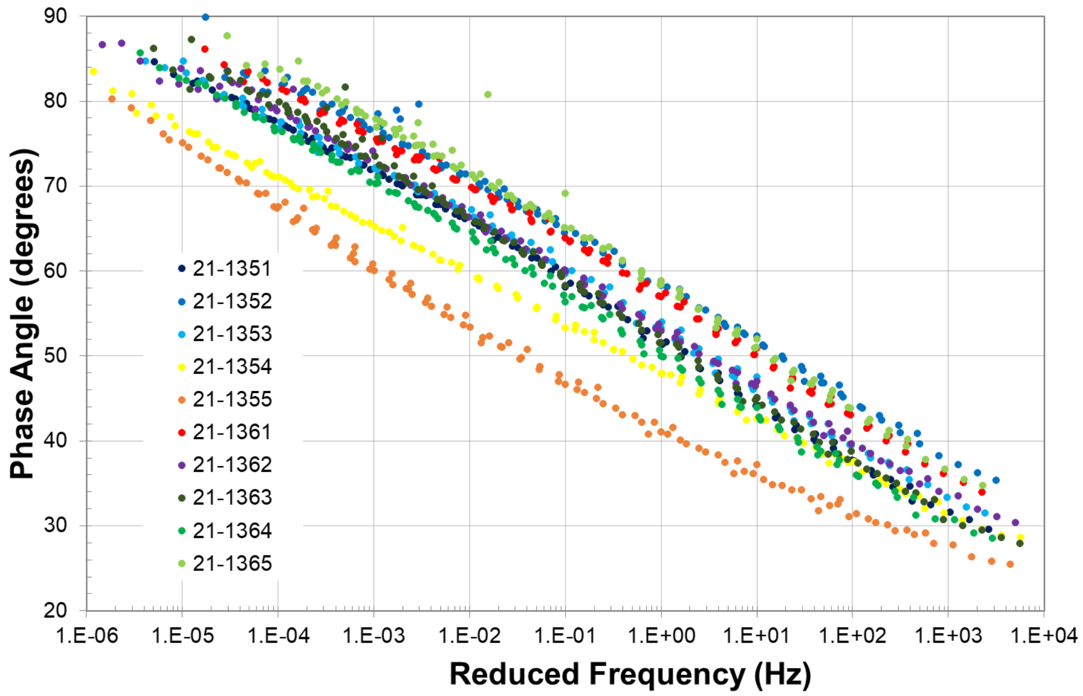


Figure 9-6 - Phase angle master curves for recovered binders at 25°C

Lower phase angle master curves over the frequency range indicate a stronger elastic to viscous response when considering the viscoelastic response of the binders. The shape of the phase angle master curves are also important in representing and understanding the nature of the binder (i.e. unmodified, elastomeric or plastomeric modified, unaged or aged). The relatively consistent linear relationship of the phase angle master curves to frequency indicates a degree of binder hardening associated with oxidative ageing, lower binder penetration production or binder modification.

In terms of the viscoelastic nature of the ten binders, binders NTEC 21-1354 and 21-1355 consistently show the lowest phase angle master curves (usually associated with 'harder' binders), especially binder NTEC 21-1355. This is followed by a group of five binders (NTEC 21-1351, 21-1353, 21-1362, 21-1363 and 21-1364) with the three 'softest' binders NTEC 21-1352, 21-1361 and 21-1365 having the highest phase angle master curves.

9.4.1.2 Temperature Dependency – Shift Factors

The temperature dependency of the different master curves are shown in Figure 9-7 where the temperature shift factors (required to produce the complex modulus and phase angle master curves) versus temperature are shown for the ten binders. These shift factor results represent the Williams-Landel-Ferry (WLF) equation (and determined C1 and C2 constants) used to produce the G* master curves. Although the curves are very similar, there is an indication that they are grouped in a similar manner to the previous empirical and oscillatory rheology observations in terms of the group of 'harder' and 'softer' binders.

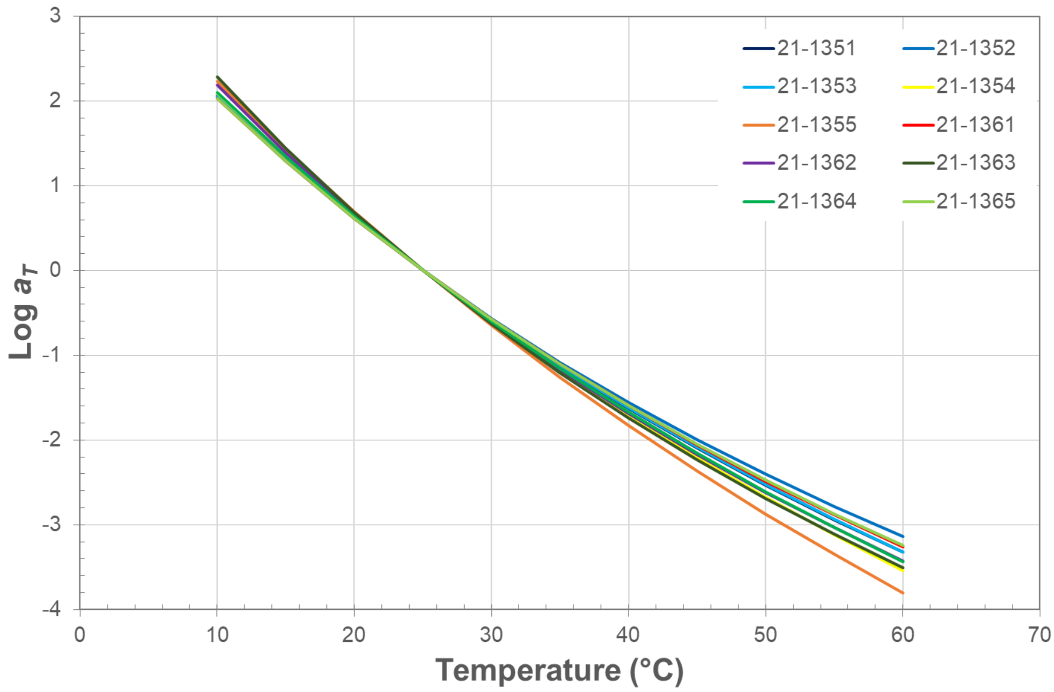


Figure 9-7 – WLF shift factor versus temperature plot for recovered binders

9.5 PERFORMANCE-RELATED TESTS

9.5.1 MULTIPLE STRESS CREEP RECOVERY TEST

The high temperature permanent deformation properties of the ten recovered binders were determined using the MSCR test in accordance with AASHTO TP 70-13. Following the empirical and DSR frequency sweep tests on the binders in Sections 9.3 and 9.4, it is envisaged that the binder performance tests (such as the MSCR test) will provide additional information on the properties of the recovered binders.

9.5.1.1 Repeated Load and Recovery Curves

The load and recovery curves at the testing temperature of 60°C and the two stress levels of 100 Pa and 3.2 kPa for the recovered binders are shown respectively in Figure 9-8 and Figure 9-9 in terms of strain versus time (loading and recovery periods).

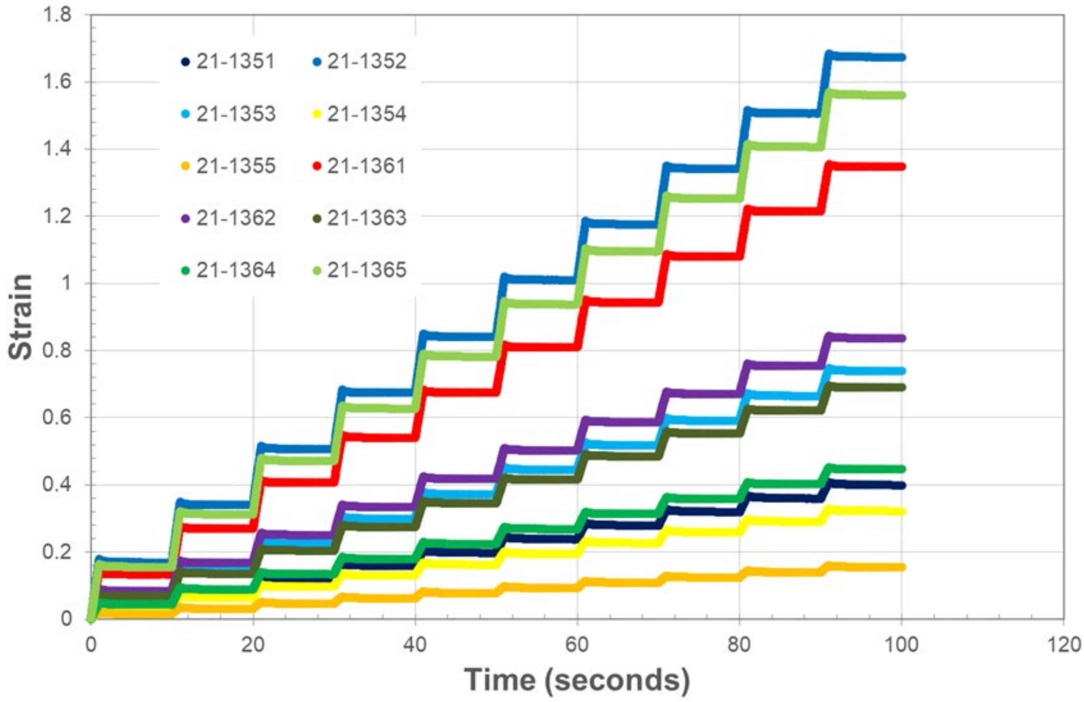


Figure 9-8 - Strain versus time for recovered binders at 100 Pa and 60°C

The strain versus time results from the MSCR test at both 100 Pa and 3.2 kPa show the same performance ranking of the recovered binders with the best performance being seen for NTEC 21-1351, 21-1354, 21-1355 and 21-1364. These four binders were shown to have the highest stiffness from the DSR testing in Section 9.4 and the 'hardest' nature from the empirical tests in Section 9.3. The next set of binders consisted of NTEC 21-1353, 21-1362 and 21-1363 with the worst permanent deformation performance being found for NTEC 21-1352, 21-1361 and 21-1365. Again, these three recovered binders had the lowest overall stiffness as demonstrated in the DSR oscillatory tests in Section 9.4 and the empirical binder tests in Section 9.3.

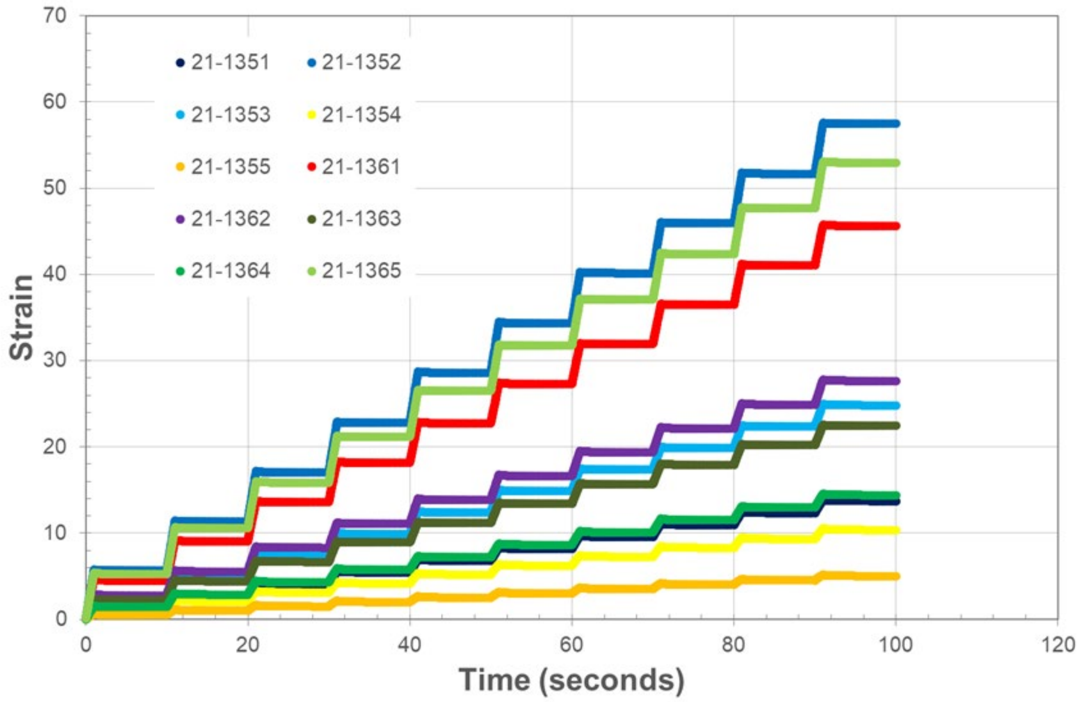


Figure 9-9 - Strain versus time for recovered binders at 3200 Pa and 60°C

9.5.1.2 Percentage Recovery and Non-recoverable Creep Compliance Parameters

As the MSCR test has been designed to determine not only the permanent deformation (strain) under creep loading and recovery but also the elastic response of the material, a series of parameters can be produced from the MSCR test data. These include recovery and compliance measurements at the two stress levels as detailed in Appendix B.3. The values of these six parameters as determined from the 0.1 kPa and 3.2 kPa MSCR tests were calculated for each of the ten recovered binders and presented in Table 9-2.

Table 9-2 – MSCR test recovery and creep compliance at 60°C

Materials	$R_{0.1}$ (%)	$R_{3.2}$ (%)	R_{diff} (%)	$J_{nr0.1}$(kPa^{-1})	$J_{nr3.2}$(kPa^{-1})	J_{nrdiff} (%)
NTEC 21-1351	17.35	10.82	37.6	0.399	0.429	7.5
NTEC 21-1352	5.26	1.84	65.0	1.674	1.796	7.3
NTEC 21-1353	10.15	6.18	39.1	0.739	0.776	5.0
NTEC 21-1354	17.88	15.29	14.5	0.322	0.324	0.6
NTEC 21-1355	25.52	23.31	8.7	0.155	0.157	1.3
NTEC 21-1361	5.61	2.54	54.7	1.347	1.427	5.9
NTEC 21-1362	7.58	4.91	35.2	0.837	0.865	3.3
NTEC 21-1363	7.84	5.40	31.1	0.690	0.701	1.6
NTEC 21-1364	11.40	9.64	15.4	0.447	0.451	0.9
NTEC 21-1365	5.46	2.07	62.1	1.561	1.655	6.0

The results show a similar ranking and grouping of the binders based on the non-recoverable compliance values at 100 Pa and 3.2 kPa as seem in Figure 9-8 and Figure 9-9. In addition to the creep compliance values, the percentage recovery (elastic recovery) values at 100 Pa and 3.2 kPa show a standard trend of higher recoveries for the stiffer binders with the lowest values been found for NTEC 21-1352, 21-1361 and 21-1365. It is interesting to note that there is only minimal stress sensitivity for these binders with the Jnrdiff value all being below 10%.

The non-recoverable compliance and percentage recovery values for the recovered binders have also been plotted in Figure 9-10 with all the binders situated well below the blue threshold line used to indicate potential elastomeric polymer modification.

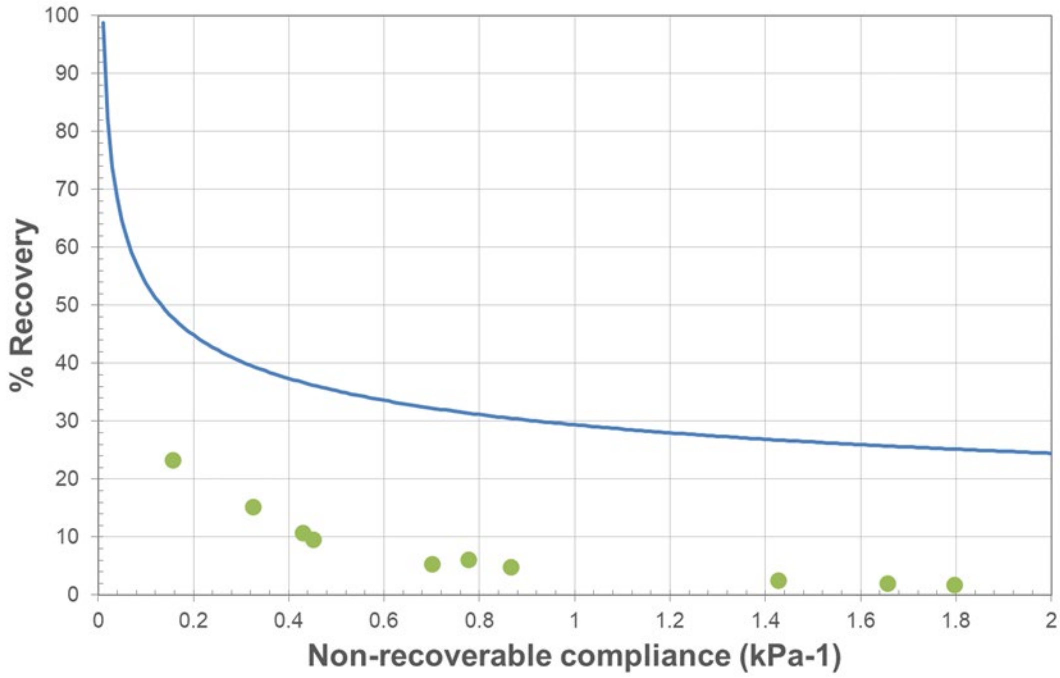


Figure 9-10 - Percent recovery v non-recoverable compliance for binders at 3.2 kPa and 60°C

9.5.2 LINEAR AMPLITUDE SWEEP (LAS) TEST

The fracture (cracking) based performance of the ten recovered binders was assessed by means of the Linear Amplitude Stress (LAS) test in terms of the binders' predicted fatigue cracking resistance.

9.5.2.1 Stress Versus Applied Strain Curves

As described in Appendix B.3, the LAS test is used to determine a binder's resistance to damage by means of cyclic loading with linearly increasing load amplitude at intermediate pavement temperatures. The stress versus strain results at a temperature of 20°C for the ten recovered binders are shown in Figure 9-11. All ten curves show a ductile type failure (gradual increase in stress with increasing strain up to the peak strength (stress) of the material followed by reducing stress with strain) as required for the analysis. Ductile failure is demonstrated by a flatter stress-strain response (curve) compared to a sharper curve for brittle fracture which would normally have a higher stress (strength) value at the peak and a much lower strain at peak stress.

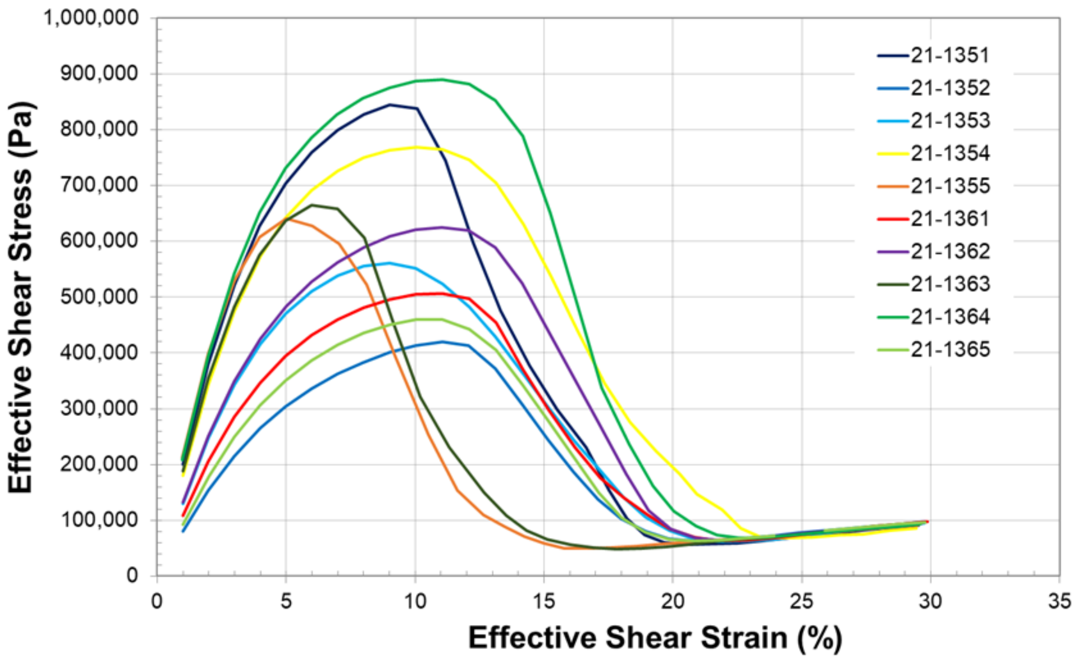


Figure 9-11 – Stress versus applied strain curves for recovered binders at 20°C

The stress-strain curves in Figure 9-11 follow the trend shown for the previous binders tests with the 'softer' binders showing a lower peak stress (strength) value as seen for NTEC 21-1352, 21-1361 and 21-1365 with the 'harder' binders having the highest peak stresses (NTEC 21-1351, 21-1354 and 21-1364). In general, the strain at peak stress is fairly consistent for most of the binders although binders NTEC 21-1355 and 21-1363 show a marginally less ductile failure behaviour (lower strain values at peak stress) than the rest of the binders. It is also interesting to note that the peak stress value for NTEC 21-1355 is considerably lower than that found for the group of 'harder' binders (NTEC 21-1351, 21-1354 and 21-1364).

9.5.2.2 Material Integrity Versus Damage Intensity Curves

Appendix B.3 describes how data generated from the LAS test can be analysed using the parameters C (material integrity) and D (damage accumulation). The C versus D relationship for the ten binders is shown in Figure 9-12. The curves are very similar for eight of the binders and almost identical for six of them (21-1352, 21-1354, 21-1361, 21-1362, 21-1364 and 21-1365) with the position of NTEC 21-1351 and 21-1353 being below the other six curves indicating a more damage susceptible behaviour. However, the position of binders NTEC 21-1355 and 21-1363 are very different from the other eight binders and indicate a severe susceptibility to cracking failure. Both these binders also showed a much lower ductile type of failure in the previous test.

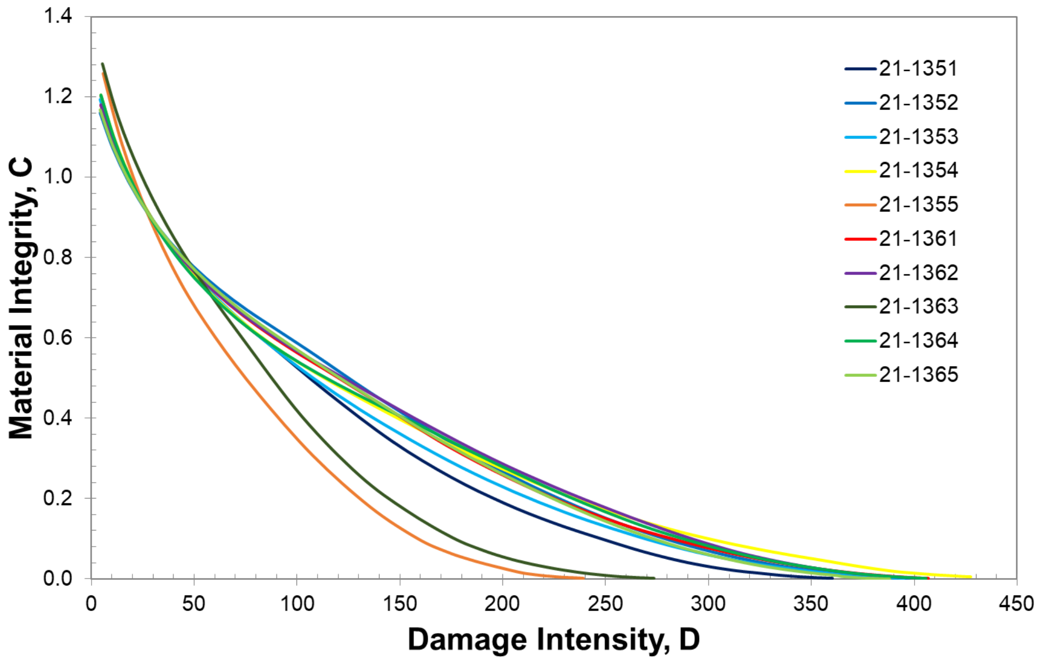


Figure 9-12 – Normalised stiffness versus damage curves for recovered binders at 20°C

9.5.2.3 Predicted Fatigue Life Versus Strain Level

The power law fitted parameters obtained from the C versus D relationships in Figure 9-12 are then used to determine the Df and A & B fatigue performance parameters that are required to allow the fatigue performance parameter (Nf) to be determined as a function of strain level as shown in Figure 9-13. Higher Nf values as a function of strain translate to better fatigue performance.

The ten fatigue curves (relationships) for the recovered binders shown in Figure 9-13 clearly show the reduction in fatigue (damage) performance of binders NTEC 21-1355 and 21-1363 compared to the other eight binders. This response is the first indication of a different performance behaviour of two of the binders outside the standard differences in binder stiffness.

In terms of the other eight binders with similar fatigue curves, the three ‘hard’ binders (NTEC 21-1351, 21-1354 and 21-1364) have almost identical slopes while the ‘softer’ binders (NTEC 21-1352, 21-1361 and 21-1365) have the shallowest slopes.

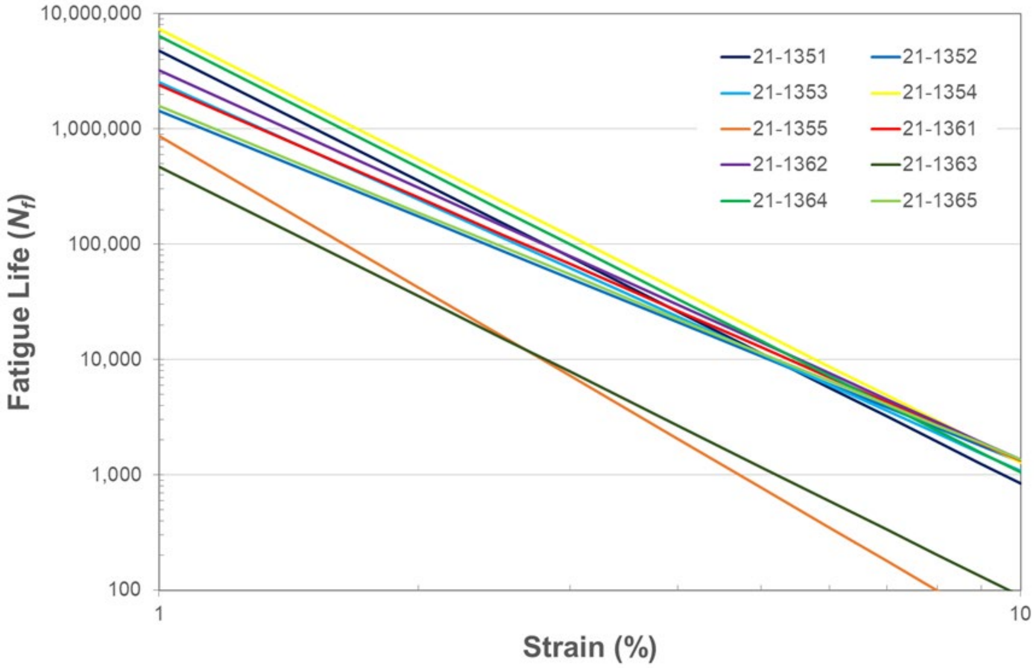


Figure 9-13 – Fatigue relationships for recovered binders at a temperature of 20°C

9.5.3 DOUBLE-EDGE NOTCHED TENSION (DENT) TEST

The intermediate temperature fracture properties of the ten recovered binders were determined using the DENT test based on AASHTO TP-113-15.

The key parameters from the DENT test are presented in Table 9-3 in terms of the specific essential work of fracture (we), the specific plastic work of fracture (wp), the net section stress (σn) and the critical tip opening displacement (CTOD). The CTOD and 'we' are also presented in Figure 9-14 for the ten recovered binders.

Table 9-3 - DENT fracture parameters

Materials	w_e (kJ/m^2)	βw_p (MJ/m^3)	σ_n (kPa)	CTOD (mm)
NTEC 21-1351	7.397	0.3852	583	12.7
NTEC 21-1352	2.923	0.0775	121	24.2
NTEC 21-1353	4.948	0.3013	319	15.5
NTEC 21-1354	8.396	0.4958	693	12.1
NTEC 21-1355	7.799	0.6441	922	8.5
NTEC 21-1361	4.384	0.1275	236	18.6
NTEC 21-1362	5.303	0.2705	345	15.4
NTEC 21-1363	6.772	0.5371	575	11.8
NTEC 21-1364	7.870	0.4738	650	12.1
NTEC 21-1365	3.988	0.1288	208	19.2

![WSP logo]

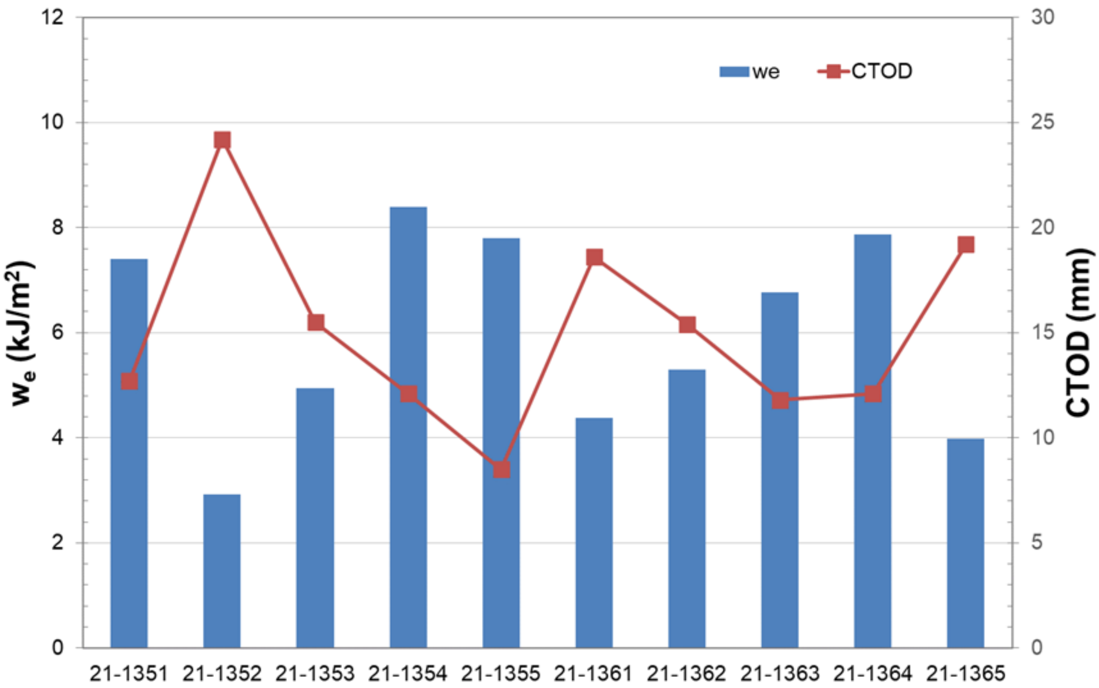


Figure 9-14 – Specific essential work of fracture and CTOD for recovered binders at 20°C

As expected, the three 'softer' binders (NTEC 21-1352, 21-1361 and 21-1365) have the lowest essential work of fracture and the highest CTOD values and therefore the best intermediate temperature cracking (fracture) resistance of all the binders. The 'harder' binders (NTEC 21-1351, 21-1354, 21-1355, 21-1363 and 21-1364) have the highest essential work of fracture values and the lowest CTOD values indicating poor fracture performance.

9.5.4 BENDING BEAM RHEOMETER (BBR) TEST

The low temperature properties of the ten recovered binders were determined using the bending beam rheometer (BBR) test based on the AASHTO T 313 standard.

9.5.4.1 Stiffness and m-value Parameters

The low temperature stiffness and m-values for the ten binders are presented in Figure 9-15 and Figure 9-16. The stiffness results in Figure 9-15 confirm the ranking in terms of stiffness of the different binders as already seen in the previous sections. The binders NTEC 21-1351, 21-1354, 21-1355, 21-1363 and 21-1364 again can be considered the 'hardest' binders in the group with lower stiffnesses seen for NTEC 21-1353, 21-1361 and 21-1362. The two 'softest' binders (NTEC 21-1352 and 21-1365) have the lowest stiffness values with only test results being possible at -18°C and -12°C.

The m-values in Figure 9-16 show the same trend to that seen for the stiffness results in Figure 9-15 with the same groupings of 'harder' binders having the lower m-values with the 'softer' binders having higher m-values.

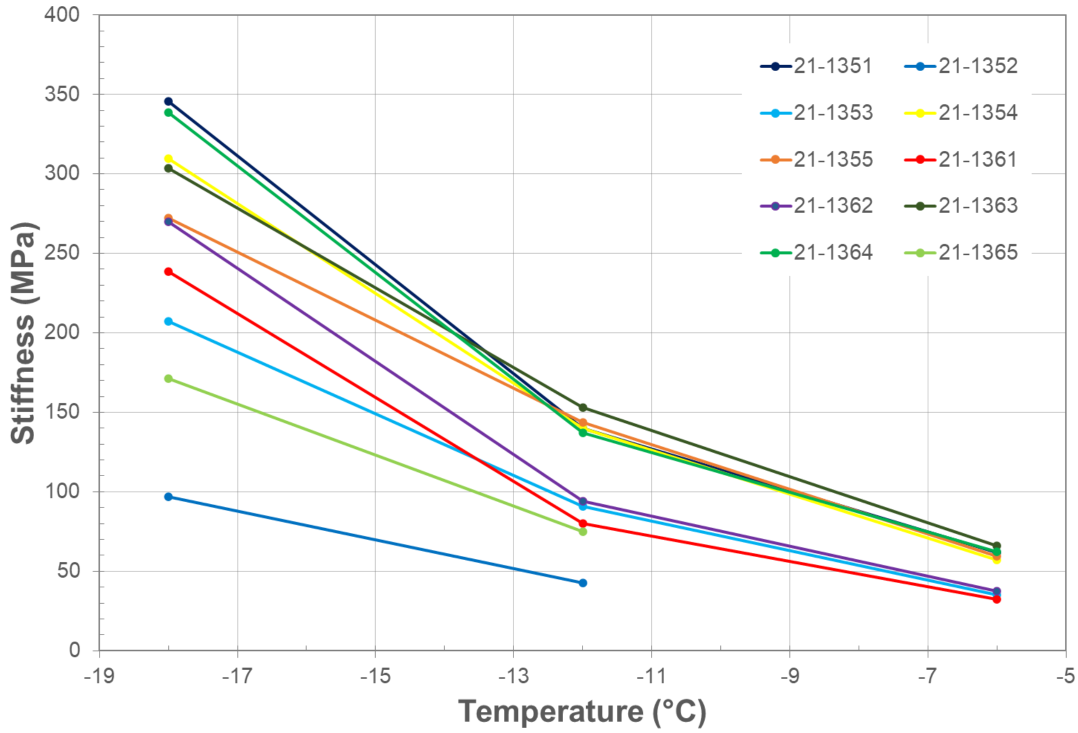


Figure 9-15 - Stiffness versus temperature for recovered binders

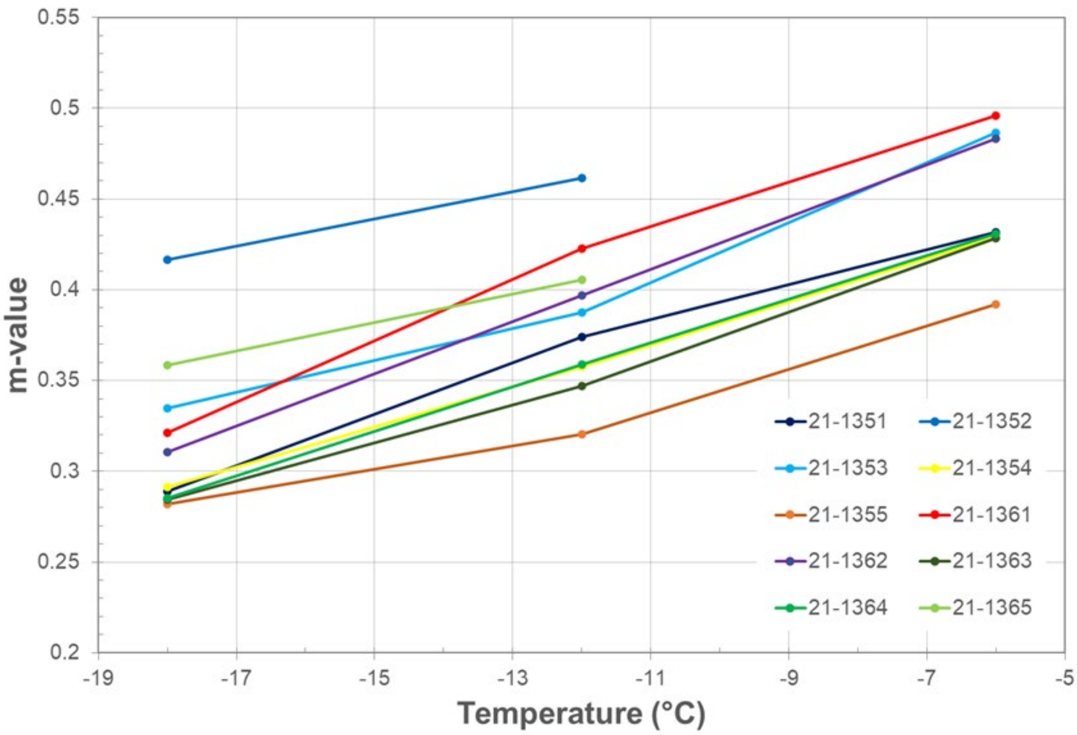


Figure 9-16 - m-value versus temperature for recovered plastic modified binders

9.5.4.2 Critical (limiting) Temperatures and Delta Tc Parameter

The critical low-temperature values (Tc(S) and Tc(m)) and the differential of these values (ΔTc) have been calculated using Equations 23 to 25 in Appendix B.3 and presented in Table 9-4. The two critical temperatures correspond to a limiting maximum creep stiffness value of 300 MPa and a minimum m-value of 0.300. The values of Tc(S), Tc(m) and ΔTc for the two 'softest' binders (NTEC 21-1352 and 21-1365) should be treated with care as these values have been calculated by extrapolating the data at -18°C and -12°C rather than interpolating the data either side of the limiting stiffness and m-value values. As expected, higher critical temperatures were found for the 'harder' binders (NTEC 21-1351, 21-1354, 21-1355, 21-1363 and 21-1364). The ΔTc values in Table 5 indicate that NTEC 21-1355 has the highest negative value (-3.7°C) and the potential therefore to be more susceptible to non-load related cracking or other age-related embrittlement distresses in an asphalt pavement. The other binders either have very low ΔTc values or positive values.

Table 9-4 - Critical (limiting) stiffness and m-value temperatures and ΔTc temperatures

Materials	$T_{c,S}$ (°C)	$T_{c,m}$ (°C)	ΔT_c (°C)
NTEC 21-1351	-27.1	-27.2	0.2
NTEC 21-1352	-36.3	-43.5	7.3
NTEC 21-1353	-30.7	-31.9	1.2
NTEC 21-1354	-27.8	-27.2	-0.5
NTEC 21-1355	-28.9	-25.2	-3.7
NTEC 21-1361	-29.3	-29.2	0.0
NTEC 21-1362	-28.6	-28.7	0.1
NTEC 21-1363	-27.9	-26.5	-1.4
NTEC 21-1364	-27.2	-26.8	-0.4
NTEC 21-1365	-32.1	-35.5	3.4

9.6 COMPARISON WITH CONVENTIONAL BINDER AND SBS PMB

In addition to the rheological testing carried out, NTEC were asked if they could compare the performance properties of the ten recovered binders to those of a conventional 40/60 pen bitumen and an SBS modified PMB in terms of the MSCR test, LAS and DENT tests. The main reason for this stemmed from the observations that: a) the recovered control binder (no additive) was harder than normally expected; and b) although the recovered binders with an additive showed a range in performance, their performance was not typical of polymerically modified binder.

9.6.1 MULTIPLE STRESS CREEP RECOVERY (MSCR) TEST

The load and recovery curves at the testing temperature of 60°C and the two stress levels of 100 Pa and 3.2 kPa for selected recovered plastic modified binders and a conventional 40/60 pen bitumen and SBS PMB are shown respectively in Figure 9-17 and Figure 9-18 in terms of strain versus time (loading and recovery periods).

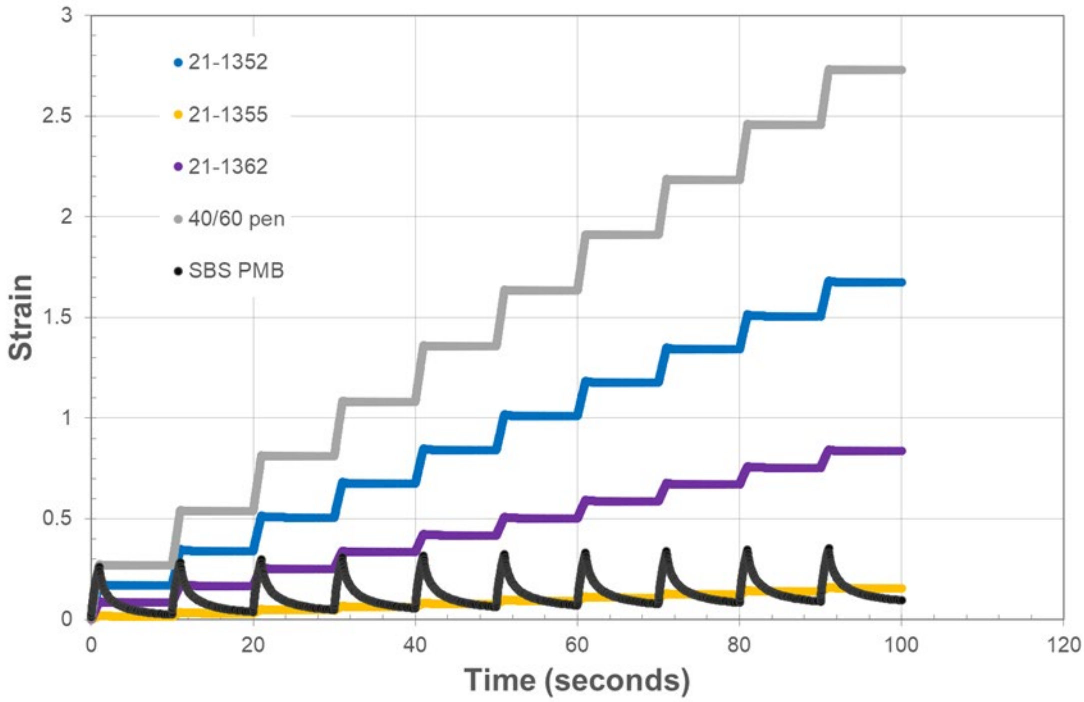


Figure 9-17 - Strain versus time for selected recovered plastic modified binders, 40/60 pen and SBS PMB at 100 Pa and 60°C

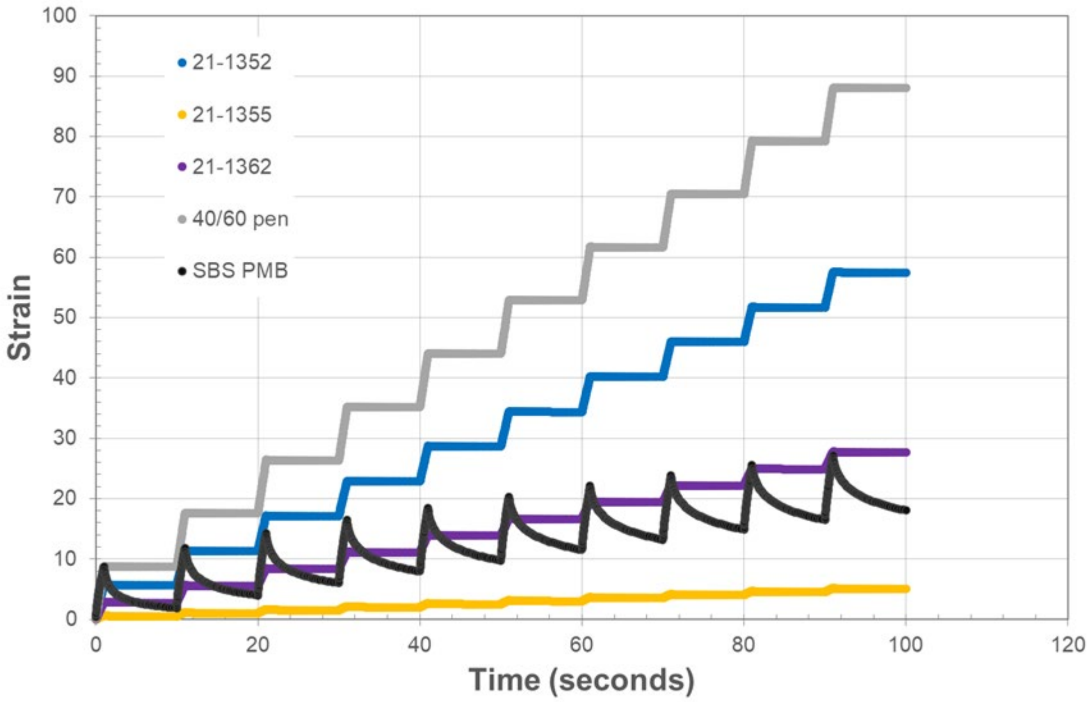


Figure 9-18 - Strain versus time for selected recovered plastic modified binders, 40/60 pen and SBS PMB at 3200 Pa and 60°C

The strain versus time results at both 100 Pa and 3.2 kPa show the same trends with the 40/60 pen bitumen demonstrating much higher permanent deformation compared to the three recovered binders (NTEC 21-1352, 21-1355 and 21-1362). The strain versus time plot for the SBS PMB is markedly different from the other four binders with high amounts of elastic recovery for each of the ten loading cycles. This means that although this SBS PMB can be considered to be quite 'soft', as shown by the high strain increments after loading, the elastomeric nature of the polymer means that the overall final strain level after ten loading and recovery cycles is similar to that found for the 'harder' recovered binders.

The non-recoverable compliance and percentage recovery values at 3.2 kPa applied stress for the SBS PMB have also been plotted in Figure 9-19 along with the ten recovered binders. The plot shows that the data for the elastomeric SBS PMB is situated well above the blue threshold line used to indicate potential elastomeric polymer modification.

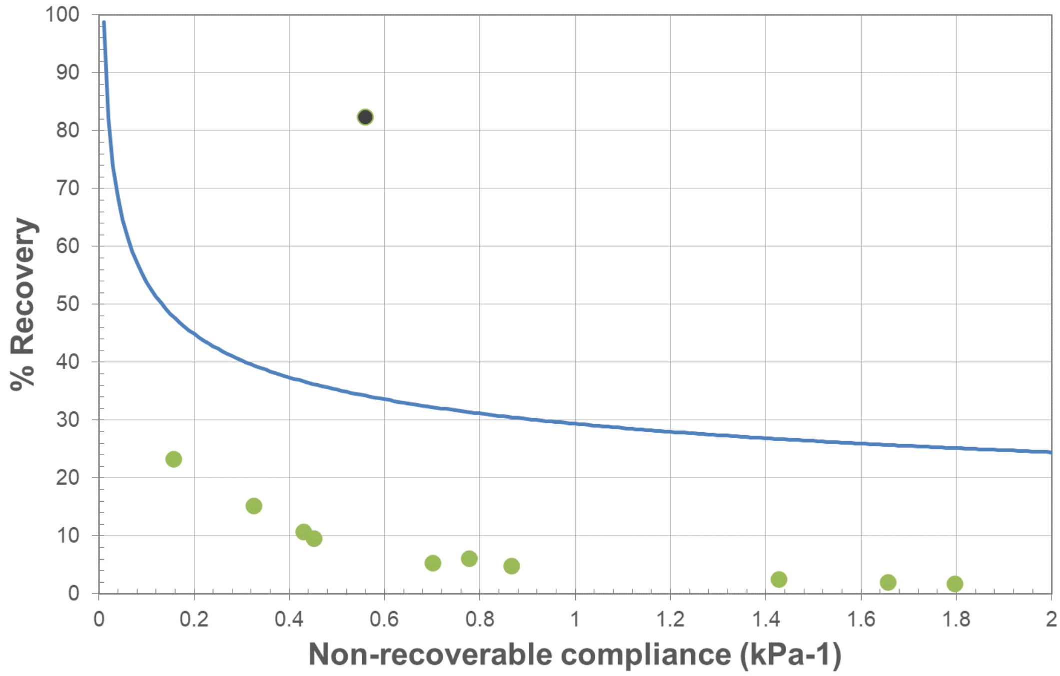


Figure 9-19 - Percentage recovery versus non-recoverable compliance for recovered plastic modified binders and SBS PMB at 3.2 kPa and 60°C

9.6.2 LINEAR AMPLITUDE SWEEP (LAS) TEST

The stress versus strain results at a temperature of 20°C for a selection of the recovered binders together with the 40/60 pen bitumen and SBS PMB are shown in Figure 25.

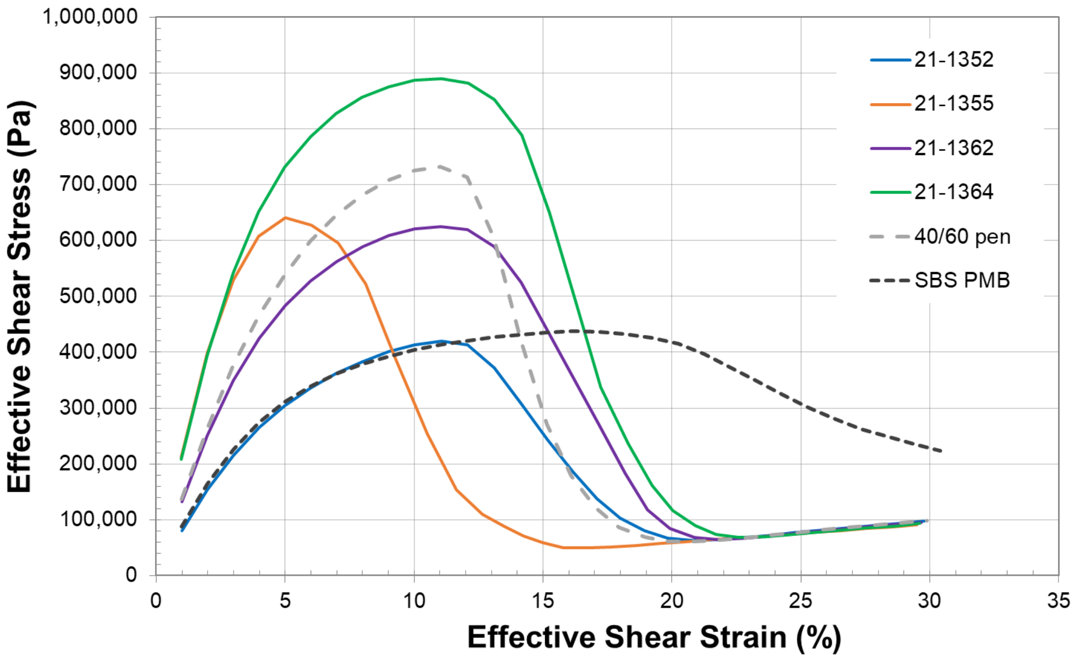


Figure 9-20 - Stress versus applied strain curves for selected recovered plastic modified binders, 40/60 pen and SBS PMB at 20°C

The stress-strain curve for the 40/60 pen bitumen is similar in shape to the recovered binders NTEC 21-1352 (‘soft’), 21-1362 (‘intermediate’) and 21-1364 (‘hard’) with a standard ductile-type failure. However, the shape of the stress-strain curve for the SBS PMB is very different with a relatively low peak stress but an extended effective shear strain showing increased ductility for the binder.

The material integrity (C) versus damage intensity (D) relationships for the selected recovered binders, 40/60 pen bitumen and SBS PMB are shown in Figure 9-21. As discussed in Section 9.5, the three recovered binders (NTEC 21-1352, 21-1362 and 21-1364) have very similar curves with the position of NTEC 21-1355 being below these three binders. The C versus D curve for the 40/60 pen bitumen is positioned between these two areas indicating a slightly more damage susceptible behaviour compared to NTEC 21-1352, 21-1362 and 21-1364 but better damage resistance compared to NTEC 21-1355. The C versus D curve for the SBS PMB lies well above the curves of the other five binders and is evidence of a superior damage resistance usually associated with these types of elastomeric modified binders.

Finally, the fatigue curves (relationships) for the six binders are determined and shown in Figure 9-22. The results clearly show the reduction in fatigue (damage) performance of binder NTEC 21-1355 compared to the 40/60 pen bitumen and the other three recovered binders (NTEC 21-1352, 21-1362 and 21-1364). As expected, following the stress-strain behaviour shown in Figure 9-20 and the C versus D curves in Figure 9-21, the SBS PMB shows the best fatigue performance compared to all the other binders.

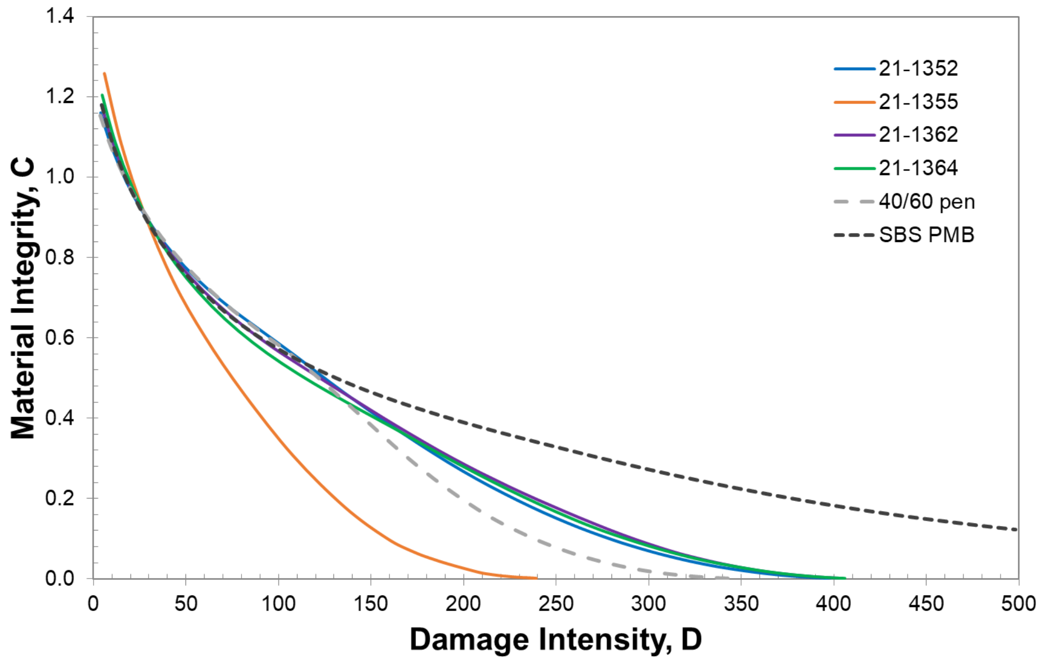


Figure 9-21 - Normalised stiffness versus damage curves for selected recovered plastic modified binders, 40/60 pen and SBS PMB at 20°C

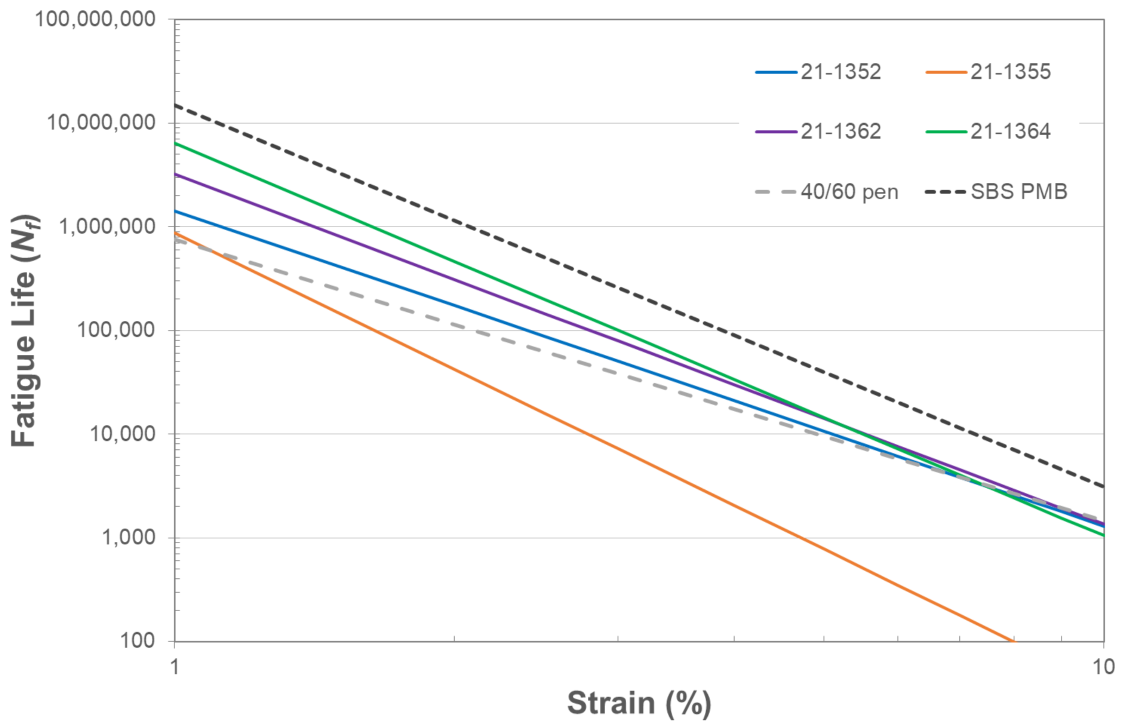


Figure 9-22 - Fatigue relationships for selected recovered plastic modified binders, 40/60 pen and SBS PMB at 20°C

9.6.3 DOUBLE-EDGE NOTCHED TENSION (DENT) TEST

The key parameters associated with intermediate temperature fracture properties from the DENT test are presented in Figure 9-23. It shows the specific essential work of fracture (W_e) and critical tip opening displacement (CTOD) for three of the selected recovered binders, the 40/60 pen bitumen and the SBS PMB.

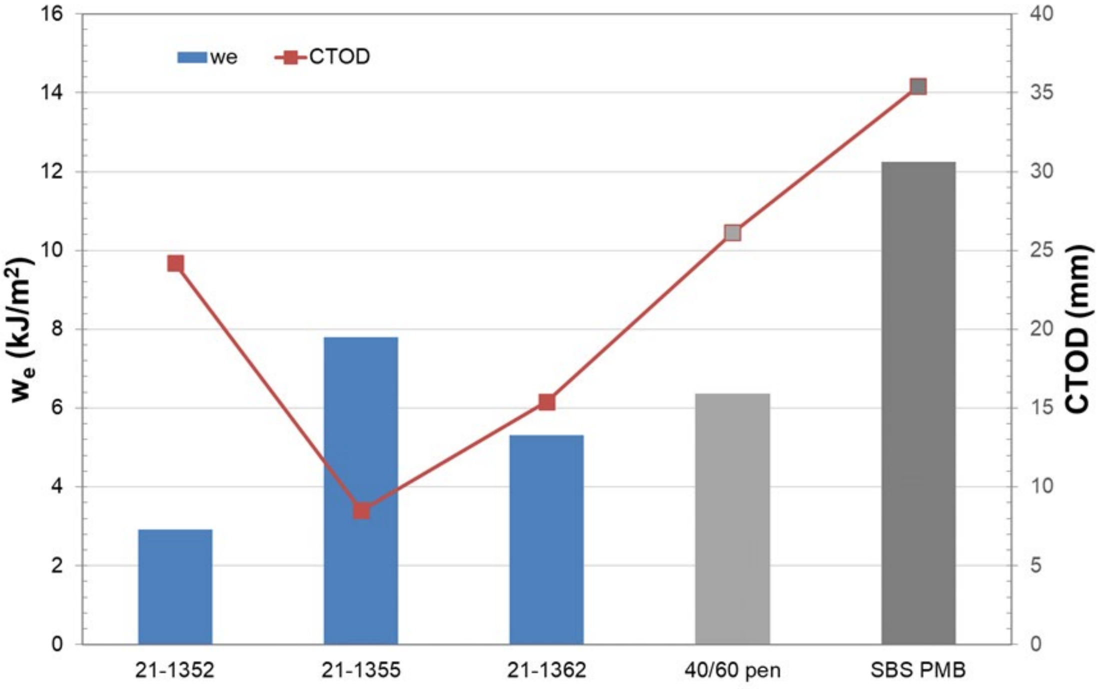


Figure 9-23 - Specific essential work of fracture and CTOD for selected recovered plastic modified binders, 40/60 pen and SBS PMB at a temperature of 20°C

The results show that even with the higher W_e values, both the 40/60 pen bitumen and particularly the SBS PMB show superior intermediate fracture performance compared to the three recovered binders (NTEC 21-1352 ('soft'), 21-1355 ('hard') and 21-1362 ('intermediate')) with high CTOD values.

9.7 DISCUSSION

This section presents the data for a set of ten recovered binders which have been subjected to empirical binder tests, rheological assessment performance-related tests.

The results from the study show that the recovered binders can be grouped into two (and possibly) three stiffness-related groups in terms of all the testing methods. The 'harder' recovered binders (NTEC 21-1351, 21-1354, 21-1355 and 21-1364) as well as the slightly 'softer' binders (NTEC 21-3153, 21-1362 and 21-1363), have low needle penetration results, high softening points and viscosities, higher G* master curves and lower phase angle (more elastic response) master curves. They are also better at resisting permanent deformation as shown by the MSCR test. The three 'softest' binders (NTEC 21-3152, 21-1361 and 21-1365) have high penetration, low softening points and viscosities, low G* master curves and more viscous response, and more permanent deformation under creep stress conditions. The LAS results show the same trends in terms of the failure stress-strain response of the different binder groups but overall, the fatigue properties of the different recovered binders are very similar with the only exceptions being NTEC 21-1355 and 21-1363 which demonstrated poor fatigue performance. The DENT intermediate fracture properties followed the trend seen in terms of different responses based on binder stiffness. The three 'softer' binders (NTEC 21-1352, 21-1361 and 21-1365) had the highest CTOD values and therefore the best intermediate temperature cracking (fracture) resistance of all the binders. The 'harder' binders (NTEC 21-1351, 21-1354, 21-1355, 21-1363 and 21-1364) showed low CTOD values indicating poor fracture performance. Finally, the low temperature properties as determined by the BBR and delta Tc parameter once again showed that the 'harder' binders (NTEC 21-1351, 21-1354, 21-1355, 21-1363 and 21-1364) had higher low temperature stiffness results and lower m-values, while the reverse was seen for the 'softer' binders.

Selected MSCR test, LAS and DENT results for selected recovered binders were also compared to the properties of a conventional 40/60 pen bitumen and an elastomeric modified SBS PMB. Overall, the results showed similar types of behaviour for the recovered binders versus the 40/60 pen bitumen but the rutting, fatigue and fracture properties of the SBS PMB were shown to be superior to all the other binders.

9.8 RHEOLOGICAL STUDY CONCLUSIONS

Based on the results of the recovered binder testing carried out by NTEC, the following conclusions are made.

- The behaviour of the recovered binders could be broadly divided into two or three stiffness-related groups in terms of all the testing methods.
- Based on empirical binder tests and rheological assessment, the groups could be described as 'hard' (penetration values of about 25); 'intermediate' (penetration values of about 35); and 'soft' (penetration values of about 45).
- In terms of the rheological master curves and performance related tests, none of the recovered binders exhibited the behaviour traditionally seen for a bitumen that has been polymerically modified, i.e. elastomeric or plastomeric.
- The sophisticated rheological testing data could be seen to separate the individual behaviour of the recovered binders but most of the recovered binders could be considered to fall within the typical performance range of a straight run 40/60 penetration bitumen.
- The Four top performing binders, in terms of stiffness, elastic response and resistance to deformation, included the control (no additive), one containing Additive 1 and two containing Additive 2.
- The fatigue properties of the recovered binders were considered to be very similar with the exception of NTEC 21-1355 and 21-1363, which contained additive 2 and additive 1, respectively. Results for these binders indicate a severe susceptibility to fatigue cracking failure.
- As to be expected the harder binders showed poorer fracture properties than the softer.
- The penetration of the recovered 40/60 control binder was harder than typically expected at 23 pen.
- When performance-related test results of the recovered binders were compared to the properties of a conventional 40/60 pen bitumen and an elastomeric modified SBS PMB, the results showed similar types of behaviour to the conventional bitumen. The main difference was linked to the relative stiffness of the recovered binders compared to the conventional 40/60 pen bitumen. The

SBS PMB was shown to be superior to all the other binders in terms of rutting, fatigue and fracture properties.

10

CONCLUSIONS AND RECOMMENDATIONS

10 CONCLUSIONS AND RECOMMENDATIONS

10.1 LITERATURE & DATA REVIEW

10.1.1 KEY FINDINGS

In recent times, there has been increasing public interest in reducing the amount of plastic waste that is destined for landfill. It follows that if some of this waste can be used to improve the performance of roads then it could provide a sustainable solution for the future. However, it is essential that the influence of plastic additives is fully understood to ensure it does not adversely affect the long-term performance of road materials, and it is safe to use for plant and construction operators.

The literature review highlighted that the scientific and engineering understanding of using recycled plastic is still at an early stage and more research is required. In general, the literature review demonstrated that most research is laboratory based, with insufficient technical information from studies based on the in-service performance of pavements.

Key findings from the literature review included:

- Sample preparation
  - It was not always clear from the published papers how the test specimens were prepared and what compaction method was used prior to stiffness testing.
  - The high stiffness properties reported may be due the method of specimen preparation.
- Laboratory-based studies
  - Adding recycled plastics is shown to significantly increase mixture stiffness and rutting resistance.
  - Indirect tensile strength ratio (ITSM) testing – a comparison of strength between dry and wet (soaked samples) – showed the mixtures containing additives were not water sensitive.
  - Indirect tensile fatigue testing (ITFT) showed slightly better fatigue life for a binder course containing additives but a lower fatigue life for a surface course mixture with additives.
- No large-scale road trial performance data was identified.
  - High performance values may not be replicated when the asphalt and additive is produced at a plant using the dry process and then compacted using conventional compaction plant.

10.1.2 RECOMMENDATIONS

Information gathered as part of the literature review identified some gaps in knowledge. Key recommendations include:

- A method of determining the properties and consistency of the feedstock of waste plastic needs to be established to ensure consistency of performance in the future.
- Guidance on fume is required by a specialist in the Control of Substances Hazardous to Health to ensure suitable workplace exposure limits.
- Some additional laboratory testing is likely to be required to examine low temperature properties of bitumen incorporating waste plastic and the durability of adhesion in asphalt mixes.

- Testing should be considered to examine the low temperature properties of bitumen incorporating waste plastic and the durability of adhesion in asphalt mixes.
- Testing is required to establish the dispersion and digestion of waste plastic polymers, particularly when using the dry process.

10.2 CIRCULAR ECONOMY

Based on a review of available information provided by CCC, findings and recommendations are made in Chapter 5. It should be noted that the recommendations could equally be adopted by other local government authorities seeking to make progress on circular economy activity. Key recommendations include:

- Policy
  - Review the current policy on plastic consumption to ensure it is set within the context of a circular economy, including alignment with pending legislation, and the provision of a clear strategy on resource management.
- Council activity and context
  - Form an authority-wide forum through which highways materials and waste can be centrally monitored and managed, including ensuring there is a standard suite of metrics and data that can be collected and reviewed.
  - Review model contracts to identify opportunities to make more specific information provision and where information cannot be refined and collected, agree workstreams to resolve such situations.
- Data management
  - Review the current approach to collecting materials, waste and associated financial and environmental data, across all applications.
  - At a time when robust value chain data on plastics (or polymers) in asphalt can be acquired, a full LCA should be conducted on a variety of different asphalt products, under different conditions.

The full findings of the circular economy assessment, findings and recommendations are provided in Chapter 5.

10.3 LIVE LAB MATERIAL TESTING

10.3.1 MIXTURE TESTING

The Live Lab quarry trials have provided an early opportunity to make comparisons between the in situ properties of mixtures that contain a range of plastic additives and more conventional control mixtures. Most of the data reported in Chapter 8 comes from the three Live Lab quarry trials.

10.3.1.1 Key findings

The key findings from the mixture testing are as follows:

- Stiffness
  - Test data from AC 20 cores (binder course) show an average increase of around 12% when using Additive 1.
  - Stiffness data for the AC 20 using Additive 1 is observed to show a wider spread in results than the control mixture indicating the increase in stiffness is variable.
  - Stiffness results from a range of combined surface course types indicate a 14% increase in stiffness with the addition of Additive 1; the addition of Additive 2 produces a more modest increase of 9%, with a slight increase in the spread of results.
  - When Stiffness results from bulk sample are compared against each other, there is no clear trend in the data, i.e. mixtures with Additive 1 and Additive 2 produce similar results to the control mixtures.
- Other properties
  - The recovered binder content was found to be marginally lower in mixtures that contained Additive 1 and Additive 2 when compared to the control mixtures by around 0.3%.
  - In general, the voids content in mixtures containing Additive 2 are slightly higher than the control and Additive 1 mixtures.
  - Wheel tracking results are improved with the addition of plastic additives, although all results are acceptable.
  - Water sensitivity assessed using the ITSR test showed that all results were above the standard specification of 80%.

10.3.2 RHEOLOGICAL TESTING

A total of ten asphalt mixture samples were taken during laying operations at the trial sites and supplied to NTEC at the University of Nottingham. The bitumen and plastic additive components of the 10 different asphalt mixtures were recovered and subjected to a series of rheological and binder performance tests to determine their relative rheological properties and performance.

10.3.2.1 Key Conclusions

Based on the results of the recovered binder testing, the key conclusions were made:

- In terms of the rheological master curves and performance related tests, none of the recovered binders exhibited the behaviour traditionally seen for a bitumen that has been polymerically modified, i.e. elastomeric or plastomeric.
- The behaviour of the recovered binders could be broadly divided into two or three stiffness related groups in terms of all the testing methods.
- Based on empirical binder tests and rheological assessment, the groups could be described as ‘hard’ (penetration values of about 25); ‘intermediate’ (penetration values of about 35); and ‘soft’ (penetration values of about 45).
- The four top performing binders, in terms of stiffness, elastic response and resistance to deformation, included the control (no additive), one containing Additive 1 and two containing Additive 2.

- Results for two recovered binders, which contained Additive 1 and Additive 2, indicated a severe susceptibility to fatigue cracking failure.
- As to be expected the harder binders showed poorer fracture properties than the softer.
- The sophisticated rheological testing data could be seen to separate the individual behaviour of the recovered binders but most of the recovered binders could be considered to fall within the typical performance range of a straight run 40/60 penetration bitumen.
- When performance-related test results of the recovered binders were compared to the properties of an elastomeric modified SBS PMB, the latter was shown to be superior to all the other binders in terms of rutting, fatigue and fracture properties.

Test results for samples containing additive 4 were not available at the time of writing.

10.3.3 ADDITIONAL MIXTURE TESTING RECOMMENDATIONS

Based on the key findings of mixture testing the additives appear to increase stiffness, albeit there is typically an increased spread in results with mixtures containing additives. Results from binder testing do not explain the increased mixture stiffness. However, the results do show that the recycled plastics appear to change the rheology of the binder into three groups. The behaviour and performance of these groups of binders are different but not typical of a polymerically modified bitumen.

There still remains a question or uncertainty as to what is causing the increased stiffness observed. It is possible that some of the plastic does not achieve dispersion in the bitumen and acts as a filler within the mixtures. Achieving adequate dispersion and digestion of the waste plastic in bitumen may be a critical factor in achieving reliable results from asphalt mixtures. Work undertaken to date does not appear to have assessed this. Further work should be considered to assess the degree of dispersion and digestion that has occurred after asphalt mixing, as the mixing time in the dry process may be less than that required to achieve digestion or dissolution.

It is recommended that the approach recently developed in Australia[35] be considered to assess the release of microplastics from plastic-modified asphalt by providing abrasion to asphalt samples in a controlled environment followed by a microplastic extraction and characterisation procedure. The procedure has been shown to successfully separate microplastics from bitumen and aggregate residues and their size distribution can be validated by fluorescence microscopy analysis.

10.4 LIVE LAB TRIAL MONITORING

The six live road trials have been in service between 11 and 26 months. It is essential that the performance be assessed on a regular basis. Subtle changes in the early-life performance of the trials could provide an indication of longer-term performance. It is recommended that the live road trials be assessed visually by a panel representing the client, suppliers and WSP. The visual assessments should be carried out on an annual basis utilising an established inspection and

[35] Austroads Research Report AP-R663-2: Use of Road-grade Recycled Plastics for Sustainable Asphalt Pavements

marking system[36,37] that ranks the performance of the control sections and those that include additives.

[36] TRL PPR898 [link]
[37] MCHW Vol 1, Series 900, Cl 942.31.

Appendix A

MIXTURE TESTING DATA

APPENDIX A

Appendix A.1 Keepershield – summary of results from Bulk samples & cores

			Bulk Samples									Cored Samples					
Description	SAP Code & Target binder	Aggregate Package	Binder Content (%)	Max Density (Mg/m³)	Bulk Density (Mg/m³)	Voids (%)	ITSM (MPa)	Water Sensitivity (%)	(WTS) Wheel Tracking (mm/10³ Cycles)	Refusal Density (Mg/m³)	Refusal Voids (%)	Bulk Density - In situ (Mg/m³)	Density at Refusal (Mg/m³)	Voids in situ (%)	ITSM (MPa)	Refusal Voids (%)	PRD (%)
AC 20 HD 40/60	70000592 4.8%	Keepershield / Keepershield	4.9	2.675	2.534	5.3	11296	102	0.04	2.641	1.3	N/A					
AC 20 HD 40/60 ADD1			4.5	2.708	2.566	5.2	12527	99	0.05	2.600	4.0						
AC 20 HD 40/60 ADD2			4.5	2.659	2.515	5.4	11271	92	0.04	2.622	1.4						
Tufflex D 10 68psv	70014418 6.4%	CYH / Keepershield	5.7	2.502	2.382	4.8	6467	88	0.02	2.449	2.1	2.323	2.439	7.2	2138	2.5	95.2
Tufflex D 10 68psv ADD1			5.6	2.483	2.380	4.1	6974	82	0.01	2.439	1.8	2.356	2.455	5.1	2565	1.1	96
Tufflex D 10 68psv ADD2			5.5	2.501	2.328	6.9	7089	88	0.01	2.448	2.1	2.349	2.457	6.1	2185	1.8	95.6
												2.485					
Countyfalt 14 55psv	70005232 5.3%	Keepershield / Keepershield	4.9	2.670	2.456	8.0	10531	89	0.05	2.590	3.0	2.485	2.602	6.9	4040	2.5	95.5
Countyfalt 14 55psv ADD1			4.9	2.652	2.425	8.6	9260	100	0.04	2.610	1.6	2.437	2.587	8.4	3628	2.5	94.2
Countyfalt 14 55psv ADD2			5.1	2.657	2.469	7.1	9061	96	0.07	2.610	1.8	2.540	2.613	4.1	4696	1.7	97.2
Tufflex 14 55 psv	70028849 5.3%	Keepershield / Keepershield	5.5	2.650	2.555	3.6	6023	99	0.06	2.609	1.5	2.591	2.612	2.3	2540	1.4	99.2
Tufflex 14 55 psv ADD1			4.1	2.673	2.509	6.1	6755	100	0.03	2.597	2.8	2.571	2.613	3.7	4154	2.2	98.4
Tufflex 14 55 psv ADD2			4.5	2.669	2.436	8.7	5760	97	0.03	2.625	1.6	2.499	2.571	6.2	3367	3.7	97.2
SMA 10 40/60 PSV 55	70000883 6.0%	Keepershield / Keepershield	5.6	2.653	2.478	6.6	7261	82	0.13	2.576	2.9	2.482	2.556	6.4	2837	3.7	97.1
SMA 10 40/60 PSV ADD1			5.7	2.603	2.416	7.2	6484	84	0.05	2.552	2.0	2.459	2.603	5.5	4143	3.1	97.5
SMA 10 40/60 PSV 55 ADD2			5.3	2.629	2.428	7.6	7731	89	0.05	2.551	3.0	2.313	2.570	10.3	2805	2.2	90
									(WTR) Wheel Tracking (µm/cycle)		Rut depth (mm)						
HRA 35/14 55psv + chips	70000717 6.5%	Keepershield / Keepershield - Low Gelt Blend	6.6	2.484	2.354	5.2	N/A		0.6		1.6	N/A					
HRA 35/14 55psv + chips ADD1			6.1	2.479	2.354	5.0			0.1		0.6						
HRA 35/14 55psv + chips ADD2			6.0	2.482	2.295	7.5			0.6		1.8						

Appendix A.2 Keepershield laying records

Laying Records				Additive	Aggregate PSV	Texture Depth (mm)
Section	Chainage (m)	Rolling temperature (°C)	Material			
1	0-22	153	Tufflex D10 surf PMB	-	68	1.1
2	22-45	153	Tufflex D10 surf PMB	1	68	1.0
3	45-67	153	Tufflex D10 surf PMB	2	68	0.9
6	67-92	146	HRA 35/14 + chips	1	55	
6a	92-102	148	HRA 35/14 + chips	2	55	
12	0-15	136	Countyfalt 14 40/60	-	55	
11	15-26	136	Countyfalt 14 40/60	1	55	
10	26-36	135	Countyfalt 14 40/60	2	55	
9	36-52	137	Tufflex 14	-	55	
8	52-66	142	Tufflex 14	1	55	
7	66-72	142	Tufflex 14	2	55	
4	63-83	148	HRA 35/14 + chips	-	55	
5	83-92	148	HRA 35/14 + chip	2	55	
1	0-22	123	*AC 20 HDM 40/60*	-	-	
2	22-42	135	*AC 20 HDM 40/60*	*2*	-	
3	42-67	120	*AC20 HDM 40/60*	*1*	-	
4	67-80	126	*SMA 10 40/60*	-	*55*	
5	80-100	126	*SMA 10 40/60*	*1*	*55*	
6	67-90	126	*SMA 10 40/60*	*2*	*55*	

Appendix A.3 Lowther Street

Material				BS EN 13036-1:2010	In situ Density		Binder content (%)	Bond coat: BS EN 12272-1: 2002				Surface irregularity ≥ 4mm	Surface irregularity ≥ 7mm
Section	Chainage (m)	Rolling Temperature (°C)	Material	Texture Depth	Density (kg/m³)	air voids (%)		Temperature of Binder during test (°C)	Rate of Spread (kg/m²)	Residual rate of spread (kg/m²)	Proportional Range		
1, 4 & 6	various	±160	Tufflex D 10 Surf PMB PSV68	1.2			6.5					4	4
2, 3 & 5	various	±160	Tufflex D 10 Surf PMB ADD 1 PSV68	1.2			6.7					4	4
1, 3	various	±140	AC20 HDM Bin 40/60 ADD 1		2548	4.5	4.5	73	0.7	0.35	0.04		
2, 4, 5 & 6	various	±140	AC20 HDM Bin 40/60 Des		2550	4.0	4.8	88	0.7	0.35	0.045		

Appendix A.4 Back Lane quarry

Material				BS EN 13036-1:2010	In situ Density		BS EN 12697-5: 2018: Procedure A (using de aired water)		ITSM (MPa) from Cores
Section	Chainage (m)	Rolling Temperature (°C)	Material	Texture Depth	Density (kg/m³)	air voids (%)	Max Density (kg/m³)	Voids (%)	
2 & 5	various	138	10mm SMA PMB ADD2	1.15					2516
1 & 6	various	133	10mm SMA PMB Control	1.30					2336
2 & 3	various	134	10mm SMA PMB ADD 1	1.15					2695
3 & 4	various	134	AC20 DBM 40/60 ADD1		2463	2.3	2449	2.83	4509
1, 2, 5 & 6	various	137	AC20 DBM 40/60 Control		2445	3.0	2443	3.04	4838

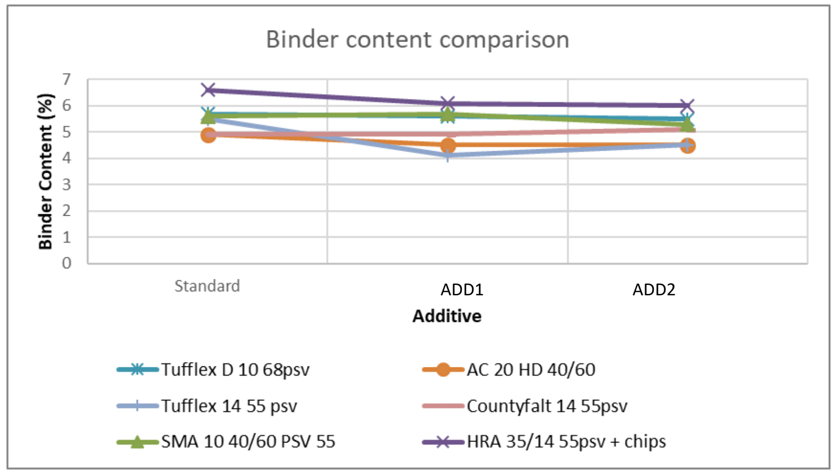
Appendix A.5 Moota Quarry

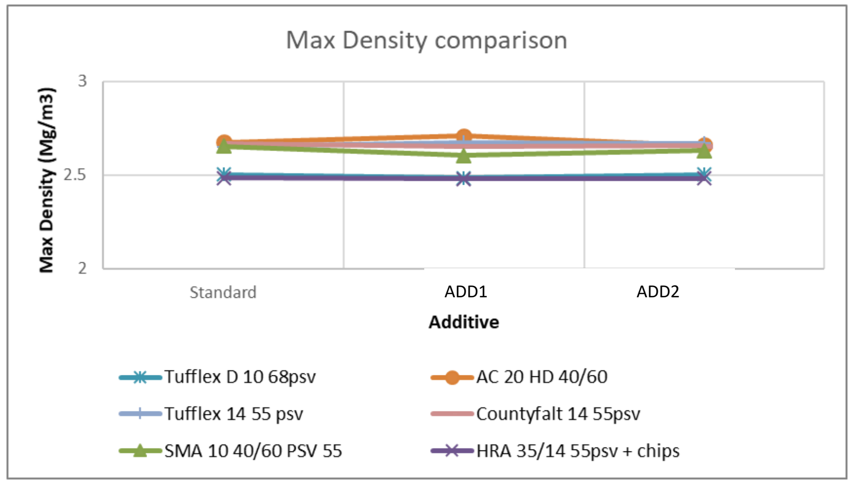
Material				BS EN 12697-22:2003 Procedure A in Air			BS EN 12697-5: 2009 Procedure A		BS EN 12697-22:2003 Procedure A in Air	In situ Density		BS EN 12697-5: 2018: Procedure A (using de aired water)		BS EN 12697-6 : 2012 Procedure B (SSD)		BS EN 12697-5 : 2009, BS EN 12697-6 : 2012 Procedure (SSD); BS EN 12697-32 :2019 - from core		ITSM BS EN 12697: Part 26: 2004: Annex C
Section	Chainage (m)	Rolling Temperature (°C)	Material	Mean TR (µm/cycles)	(WTR) Wheel Tracking (µm/cycles)	Mean RD @ 1,000 cycles (mm)	Max Bulk Density (Mg/m³)	Voids (%)	RDm	Density (kg/m³)	Air voids (%)	Max Density (Mg/m³)	Voids (%)	Bulk Density (Mg/m³)	Voids (%)	Bulk Density to Refusal	Voids (%)	150 mm diameter
4 & 6	various	±120	HRA	0.5	0.4	1.9						2.401						3556
3	various	±120	HRA ADD 1	0.4	0.3	1.2			1.2			2.382	8.45	2.390	9.2			3597
2	various	±120	SMA															
1	various	±130	SMA ADD1									2.473		2.481	7.9			4806
2 & 4	various	±120	AC20	0.3	7.9	11.5				2411	5.4	2.427		2.373	8.9			4276
1 & 3	various	±120	AC20 ADD1	0.1	3.1	7.6	2.489	8.15		1535	6.1	2.479		2.360	8.1			4823
5	various	±120	AC20 ADD 2							2431	4.6							

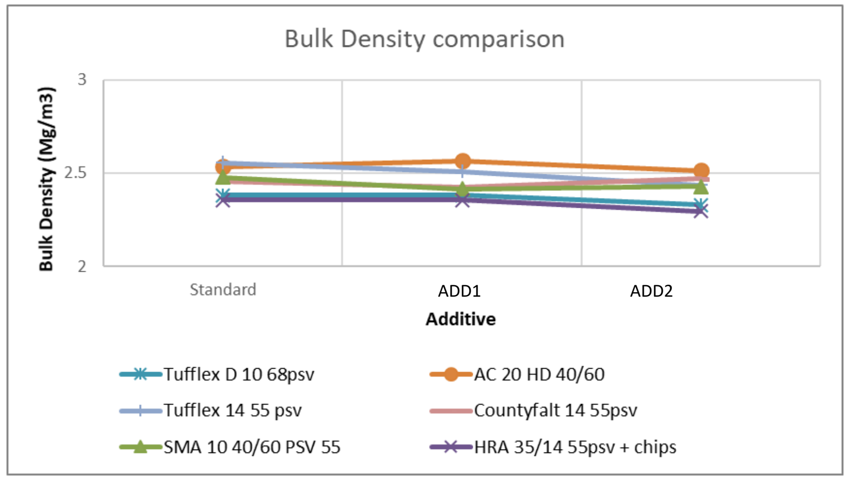
NOTES:

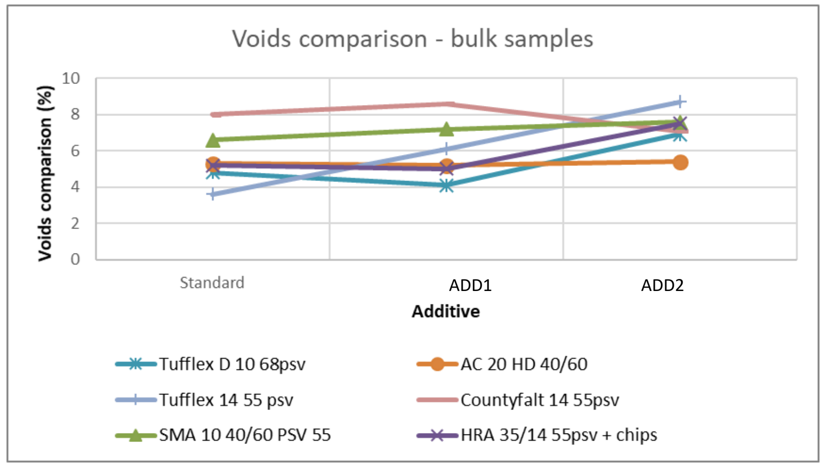
RD Denotes Rut Depth

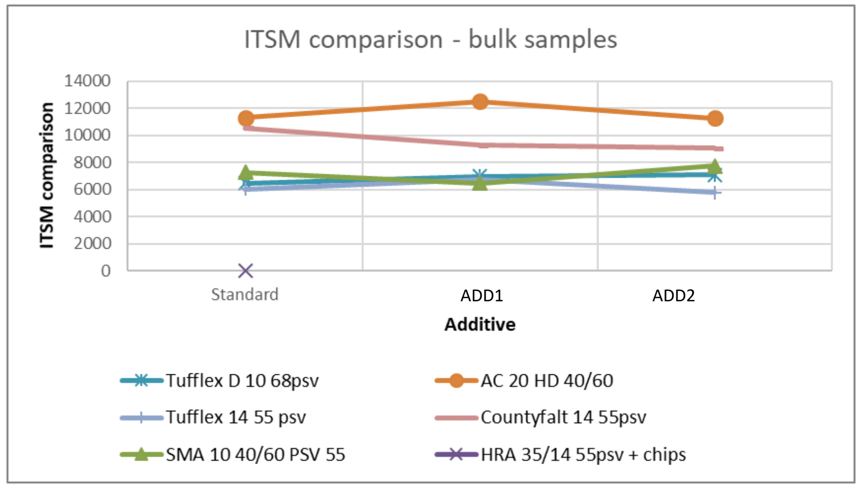
Appendix A.6 keepershield trial line graphs

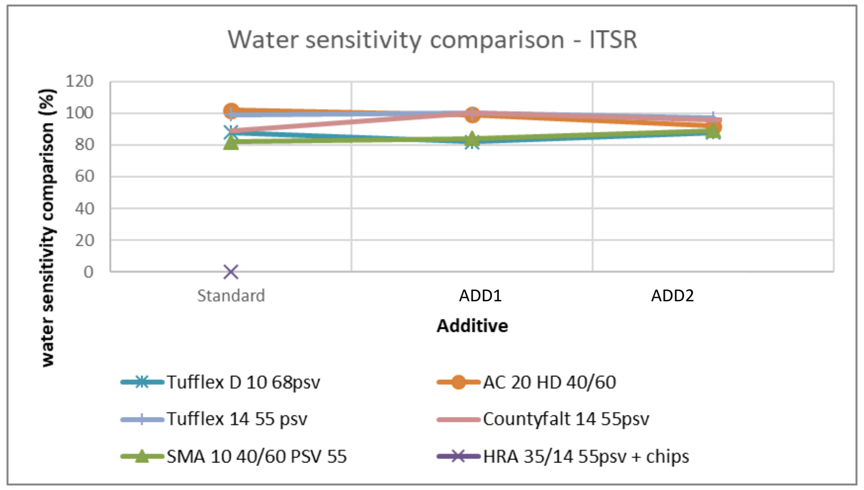


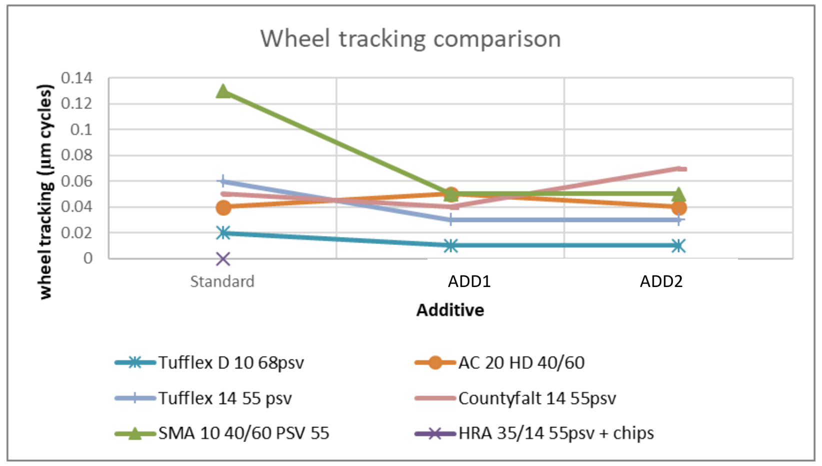


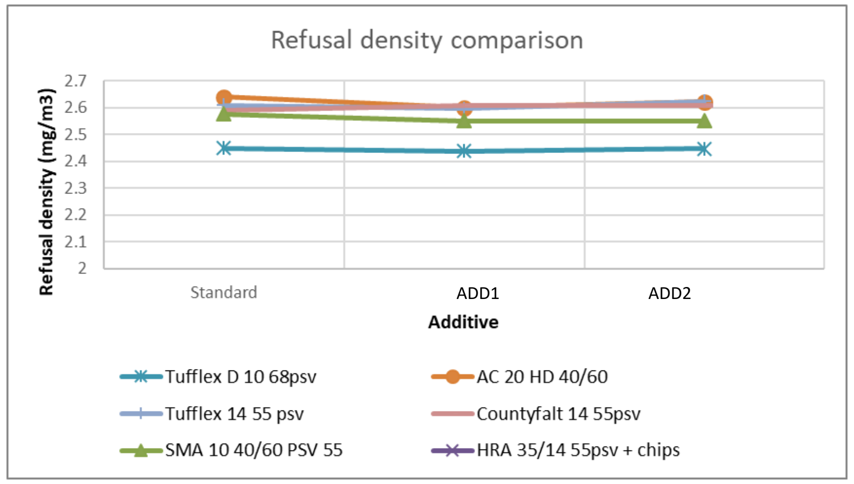


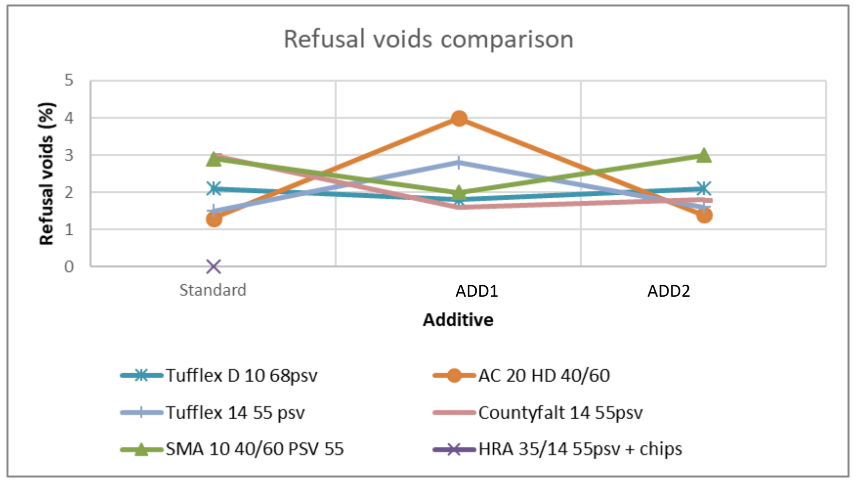


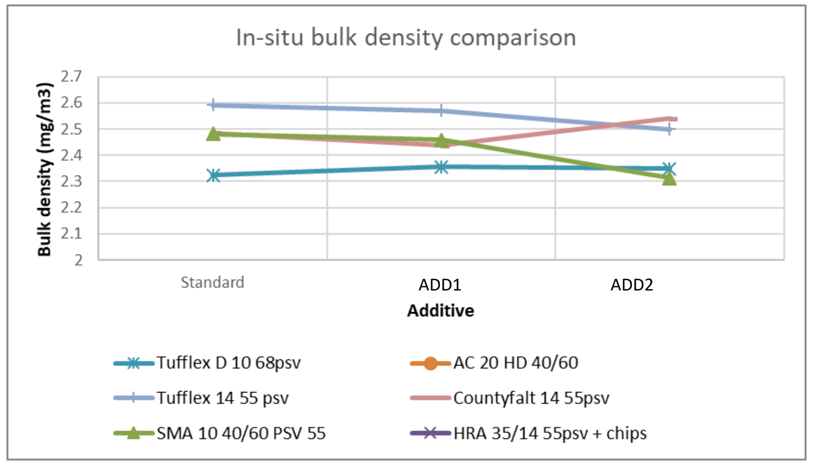


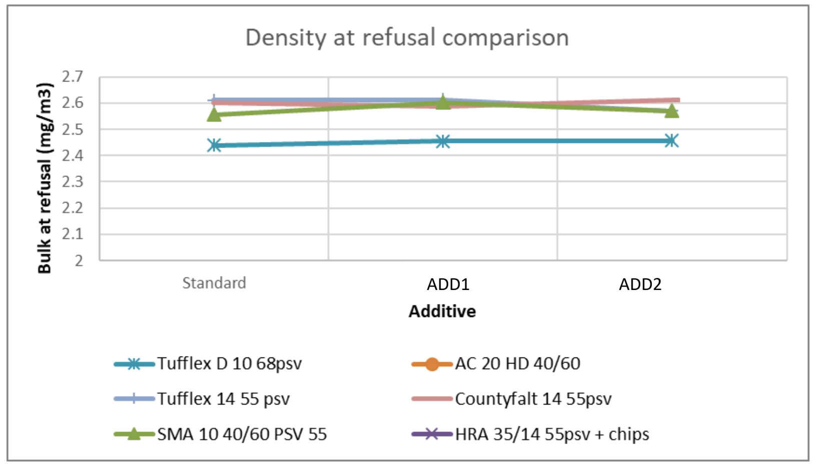


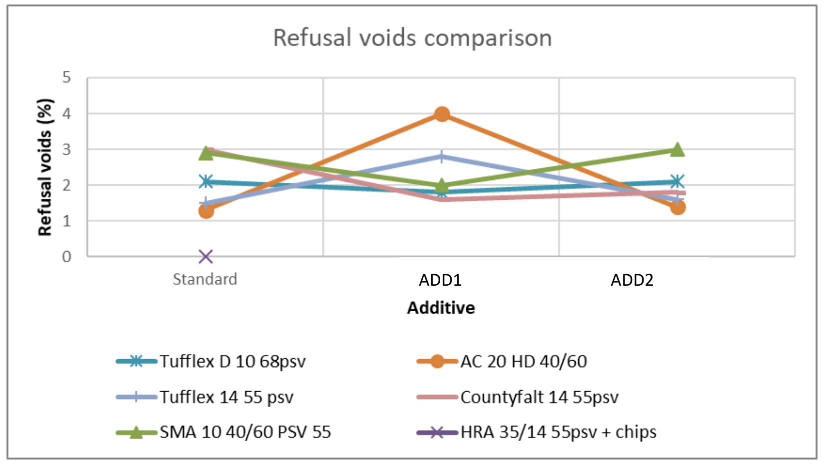


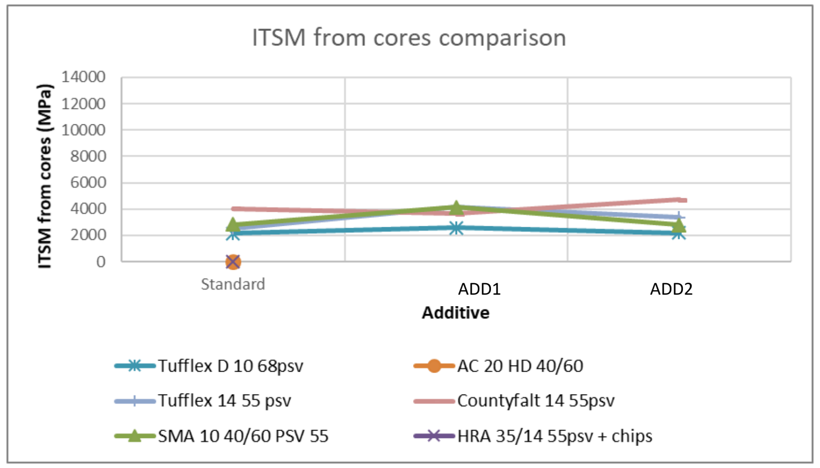


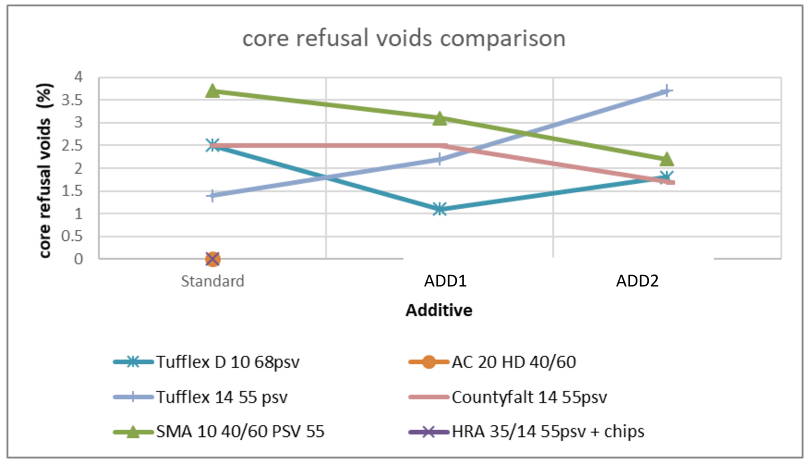


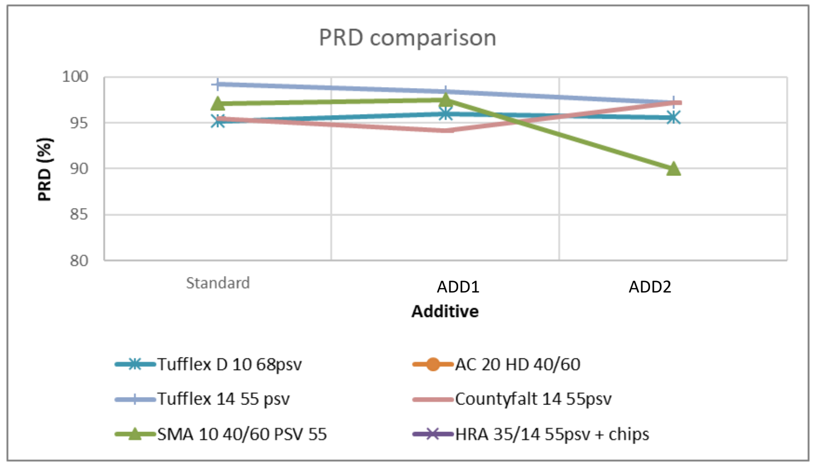

In-situ bulk density comparison
Bulk density (mg/m3)
2.7
2.6
2.5
2.4
2.3
2.2
2.1
2
Standard
ADD1
ADD2
Additive
Tufflex D 10 68psv
AC 20 HD 40/60
Tufflex 14 55 psv
Countyfalt 14 55psv
SMA 10 40/60 PSV 55
HRA 35/14 55psv + chips


Density at refusal comparison
Bulk at refusal (mg/m3)
2.7
2.6
2.5
2.4
2.3
2.2
2.1
2
Standard
ADD1
ADD2
Additive
Tufflex D 10 68psv
AC 20 HD 40/60
Tufflex 14 55 psv
Countyfalt 14 55psv
SMA 10 40/60 PSV 55
HRA 35/14 55psv + chips


Refusal voids comparison
Refusal voids (%)
5
4
3
2
1
0
Standard
ADD1
ADD2
Additive
Tufflex D 10 68psv
AC 20 HD 40/60
Tufflex 14 55 psv
Countyfalt 14 55psv
SMA 10 40/60 PSV 55
HRA 35/14 55psv + chips


ITSM from cores comparison
ITSM from cores (MPa)
14000
12000
10000
8000
6000
4000
2000
0
Standard
ADD1
ADD2
Additive
Tufflex D 10 68psv
AC 20 HD 40/60
Tufflex 14 55 psv
Countyfalt 14 55psv
SMA 10 40/60 PSV 55
HRA 35/14 55psv + chips


core refusal voids comparison
core refusal voids (%)
4
3.5
3
2.5
2
1.5
1
0.5
0
Standard
ADD1
ADD2
Additive
Tufflex D 10 68psv
AC 20 HD 40/60
Tufflex 14 55 psv
Countyfalt 14 55psv
SMA 10 40/60 PSV 55
HRA 35/14 55psv + chips


PRD comparison
PRD (%)
100
95
90
85
80
Standard
ADD1
ADD2
Additive
Tufflex D 10 68psv
AC 20 HD 40/60
Tufflex 14 55 psv
Countyfalt 14 55psv
SMA 10 40/60 PSV 55
HRA 35/14 55psv + chips

Appendix B

BINDER RHEOLOGY TESTS

Appendix B – Description of binder tests

Appendix B.1 Empirical Binder Tests

B1.1 *Penetration test*

The penetration test (BS EN 1426:2007) is used to measure the consistency (‘hardness’) of bitumen. This is done by expressing the distance, in tenths of a millimetre (decimillimetre), that a standard needle (specified dimensions) will penetrate vertically into a sample of bitumen under a load of 100g at a fixed temperature of 25°C for a loading duration of 5 seconds. The greater the penetration of the needle, the ‘softer’ the bitumen, and conversely the lower the value of penetration, the ‘harder’ the bitumen. This test is the basis upon which penetration grade bitumen is classified into standard penetration ranges. Other combinations of load, temperature and loading time may also be used, although meaningful comparison of the penetration of bitumen over a range of temperatures is only possible if the same load and loading times are used consistently. The penetration test can be considered as an indirect measurement of the viscosity of the bitumen at a temperature of 25°C.

B1.2 *Softening point test*

The ring-and-ball softening point test (BS EN 1427:2007) is an empirical test used to determine the consistency of bitumen by measuring the equiviscous temperature at which the consistency of the bitumen is between solid and liquid behaviour. Therefore, regardless of the grade of the bitumen, the consistency will be the same for different bitumens at their respective softening point temperatures. The American Society for Testing Materials (ASTM) also specifies a softening point test but unlike the BS EN 1427:2000 method no stirrer is used in the liquid bath and, consequently, the ASTM softening point is 1.5°C higher than the EN method.

The softening point test consists of placing a steel ball on a disc of bitumen contained within a brass ring and suspended in a water or glycerol bath. The temperature of the fluid bath is then raised at a constant rate of 5°C/min. The softening point is the temperature at which the bitumen softens enough to allow the ball enveloped in bitumen to fall a distance of 25 mm before hitting a base plate. The test is commonly referred to as the ring-and-ball test due to the components used in the test. Van der Poel (1954) showed that softening point is approximately the temperature at which penetration is 800. Hence the notation “T800PEN” is commonly used to describe softening point temperature.

B1.3 *Viscosity*

Viscosity is the measure of the resistance to flow of a liquid and is defined as the ratio between the applied shear stress and the rate of shear strain measured in units of Pascal seconds (Pa.s). It is a fundamental characteristic of bitumen and determines how the material will behave at a given temperature and over a temperature range. In addition to absolute or dynamic viscosity, viscosity can also be measured as kinematic viscosity in units of m^2/s or more commonly mm^2/s with 1 mm^2/s being equivalent to 1 centistoke (cSt).

The viscosity of bitumen can be measured with a variety of devices in terms of its absolute and kinematic viscosities. Specifications are generally based on a measure of absolute viscosity at 60°C and a minimum kinematic viscosity at 135°C using vacuum and atmospheric capillary tube viscometers respectively. Absolute viscosity can also be measured using a fundamental method known as the sliding plate viscometer. The sliding plate test monitors force and displacement on a thin layer of bitumen contained between parallel metal plates at varying combinations of temperature and loading time.

The rotational viscometer test (ASTM D4402-0216) is presently considered to be the most practical means of determining the viscosity of bitumen. The Brookfield rotational viscometer and Thermocel system allows the testing of bitumen over a wide range of temperatures (more so than most other viscosity measurement system). The operation of the rotational viscometer consists of one cylinder rotating coaxially inside a second (static) cylinder containing the bitumen sample all contained in a thermostatically controlled environment. The material between the inner cylinder and the outer cylinder (chamber) is therefore analogous to the thin bitumen film found in the sliding plate viscometer. The torque on the rotating cylinder or spindle is used to measure the relative resistance to rotation of the bitumen at a particular temperature and shear rate. The torque value is then altered by means of calibration factors to yield the viscosity of the bitumen.

Appendix B.2 Linear Viscoelastic Rheological Characterisation

Empirical tests, such as penetration and softening point, and even the more fundamental tests such as viscosity, do not provide a complete rheological characterisation of the bitumen as they do not quantify the time dependent response of the binder (Anderson et al., 1991). This has led to the use of dynamic mechanical methods using oscillatory-type testing to fully characterise the rheological properties of bitumen. These tests are generally conducted under linear viscoelastic (LVE) conditions where the rheological response of the bitumen can be considered to be independent of stress and strain level.

These advanced rheological tests are undertaken using dynamic shear rheometers (DSRs), which apply oscillating, sinusoidal shear stresses and strains to samples of bitumen sandwiched between parallel plates (Goodrich, 1988). The DSR tests are performed at different loading frequencies and temperatures. The sinusoidal stress and strain readings are then used to calculate various stiffness, viscosity and viscoelastic parameters that are used to build a complete picture of the rheological properties of the bitumen as a function of temperature and time of loading (or loading frequency).

The principal viscoelastic parameters that are obtained from the DSR are the complex shear modulus, G^*, and the phase angle, δ. G^* is defined as the ratio of maximum stress to maximum strain and provides a measure of the total resistance to deformation of the bitumen when subjected to loading. It contains elastic and viscous components which are designated as the storage modulus, G', and loss modulus, G'', respectively. These two components are related to the complex modulus and to each other through the phase (or loss) angle which is the phase, or time, lag between the applied shear stress and shear strain responses during a test. The phase angle is a measure of the viscoelastic balance of the bitumen behaviour. If δ equals 90° then the bituminous material can be considered to be purely viscous in nature, whereas δ of 0° corresponds to purely elastic behaviour. Between these two extremes the material behaviour can be considered to be viscoelastic in nature with a combination of viscous and elastic responses.

DSR testing of bitumen is standardised in Clause 928 of the UK Highways Agency Specification for Highways Works and in the AASHTO T 315-06 Standard. In general, two testing geometries are used with the DSR, namely 8 mm diameter parallel plates with a 2 mm testing gap and 25 mm diameter plates with a 1 mm testing gap. The selection of the testing geometry is based on the operational conditions with the 8 mm geometry generally being used at low temperatures (-5°C to 20°C) and the 25 mm geometry at intermediate to high temperatures (20°C to 80°C).

The DSR generated rheological results can be presented in several forms. The most common forms consist of isochronal plots (viscoelastic parameters versus temperature at constant frequency), isothermal plots (viscoelastic parameters versus frequency at constant temperature), master curves (several isothermal plots shifted along the frequency axis to produce a smooth curve) and Black Space diagrams (complex modulus against phase angle). The construction of master curves relies of the ability to shift rheological data through the equivalency between time and temperature (known as thermo-rheological simplicity) using a concept known as the time-temperature superposition principle (TTSP) (Ferry, 1980). The shifting of the data is usually done using a 25°C reference temperature with the application of the Williams-Landel-Ferry (WLF) model or an Arrhenius equation.

The form of the WLF equation is given in Equation 1.

$$\log a_T = -\frac{C_1\left(T - T_{Ref}\right)}{C_2 + \left(T - T_{Ref}\right)} \quad (1)$$

Where,

- aT is the shift factor at temperature T
- C_1 is an empirical parameter (coefficient) which is a function of the free volume
- C_2 is an empirical function of the free volume and is an indicator of the thermal dependency of the material
- T_{Ref} is the selected reference temperature
- T is the testing temperature

The form of the Arrhenius equation is given in Equation 2.

$$\log a_T = \frac{\Delta H_a}{2.303R}\left(\frac{1}{T} - \frac{1}{T_{Ref}}\right) \quad (2)$$

Where,

- ΔH_a is the activation energy, typically 250 kJ/mol T
- R is the universal gas constant (8.314 J/°K-mol)

Appendix B.3 Performance-related Tests

B3.1 *Linear Amplitude Sweep (LAS) Test*

The Linear Amplitude Sweep (LAS) test, undertaken according to the AASHTO TP101 standard, can be used to predict the intermediate temperature, fatigue resistance of conventional and modified bituminous binders. The LAS test method is undertaken to accelerate damage in bitumen samples and involves cyclic loading of these samples by subjecting them to increasing strain amplitudes. This leads to damage accumulation, which is used to assess fatigue performance in terms of the number of cycles required to failure (i.e., a decrease of the initial complex modulus (G*) value at the peak shear stress, as per AASHTO TP101).

The LAS test is conducted in a Dynamic Shear Rheometer (DSR) where bitumen samples of 8 mm diameter with a 2 mm thickness are tested in a strain-controlled mode using the DSR parallel plate geometry. Two test stages are carried out as follows: (1) The initial stage is non-destructive and involves assessing the undamaged linear viscoelastic (rheological) properties of the bitumen samples in terms of the complex modulus (G*) and phase angle (δ). This stage is done via a frequency sweep test (i.e., oscillatory loading from 0.2 Hz to 30 Hz at 0.1% strain amplitude). (2) The bitumen sample is then subjected to a rest period of 10s before the onset of the secondary stage. This secondary stage is destructive in nature where damage is induced through applying increasing strain amplitude loading cycles (from 1% to 30% strain) at a constant frequency of 10 Hz and is referred to as the continuous oscillatory strain sweep test.

In brief, the test parameters include: (1) loading cycles at 0.1% strain to obtain undamaged linear material response (parameter α representing the damage accumulation rate (energy release rate) determined within the linear viscoelastic (undamaged conditions) region), and (2) 30 subsequent rounds of 100 cycles from 1%-30% strain, increasing linearly by 1% strain, for a total of 3,000 cycles of loading (Hintz et al., 2011).

The LAS test data is then analysed according to viscoelastic continuum damage (VECD) mechanics, based on Schapery's theory, to simulate damage growth and thus predict fatigue life as a function of strain using Equation 3.

$$N_f = \frac{f(D_f)^k}{k(\pi C_1 C_2)^\alpha}(\gamma_{max})^{-2\alpha} \quad (3)$$

Where,

- $k = 1 + (1 - C_2)\alpha$
- f is the loading frequency, Hz (10 Hz for the amplitude sweep portion of the LAS test)
- γ_{max} is the maximum expected binder strain for a given pavement structure in %

- D_f is the damage accumulation at failure (damage intensity), defined as the *D(t)* corresponding to the reduction in initial $|G^*|$ at the peak shear stress (Equation 4)
- C_1 and C_2 are determined from the empirical equation of *C(t)* versus *D(t)* (Equation 10)
- α is the inverse of the slope of the isotherm of storage modulus obtained in the frequency sweep test. It is the exponent that determines the energy release rate (Equation 8).

Various failure criteria can be used to represent *D(f)* including a reduction of 35% in the initial viscous modulus. However, the most accepted failure criterion is defined as the *D(t)* corresponding to the reduction in initial |*G**| at the peak shear stress as represented by Equation 4.

$$D_f = \left(\frac{C_0 - C \ at \ peak \ stress}{C_1}\right)^{1/C_2} \tag{4}$$

Where,

- C_0, C_1 and C_2 are regression coefficients used to fit the model in Equation 10

Equation 3 is based on the simplified classic fatigue law (Equation 5) with *A* and *B* being obtained from the mathematical relationship between strain (γ) and cycles to failure (N_f) as shown in Equation 5.

$$N_f = A(\gamma_{max})^B \tag{5}$$

Coefficient *A* (Equation 6) represents the intercept with the y-axis of the fatigue law and depends on the material integrity versus the damage curve, and the criterion selected as failure (Equation 4). Coefficient *B* (Equation 7) is the slope of the Wohler curve and it is a function of parameter α, which depends on the time-temperature dependency of the material. A decrease in the time-temperature dependency of the material corresponds to a decrease in *B*.

$$A = \frac{f(D_f)^k}{k(\pi C_1 C_2)^\alpha} \tag{6}$$

$$B = -2\alpha \tag{7}$$

Parameter α is calculated from the frequency sweep data. Specifically, α represents the inverse of the slope (*m*) of the isotherm of the logarithm of the storage modulus versus the logarithms of the frequency. Parameter α is calculated using Equation 8.

$$\alpha = \frac{1}{m} \tag{8}$$

Where,

- *m* represents the slope of the isotherm curve log (*G'*) versus log (*f*).

Therefore *α* is a measure of the time-temperature dependency of the materials. With parameter *B* being a function of the parameter *α* only, it is also a function of the time-temperature dependency of the material.

The damage accumulation is calculated through Equation 9 by using the data from the strain-sweep test.

$$D(t_N) \cong \sum_{i=1}^{N} [\pi \cdot \gamma_0^2 (C_{i-1} - C_i)]^{\frac{\alpha}{1+\alpha}} (t_i - t_{i-1})^{\frac{1}{1+\alpha}} \tag{9}$$

Where,

- *C* represents the variation of the complex modulus (*G**) with damage expressed as the ratio of *G** at the i-cycle versus *G** at the initial conditions
- γ_0 is the strain applied at the i-cycle
- *t* is the time
- *α* is determined in Equation 8

The parameters C_1 and C_2 are determined from the empirical equation of *C(t)* versus *D(t)* in Equation 10.

$$C(t) = C_0 - C_1\big(D(t)\big)^{C_2} \tag{10}$$

Where,

- C_0 is the initial value of *C* ($C_0 = 1$)
- C_1 and C_2 are the curve-fitted coefficients derived from the linearization of the power-law form (Equation 10) in the form suggested by Hintz and co-workers (2011) given in Equation 11.

$$\log\big(C_0 - C(t)\big) = \log C_1 + C_2 \log\big(D(t)\big) \tag{11}$$

Finally, to minimize the risk of delamination (i.e., poor bitumen/plate bonding), caution needs to be taken to select the testing temperature.

The LAS test undertaken in this report according to AASHTO TP 101-14 was performed under the following test conditions:

- Test temperature - 20°C
- Frequency sweep – 0.2 to 30 Hz
- Applied strain level – 0.1%
- Amplitude sweep (continuous oscillatory strain sweep) – zero to 30%
- Loading frequency – 10 Hz
- Loading amplitude sweep duration – 300 seconds

The data generated from the LAS test was then analysed based on viscoelastic continuum damage (VECD) to determine the following key parameters:

- α – undamaged material parameter determined from the low strain oscillatory frequency sweep stage.
- *D(t)* – damage accumulation based on measurements of complex modulus (*G**) for the undamaged and damaged material and the unaged material parameter α.
- *C(t)* – material integrity determined as a ratio of material stiffness (*G*(t)*) to initial (undamaged) material stiffness ($G^*_{initial}$).
- C versus D relationship – fitted curve based on a power law relationship with *C* = 1 being unaged and *C* = 0 being fully damaged.
- D_f – damage accumulation at failure corresponding to C at peak stress in the stress versus strain plot.
- *A* & *B* – fatigue model parameters determined as functions of D_f, *C* material parameters and average α.
- N_f – binder or mastic fatigue (damage) performance parameter based on the power law function of *A* & *B* and determined as specific strain (γ) levels.

In this study, two strain levels were considered to take into account both 'strong' and 'weak' pavement structures. For a 'strong' layer with thickness higher than 100 mm, a low strain (γ = 2.5%) was selected. Similarly, for a 'weak' layer with thickness lower than 100 mm, a higher strain (γ = 5.0%) was considered.

B3.2 *Double-Edge Notched Tension (DENT) Test*

The Double Edge Notched Tension (DENT) test can be used to determine the fracture characteristics in the ductile state of the recovered binders following the Canadian Standard (Test Method LS-299). The DENT test is used to determine the ductile failure resistance under horizontal tensile load application, at a specified temperature. The test is used to calculate the essential work of fracture (w_e), plastic work of fracture (w_p), and the approximated critical crack-tip opening displacement (CTOD). The test consists of performing a ductile fracture test on binder samples that have been conditioned in a water bath (submerged 25mm below water surface) at the target test temperature (20°C for this study) for 180 minutes.

The test is performed on similar specimens with different ligament lengths (i.e. 5, 10, and 15 mm). The total work of fracture W_T is obtained by measuring the area under the force-displacement curve. The total specific work of fracture is then calculated by dividing the later by the ligament cross-sectional area (*l* x *B*). The load is applied at a deformation rate of 50 mm/min until the samples reached ductile failure as shown in Figure 2. During testing, data of the elongation length (in mm), and force (in Newtons) is recorded and subsequently analysed to determine the fracture parameters (i.e., w_e, w_p and CTOD).

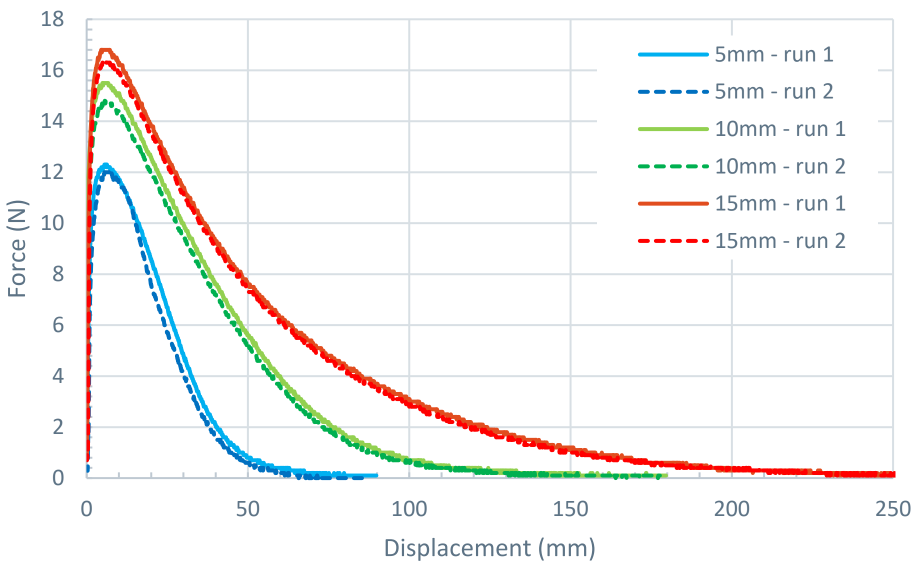


Figure 2: Force versus displacement curves at different ligament lengths

Calculation of fracture properties include: (1) the total work of fracture (W_T), which refers to the area under the load versus load-line displacement curve, kJ (Equation 12); (2) the specific total work of fracture (w_t), related to each replicate sample tested, kJ/m^2 (Equation 13); (3) the specific essential work of fracture (w_e), the energy required to fracture or break the sample without plastic deformation away from the fracture zone, kJ/m^2; (4) the specific plastic work of fracture (w_p), the non-essential work dissipated during the deformation of a volume of bitumen around the fracture zone, MJ/m^3; (5) the geometric constant of the plastic zone (β), and (6) the critical tip opening displacement (CTOD), mm (Equations 14 and 15).

$$W_T = \int_0^{t_f} P \times d \qquad (12)$$

Where,

- *P* is the load in Newtons,
- *d* is the displacement in the test in m,
- t_f is the time when the maximum stroke is reached or ductile failure, whichever is attained first.

$$w_t = \frac{(average\ W_T)}{(B \times l)} \tag{13}$$

Where,

- *B* is the sample thickness in m, and
- *l* is the ligament length (the space between the notches) in m.

$$\text{CTOD} = \frac{w_e}{\sigma_n} \tag{14}$$

Where,

- σ_n is the net section stress of specimen in N/m^2, calculated using Equation 15.

$$\sigma_n = \frac{P_{peak}}{(B \times l)} \tag{15}$$

Where,

- P_{peak} is the average peak load of the specimen tested with the smallest ligament length (i.e., the average maximum load for the 5 mm ligament specimens).

The relationship between net section stress and ligament length is shown in Figure 3.

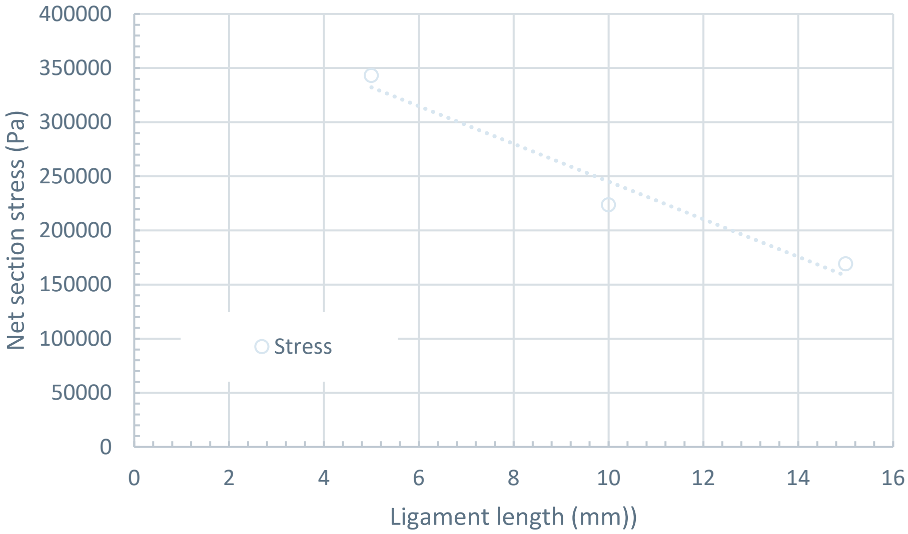


Figure 3: Net section stress as a function of ligament length

Determination of w_e and βw_p is done graphically by plotting w_t for the three ligament lengths as shown in Figure 4. w_e refers to the specific essential work of fracture (i.e., w_t value when l = 0.0) and βw_p is the slope of the best fit straight line (for $w_t = w_e + \beta w_p l$).

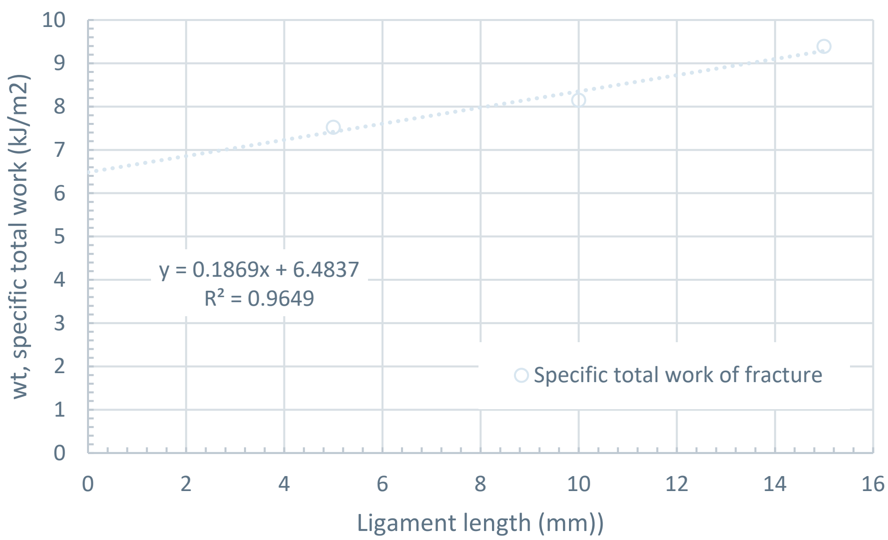


Figure 4: Graphical determination of the essential and plastic works of fracture

B3.3 *Multiple Stress Creep Recovery (MSCR) Test*

The MSCR test can be used to determine the permanent deformation susceptibility of the recovered binders using a DSR parallel-plate geometry with a spindle diameter of 25 mm and 1 mm testing gap. The test follows the AASHTO TP 70 Standard method by subjecting each sample to 10 cycles of creep-recovery loading at two stress levels (0.1 kPa and 3.2 kPa). The MSCR test consists of initially applying a 1 second creep load which is subsequently released for 9 seconds. The recorded data is then analysed in terms of the % recovery (*R*-Value), the non-recoverable creep compliance (J_{nr}), and the stress sensitivity parameter ($J_{nr\text{-}diff}$). The *R*-value refers to the ability of bitumen to recover (dissipate stresses) after repeated loading and higher values reflect better material response in terms of permanent deformation. The J_{nr} is an indicator of permanent deformation resistance that for higher values indicates a higher susceptibility to rutting distress of a given bitumen. The $J_{nr\text{-}diff}$ is used to distinguish the stress sensitivity of the bitumen due to the change of low stress (0.1 kPa) to high stress (3.2 kPa) conditions. Higher values for this parameter indicate higher sensitivity to the change in the loading stress to which the bitumen is subjected to.

As the MSCR test has been designed to determine not only the permanent deformation (strain) under creep loading and recovery but also the elastic response of the material, a series of parameters can be produced from the MSCR test data. These include recovery and compliance measurements at the two stress levels as detailed below:

- $R_{0.1}$ – average percentage recovery for the 10 load and recovery cycles at 0.1 kPa applied creep stress.
- $R_{3.2}$ – average percentage recovery for the 10 load and recovery cycles at 3.2 kPa applied creep stress.
- $J_{nr0.1}$ - average non-recoverable creep compliance for the 10 load and recovery cycles at 0.1 kPa applied creep stress.
- $J_{nr3.2}$ - average non-recoverable creep compliance for the 10 load and recovery cycles at 3.2 kPa applied creep stress.
- R_{diff} – percentage difference in recovery between 0.1 kPa and 3.2 kPa.
- $J_{nr\text{-}diff}$ – percentage difference in nonrecoverable creep compliance between 0.1 kPa and 3.2 kPa.

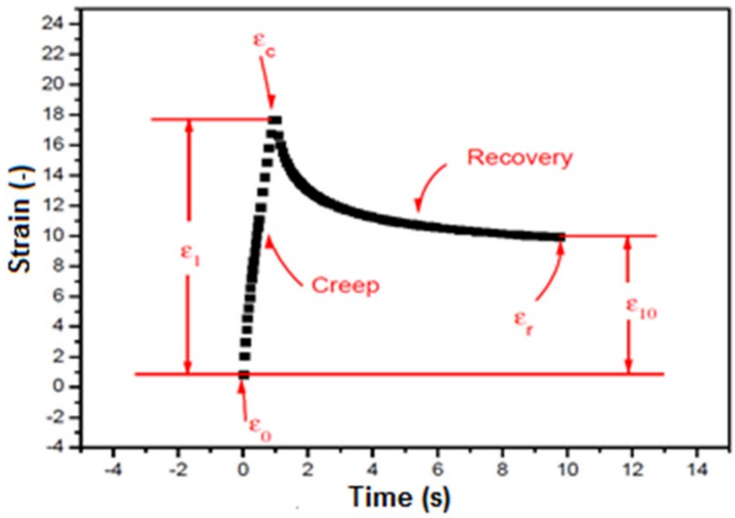


Figure 5: Typical schematic of creep and recovery for one cycle in the MSCR test

A typical one cycle of creep and recovery is shown in Figure 5 with the following definitions of the terms:

- ε_0 is the strain value at the beginning of the creep portion of the n-cycle
- ε_c is the strain value at the end of the creep portion of the n-cycle
- ε_r is the strain value at the end of the recovery portion of the n-cycle
- ε_1 ($\varepsilon_1 = \varepsilon_c - \varepsilon_0$) is the adjusted strain at the beginning of the creep portion of the n-cycle
- ε_{10} ($\varepsilon_{10} = \varepsilon_r - \varepsilon_0$) is the adjusted strain at the end of the creep portion of the n-cycle

Equations as per standard can then be used to calculate the parameters for both stress conditions (0.1 kPa and 3.2 kPa). Considering the definition of the terms, the non-recoverable compliance is calculated at the n-loading cycle using Equation 16, while average percent recovery *R* is calculated at each loading cycle using Equation 17.

$$J_{nr}^{n}(kPa^{-1}) = \frac{\varepsilon_r^n - \varepsilon_0^n}{\tau_0} \quad (16)$$

$$R(\%) = \frac{\varepsilon_c^n - \varepsilon_r^n}{\varepsilon_c^n - \varepsilon_0^n} \quad (17)$$

The average values of Jnr and R are calculated per each stress level (i.e., 0.1 and 3.2 kPa) according to Equations 18 and 19 for the non-recoverable compliance;

$$J_{nr0.1}(kPa^{-1}) = \frac{\sum_{n=1}^{10} J_{nr0.1}^{n}}{10} \quad (18)$$

$$J_{nr3.2}(kPa^{-1}) = \frac{\sum_{n=1}^{10} J_{nr3.2}^{n}}{10} \quad (19)$$

And according to Equations 20 and 21 for the average percent recovery R.

$$R_{0.1}(\%) = \frac{\sum_{n=1}^{10} R_{0.1}}{10} \quad (20)$$

$$R_{3.2}(\%) = \frac{\sum_{n=1}^{10} R_{3.2}}{10} \quad (21)$$

The stress sensitivity of the bitumen is calculated using Equation 22.

$$J_{nr-diff}(\%) = \frac{[J_{nr3.2} - J_{nr0.1}] \times 100}{J_{nr0.1}} \quad (22)$$

The stress sensitivity is expressed as the ratio between the differences in the J_{nr} at the two stress levels versus the J_{nr} at the lowest stress level considered in the test.

The high temperature permanent deformation properties of the recovered binders were determined using the MSCR test according to AASHTO TP 70-13 under the following test conditions:

- Test temperature - 60°C
- Creep loading stresses – 0.1 kPa and 3.2 kPa
- Loading time – 1 second
- Recovery (unloading) time – 9 seconds
- Repeated creep loading and recovery cycles per stress level – 10 cycles

B3.4 *Bending Beam Rheometer (BBR)*

The low-temperature rheological properties of the recovered binders were studied by means of the Bending Beam Rheometer (BBR) in accordance with the AASHTO T313-12 Standard. The test method involves the application of a 980 mN load to the beam specimen during 240 seconds of loading using the three-point-bending approach. During the loading period, the low-temperature creep stiffness (S) and relaxation properties (m-values) are recorded at 60 seconds and later analysed for assessing the temperature effects and determination of critical low-temperature values ($T_{c(S)}$ and $T_{c(m)}$) and the differential of these values (ΔT_c). Since a higher creep stiffness value indicates higher thermal stresses, a maximum creep stiffness value (300 MPa) is specified to determine $T_{c(S)}$, while a lower m-value indicates a lesser ability to relax stresses and therefore a minimum m-value (0.300) is specified to determine $T_{c(m)}$. The ΔT_c value targets cracking behaviour that is affected by binder durability related to ageing of the binder in the asphalt mixture. More specifically, ΔT_c provides insight into the relaxation properties of a binder that can contribute to non-load related cracking or other age-related embrittlement distresses in an asphalt pavement.

The measured stiffness is calculated using the loading, deflection values and geometrical features of the manufactured binder beams using standard beam theory. The estimated stiffness was calculated as indicated from a mathematical fitting of the data. The m-value refers to the slope of the relationship between the logarithmic of measured stiffness and is obtained at the logarithm of time for the total of 240 seconds of loading.

The relatively short loading time of 60 s is used in the BBR test as this can be related through time-temperature superposition to a more realistic pavement loading time of 2 hours by simply decreasing the determined limiting stiffness temperature by 10°C. The critical low-temperatures can therefore be calculated using Equations 23 and 24 which interpolate $T_{c(S)}$ and $T_{c(m)}$.

$$T_{c,S} = T_1 + \left(\frac{(T_1 - T_2) \times (\log 300 - \log S_1)}{\log S_1 - \log S_2}\right) - 10 \qquad (23)$$

$$T_{c,m} = T_1 + \left(\frac{(T_1 - T_2) \times (0.300 - m_1)}{m_1 - m_2}\right) - 10 \qquad (24)$$

Where,

- S_1 is the creep stiffness at T_1 (MPa)
- S_2 is the creep stiffness at T_2 (MPa)
- m_1 is the creep rate at T_1
- m_2 is the creep rate at T_2
- T_1 is the temperature at which S and m passes (°C)
- T_2 is the temperature at which S and m fails(°C)

Equation 25 can then be used to determine ΔT_c.

$$\Delta T_c = T_{c,S} - T_{c,m} \qquad (25)$$

The sign of ΔT_c, either positive or negative, indicates whether the performance grade of the binder is governed by its creep stiffness S ($+\Delta T_c$) or creep rate m ($-\Delta T_c$). The absolute magnitude of ΔT_c indicates the degree to which the binder is governed by either creep stiffness or creep rate. Values of -5°C would indicate potential durability cracking issues.

The low temperature properties and specifically the ability to resist low temperature cracking of the different materials were determined using the bending beam rheometer (BBR) test based on the AASHTO T 313 standard under the following test conditions:

- Test temperatures – 6°C, -12°C & -18°C
- Applied constant load – 100 g or 0.98 N
- Loading times – 8, 15, 30, 60, 120 and 240 s

The key parameters obtained from the BBR are:

- S(t) – creep stiffness usually determined at a loading time of 60 s (Pa).
- m-value – slope of the master stiffness curve at a loading time of 60 s.

Amber Court
William Armstrong Drive
Newcastle upon Tyne
NE4 7YQ

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