FINAL REPORT

Climate Resilient Sustainable Road Surfacings

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Author(s)	Dr Michael Burrow Dr Esdras Ngezahayo Dr Gurmel Ghataora Professor Nicole Metje Dr Mehran Eskandari Torbaghan Professor Ratnasamy Muniandy Dr Theuns Henning Dr Carl Wheldon Dr William Avis Mrs Susanna Zamataro Ms Karen Packham
Lead contact	Dr Michael Burrow
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Abstract	

One or several simultaneous changes in climate conditions, such as hotter seasons, extreme precipitation events, increasing severe storms and/or sea level rise, could severely affect roads in low-income countries (LICs). Failing to account for such impacts in future road design, maintenance and operating planning and protocols could result in accelerated road deterioration and increased risk of damage, traffic disruption and accidents, with knock-on effects on economies.

The aim of the Climate Resilient Sustainable Road Pavement Surfacing (CRISPS) project was to assess the engineering and economic suitability of three global best practice types of road surfacing technologies for use in LICs to counter the impacts of climate change. These technologies are modified epoxy chip seals (MECS), modified epoxy asphalt surfaces (MEAS) and Fibre mastic asphalt (FMA).

Keywords	Life cycle analysis, highway development and management model (HDM-4), asphalt concrete (AC), double bituminous surface treatment (DBST), modified epoxy chip seals (MECS), modified epoxy asphalt surfaces (MEAS), fibre mastic asphalt (FMA), pavement deterioration, fast neutron activation analysis (FNAA), Fourier-transform infrared spectroscopy (FTIR).
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ABBREVIATIONS/ACRONYMS

AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
AC	asphalt concrete
ACO	asphalt concrete overlay
AMBG	asphalt mixes on granular base
ASCE	American Society of Civil Engineers
BRITA	Belt and Road International Transport Alliance
CAPTIF	Canterbury Accelerated Pavement Testing Indoor Facility
CCWS	cross-cutting work stream
CRISPS	Climate Resilient Sustainable Road Pavement Surfacing
CS	compound standards of maintenance
DBST	double bituminous surface treatment
EBRI	Energy and Bioproducts Research Institute
EMOGPA	epoxy modified open graded porous asphalt
ERA	Ethiopian Roads Administration
FMA	fibre mastic asphalt
FMAO	fibre mastic asphalt overlay
FNAA	fast neutron activation analysis
FTIR	Fourier transform infrared spectroscopy
HDM-4	Highway Development and Management Model Four
HT	high traffic
HVT	High Volume Transport
IAA	Impact Acceleration Account
IRF	International Road Federation (Geneva)
IRI	international roughness index
IRI_{av}	average international roughness index
K_{cia}	calibration factor for cracking initiation
K_{cpa}	calibration factor for cracking progression
K_{gm}	calibration factor for roughness progression (environmental)
K_{gp}	calibration factor for roughness progression (general)
K_{rp}	calibration factor for rutting progression
LCA	life cycle analysis
LIC	low-income country
LT	low traffic
LTPP	Long-Term Pavement Performance (LTPP)

MEAS	modified epoxy asphalt surfaces
MECS	modified epoxy chip seals
MESA	million equivalent standard axles
MSA	million standard axles
MSc	Master of Science
MT	medium traffic
NPV	net present value
NZ	New Zealand
NZTA	New Zealand Transport Agency
OECD	Organisation for Economic Co-operation and Development
OGPA	open graded porous asphalt
PIARC	Permanent International Association of Road Congresses
QC	quality control
R&R	routine and reactive maintenance
RAC	road agency costs
RAMM	Road Assessment and Maintenance Management
RD	road deterioration
RM	Malaysian ringgits
RUC	road user costs
RUE	road user effects
RWE	road works effects
SA	semi-arid
SARF	South African Roads Federation
SEE	socio-economic and environmental effects
SH	sub-humid
SNP	modified structural number
T2	technology transfer
TH	tropical humid
TRB	Transport Research Board
UK	United Kingdom (of Great Britain and Northern Ireland)
UoA	University of Auckland
UoB	University of Birmingham
UPM	Universitas Putra Malaysia
VOC	vehicle operating costs
WS	work stream

1. EXECUTIVE SUMMARY

This project has addressed the High Volume Transport (HVT) Theme 1 (Strategic Road and Rail), Principal research area 1: Affordable high-volume roads resilient to climate change and traffic demands and the research question: "How could new ways of designing, and building roads using new standards and marginal materials deliver low maintenance resilient roads economically?"

In particular, the project assessed whether three global best practice types of road surfacing technologies can provide low maintenance, climate resilient roads economically in Low Income Countries (LICs). The technologies considered are Modified Epoxy Chip Seals (MECS), Modified Epoxy Asphalt Surfaces (MEAS) and Fibre Mastic Asphalt (FMA). These technologies have been developed through many years of research in New Zealand (MECS and MEAS) and Malaysia (FMA). Their in-situ performance in these countries has been demonstrated through trials and they are now used in service.

In this project, Ethiopia as a LIC was selected for the constructability of trial sections. This choice was essentially based on the following reasons:

- Ethiopia's strategic road network is subject to a variety of environments and traffic levels which can be representative of many LICs.
- An assessment of potential partner countries in Part 1 of the HVT programme found that Ethiopia was ranked in the top three LICs in Sub-Saharan Africa and was well placed to support and benefit from Part 2 research.
- The University of Birmingham's (UoB) Roads Group has established close research links with the Ethiopian Roads Administration (ERA) over several years, including undertaking a five-year research and capacity building programme for ERA to improve the resilience of Ethiopia's roads and, ERA agreed to support the constructability trials in its letter supporting the UoB's project application

The project demonstrated the engineering and economic suitability of the three technologies for the range of traffic and environmental conditions typically seen in Ethiopia and in other LICs currently and predicted to occur in the future as a result of climate change. These conditions were considered for both high-volume and medium volume roads. This was done through the following work streams and an individual report was produced for each of the work streams:

- The development of deterioration models for different surfacing technologies, which showed that generally, MEAS, MECS and FMA deteriorate less due to traffic loadings and environmental stresses.
- Development of anti-fraud and quality control systems, which proved that FTIR is an efficient, reliable, available and cost-effective method for anti-fraud when constructing epoxy modified road surfacings in LICs.
- A life cycle analysis modelling approach, which showed that MEAS, MECS, FMA could have significant engineering and economic benefits in the long term when compared to existing surfacing (AC, DBST).
- Constructability of the technologies in Ethiopia, which showed that design of trials for better monitoring and comparisons is possible, irrespective of several challenges that could manifest on field. Successful designs also showed that it is possible to utilise alternative materials and construction methods to achieve more resilient roads and reduce road maintenance burdens and associated costs from road agencies in LIS.

Another important and complimentary aspect of the project was to ensure research uptake and capacity building. This was addressed via a strategy associated with ensuring suitable communications, dissemination and skills transfer. The research was communicated to the public through the University of Birmingham's press channels, IRF's website, ASCE's website, World Highways and others. Three journal papers and two conference papers have been prepared or published, five webinars undertaken, six reading packs and two newsletters produced. A workshop was undertaken in Ethiopia for capacity building and a policy dialogue conducted with stakeholders for research impact acceleration. Two PhD research projects, both from ERA staffs, on related topics contributed to the project, at least 15 MSc projects were given to students, and the findings of the research have been integrated in the teaching materials for the MSc REM at the University of Birmingham in the UK, for the MSc in Transportation Engineering at the University of Auckland in New Zealand, and for the undergraduate in Civil Engineering at the Universiti Putra Malaysia in Malaysia.

The successes of the project are a result of immeasurable commitment and dedication from researchers at the University of Birmingham, researchers at the University of Auckland and the researchers at the University Putra Malaysia. Experts in global knowledge transfer from IRF Geneva and engineers from the Ethiopian Roads Administration made tremendous contributions to the project. All these knowledgeable and dedicated people were again supported and guided by an independent Steering Group of five global experts in road development and maintenance related fields, including the use of the trialled surfacing technologies and long-life pavements.

2. Introduction

2.1 Background to the study

One or more simultaneous changes in climate – for example warmer temperatures, increasingly extreme precipitation events and/or sea level rise – could severely affect road pavement performance in the future, in particular in low-income countries (LICs). Failure to account for such impacts in future road design, maintenance and operations planning could cause accelerated road deterioration and higher road use costs, thereby severely constraining socio-economic development.

In addition to the impact of climate change, the material used for road construction and particularly for road surfacing, plays a key role in ensuring sustainability of the road. Having the right types of materials and the correct mix design of materials for road surfacing is vital as this has a significant impact on road performance, which can be evaluated by determining the performance of the combined materials. Making wrong choices for road surfacing materials and using inappropriate mix design of these materials in road construction can lead to faster surface deterioration, which will cause higher maintenance costs and higher lifecycle costs. It will also increase costs for road users and have an environmental impact.

Long life epoxy road surfacing technologies (i.e. MECS and MEAS) and fibre reinforced asphalt (e.g. FMA) investigated in this project have been used worldwide over a number of years (1). In New Zealand the former two surfacings (the latter of them in the form of Epoxy Modified Open Graded Porous Asphalt (EMOGPA)) are now in routine use (2; 3; 4), as is FMA in Malaysia (5; 6).

The climate resilience of the surfacings has been reported extensively elsewhere (e.g. (1; 2; 3; 4; 5; 6). EMOGPA was developed to reduce age related embrittlement, specifically that due to oxidation (7) and porous asphalts in general and MECS in particular, have been found to reduce the potentially destabilising impact of increased water pressure on the road surface under wheel loads, compared to impermeable surfaces (the so called water hammer effect) (8; 9). Epoxy modified asphalts were developed to perform in very high temperature environments i.e. for military airport pavements (2). The successful in-situ performance of these technologies worldwide has nourished the idea of investigating their LCA performance in LICs of Africa and Asia to facilitate economic development.

3. Study overview

This section gives an overview of the CRISPS project leading to the study deliverables presented in this report. These deliverables are:

- Project reports.
- Deterioration models of the three technologies.
- Life cycle analysis of the technologies.
- A system to prevent fraud.
- Field application trials in Ethiopia of the modified epoxy chip seals (MECS) and fibre mastic asphalt (FMA) technologies.
- Research uptake and capacity building activities, including:
    - Webinars.
    - Laboratory construction procedures and guidelines.
    - A workshop in Ethiopia.
    - Policy dialogue.
    - Project video.
    - Peer reviewed publications.
    - Embedding the project's findings in academic curricula.
    - PhD and MSc projects.

The study comprised four work streams (WS) to demonstrate the engineering and economic suitability of three global best-practice road surfacing technologies for low-income countries (LICs) and research uptake and capacity building (see Figure 1).

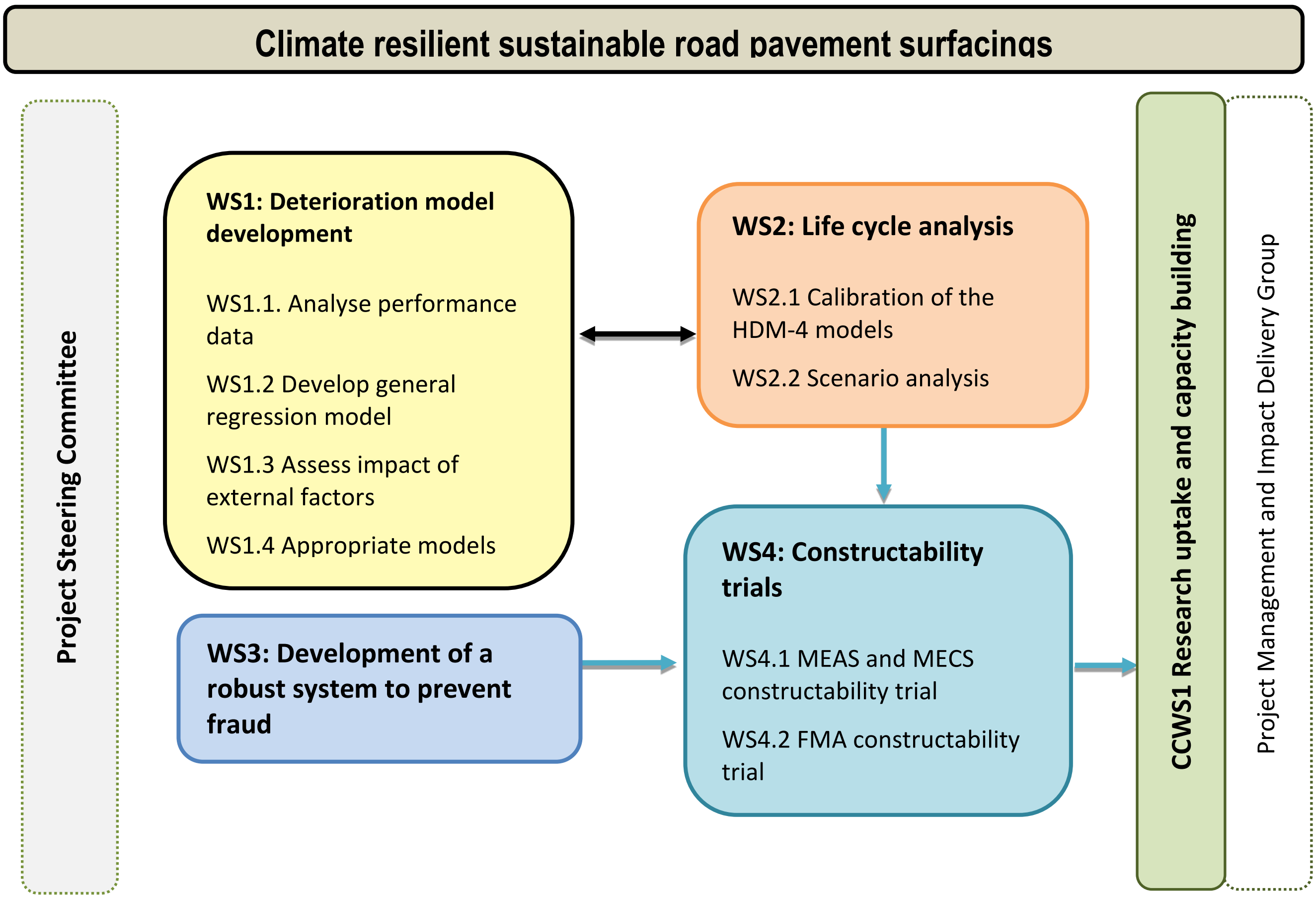

Figure 1. Project work streams

CCWS1: cross-cutting work stream; FMA: fibre mastic asphalt; HDM-4: Highway Development and Management Model Four; MEAS: modified epoxy asphalt surfaces; MECS: modified epoxy chip seals; WS: work stream

3.1 Deterioration model development

The purpose of the deterioration model development (WS1) was to prepare models to be used for the life cycle analysis (LCA) aspect of the project (WS2). Since the Highway Development and Management (HDM-4) economic model was used for the LCA work, the deterioration model development consisted of developing calibrated HDM-4 models and procedures.

The in-situ performance of modified epoxy surfacings, i.e. modified epoxy chip seals (MECS) and modified epoxy asphalt surfaces (MEAS), and fibre mastic asphalt (FMA), has been demonstrated through laboratory and trials in New Zealand and Malaysia respectively. Both are now used routinely in service in the respective countries. However, there are currently no trial or in-service data available for the surfacings in Ethiopia.

The approach for the two epoxy surfacings utilised the datasets in New Zealand (NZ) to compare the performance of traditional asphalt and epoxy modified surfaces and extrapolate the results to Ethiopia. This approach is summarised in Figure 2. The NZ datasets included Long-Term Pavement Performance (LTPP) and network datasets and results from laboratory studies, shown in yellow in Figure 2. These contain approximately 20 years of data, representing different traffic loadings and climatic regions within NZ, and were used to determine the HDM-4 calibration factors for NZ surfaces using traditional bitumen.

By scrutinising the data, the relative performance in NZ of the modified epoxy surfacings compared with the performance of traditional surfacings in NZ was determined. This resulted in multiplication factors that could be used to calibrate the default HDM-4 distress models so that they matched the actual NZ performance of the modified epoxy surfacings. Separately, using data about the performance of traditional surfacings in Ethiopian conditions, the default HDM-4 distress models were calibrated to match the Ethiopian performance of the traditional surfacings. Then, the multiplication factors developed for the NZ datasets were applied to the calibrated HDM-4 distress models of traditional surfacings in Ethiopian conditions, enabling calibrated HDM-4 models to be obtained that matched the behaviour, in Ethiopian conditions, of the modified epoxy surfacings.

In the same time, the deterioration modelling was undertaken by the UPM and followed the mechanistic approach using KENLAYER software as described (10)

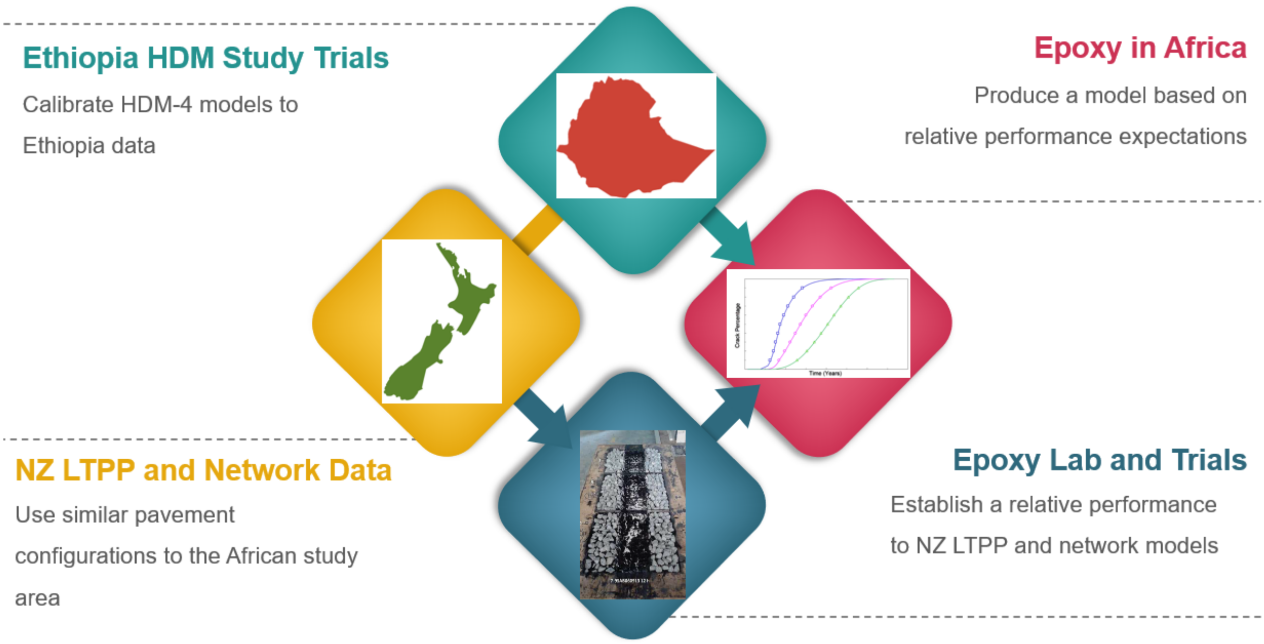

Figure 2. Approach to model development and calibration

3.2 Life cycle analysis

The purpose of the research project is to provide strategists and decision makers in LICs with information on the appropriateness of MEAS, MECS and FMA. To this end, the LCA assessed and compared, at the strategic level of road management, the benefits of MEAS, MECS and FMA compared with conventional road surfacings under a variety of conditions in a LIC. These costs and benefits are associated with road agency costs (i.e. construction costs and frequency of periodic maintenance) and road user costs (primarily vehicle operation costs and travel time costs). The conditions considered included the deleterious impacts of traffic overloading and the effects of climate, budget constraints, poor construction and corruption.

The LCA work undertaken compares the performance of conventional road surfacings and overlays used routinely in Ethiopia for high and medium volume trafficked roads (i.e. asphalt concrete [AC] and double bituminous surface treatment [DBST] with MEAS, MECS and FMA). Because of the large number of potential circumstances that could affect the outcomes of the LCA, the work focused on developing an approach that can be used to demonstrate the viability of MEAS, MECS and FMA under conditions of primary importance in any such analysis. Accordingly, the aim of LCA was to provide an approach that could be followed and tailored to the needs of any road organisation, rather than an exhaustive approach that considered all possible circumstances that may occur in Ethiopia.

To accomplish this work, the World Bank's de facto standard for road investment appraisal, HDM-4, was used. Specifically, HDM-4's project and strategic analysis functions were used to enable long-term strategic analyses of new and existing road network performance as a function of road construction type and quality, maintenance standards, traffic levels and environments. Using the findings from the development of deterioration models (see section 3.1), the modules within HDM-4 were configurated and calibrated using the findings from the development of the deterioration models and data provided by the Ethiopian Roads Administration (ERA).

A summary of the findings of the LCA work carried out in the project is provided in section 4.2. A complete description of the work undertaken is provided in the WS2 project report "Life Cycle Analysis" (11).

3.3 A robust system to prevent fraud

The two epoxy modified technologies (MEAS and MECS) require precise mix-designs incorporating a variety of materials. The deviation from these designs reduces the performance of the technologies. To address this, a quality control (QC) methodology and framework was developed for the material and methods associated with constructing roads using epoxy bitumen. The framework includes methodologies for assessing the concentration of epoxy materials and post-construction techniques to assess the quality of construction. By adopting the proposed framework, higher durability and hence lower life cycle cost can be achieved for the epoxy bitumen road surfacings.

The Fourier transform infrared spectroscopy (FTIR) method is a standard approach for assessing bitumen content and was further evaluated for determining epoxy bitumen content. An alternative approach, which utilises fast neutron activation analysis (FNAA), was developed using the University of Birmingham's (UoB's) MC40 cyclotron and the results compared with the FTIR approach.

3.4 Constructability trials

The constructability of trials took place in Ethiopia. Only MECS and FMA trial sections were constructed before the end of the project while MEAS can be constructed later on by ERA. All the preparations have been completed, including moving the materials and plants, with necessary amendments to the plants, to the construction sites. For MECS, the rainfall has hindered the construction as it started raining when all the preparations were finished. For FMA, the contractor had to re-schedule the construction of the trial due to breaking down of the decanter, just at the beginning of activities. The maintenance of decanter was completed and the construction resumed as soon as the weather allowed.

3.5 Research uptake and capacity building

The research uptake and build capacity components of the project were integral to the success of the project and received 20% of the project's core funding. An additional £25,000 of funding was obtained by the project team through the UoB's Impact Acceleration Account (IAA). This enabled a dedicated outreach expert to be employed. Experts with considerable experience of the LIC context, from the International Road Federation

(IRF) and the UoB's International Development Department, led the work. The strategy involved communications, dissemination and skills transfer, and is outlined below.

3.5.1 Communications

To secure early and meaningful engagement from LIC stakeholders, a mixture of traditional and social media platforms, email communication and direct engagement was used including:

- Establishment of an online road pavement surfacings interest group.
- Creation of dedicated web pages describing the project and associated activities hosted on the UoB website: https://more.bham.ac.uk/hvt-crisps/.
- Targeted and dedicated newsletters sent to the interest group, the IRF's membership and the UoB's alumni databases.
- Communications via:
  - UoB's press office (Twitter account, feed to other media channels).
  - Transport Research Board (TRB) network via the IRF.
  - Technology Transfer (T2) centres in Africa.
  - IRF's membership of the Board of the Belt and Road International Transport Alliance (BRITA) network.

3.5.2 Dissemination

The project's dissemination strategy included:

- Planned events:
  - Webinars: Seven webinars and reading packs to support knowledge embedded in the webinars.
  - Conferences: Due to Covid-19 restrictions one conference was attended during the funded part of the project (The 7th Regional Conference for Africa 18th to 20th October 2022 in Cape Town, South Africa).
  - Workshop: A workshop facilitated by the Ethiopian Roads Administration (ERA) was held in Addis Ababa on 8th December 2022.
  - Policy dialogue: An online policy dialogue event with senior national and regional decision makers was held on 28th February 2023.
- Printed and e-media:
  - Monthly online newsletters.
  - Articles in the IRF World Highways pages and LeStrade.
  - Four academic journal articles submitted to international journals.
  - Articles in the American Society of Civil Engineers (ASCE) and Traffic Technology International publications.
  - Two manuals and a short video.
- Academic institutions: the UoB, University of Auckland (UoA) and Universiti Putra Malaysia (UPM) disseminated research findings and other project activities through the following undergraduate and postgraduate programmes:
  - UoB's road management and engineering MSc programme.
  - UoA's transportation engineering MSc programme.
  - UPM's undergraduate Civil Engineering programme.
  - Fifteen MSc research projects based on CRISPS research.

4. Work streams

The four Work streams (WS) were set out to undertake the four main deliverables of the project. These were, as illustrated in Figure 1, the WS1 for Deterioration Modelling, the WS2 for Life Cycle Analysis, the WS3 for Development of Anti-fraud Systems, and the WS4 for Trials Constructability in Ethiopia.

4.1 Deterioration modelling

4.1.1 Introduction

The WS1 research focused on the deterioration model development for MECS and MEAS for use in the HDM-4 life cycle analysis software (as introduced in section 3.1). The approach adopted was to utilise existing datasets in NZ to determine the difference in performance, measured in terms of modes of distress, between traditional asphalt surfaces and epoxy modified surfaces, and then demonstrate how these differences can be applied in Ethiopia. A specific report on the deterioration modelling was submitted to DT Global, as a WS1 report (12).

4.1.2 Data

4.1.2.1 Control datasets

Various in-service accelerated testing and laboratory datasets available in NZ on the performance of traditional asphalt were used as control datasets. The data comprises Long-Term Pavement Performance (LTPP) study data and in-service asset inventory and condition data from the Road Assessment and Maintenance Management (RAMM) database.

The LTPP sites consist of 300 m long sections established across the country to represent a cross-section of typical pavements on both the state highway and local Administration networks. They were selected according to a design matrix that ensures representative samples from different climatic areas, traffic, pavement and network types.

As the LTPP data set consisted primarily of that from low volume pavements with a chipseal surface, additional data on NZ's high volume traffic asphalt surfaces was obtained from the NZ state highway network.

4.1.2.2 Epoxy modified surfacings datasets

The datasets included data from the accelerated pavement testing undertaken at the Canterbury Accelerated Pavement Testing Indoor Facility (CAPTIF), in-service data obtained from the RAMM database and from laboratory testing.

4.1.2.3 Accelerated pavement test data

Accelerated pavement testing was undertaken on epoxy modified open graded porous asphalt (EMOGPA) and standard open graded porous asphalt (OGPA), as a control, at the CAPTIF (see Figure 3).

Figure 3. Canterbury Accelerated Pavement Indoor Testing Facility (CAPTIF)

4.1.2.4 In-Service Data

Epoxy modified bitumen has been used since 2016 in NZ and over 1,000,000 m^2 has been laid to date on state highways. Inventory and condition data were extracted from the RAMM database for 119 sites surfaced with EMOGPA. Skid resistance, texture, roughness and rutting surface condition data were collected using an automated high-speed data survey. Cracking data was collected from visual condition surveys.

4.1.2.5 Laboratory data

Although in-service data is available for MEAS, the oldest sections were laid in 2016, and therefore data to establish long-term performance is lacking. For MECS, there are only limited field trials available. Consequently, from the outset of this research, it was realised that laboratory performance data would be required to supplement the in-service and accelerated testing data. Table 1 summarises the sources and types of data obtained.

Table 1. Epoxy modified bitumen laboratory data

Study	Description	Data input for this research
NZ Transport Agency: Epoxy-modified porous asphalt 2010 (13)	Investigate the potential of epoxy-modified asphalt as a low-maintenance, long-life (>30 years) surfacing material.	Abrasion resistance Oxidation
NZ Transport Agency: Epoxy Chipseal 2014 (14)	The use of epoxy modified bitumen as a sealing binder was investigated as an alternative for reducing or eliminating some of the problems associated with conventional seals	Resistance to flushing/bleeding Cohesive energy measurements Durability Adhesion and water-induced stripping
Delft Study 2020 - 2022 (15; 16; 17)	Assessing the effect of epoxy modification on the strength, modulus and fatigue resistance characteristics of asphalt concrete mixes.	Fatigue performance characteristics for dense graded bitumen

4.1.2.6 HDM-4 pavement distress model calibration

The calibration of the HDM-4 distress models for cracking, rutting and roughness used approaches advocated by other researchers (18; 19; 20), and the HDM-4 calibration guideline (21). Further details of the methodology can also be found in the WS1 report.

The calculated HDM-4 calibration factors based on the NZ datasets for traditional asphalt concrete (AC) and chip seal (CS) surfaces are given in Table 2 and Table 3 respectively.

Table 2. AC calibration factors

Factor	Description	Humid	Sub-humid	Semi-arid
K_{cia}	Crack initiation	0.85	0.85	0.75
K_{cpa}	Crack progression	1.18	1.18	1.33
K_{gm}	Roughness progression (environmental)	1.09	0.87	0.43
K_{gp}	Roughness progression (general)	0.98	1	1
K_{rp}	Rutting progression	1	1.07	1

Table 3. CS calibration factors

Factor	Description	Humid	Sub-humid	Semi-arid
K_{cia}	Crack initiation	1.6	1.4	1.3
K_{cpa}	Crack progression	0.63	0.71	0.77
K_{gm}	Roughness progression (environmental)	1.09	0.87	0.43
K_{gp}	Roughness progression (general)	0.97	1	0.99
K_{rp}	Rutting progression	1	1.01	1

The calibration factors for AC and CS were used within the HDM-4 distress models to compare modelled against measured performance. The comparisons are shown in Figure 4 to Figure 6. Figure 7 indicates a good agreement between modelled and predicted performance, suggesting that the determined calibration factors were appropriate.

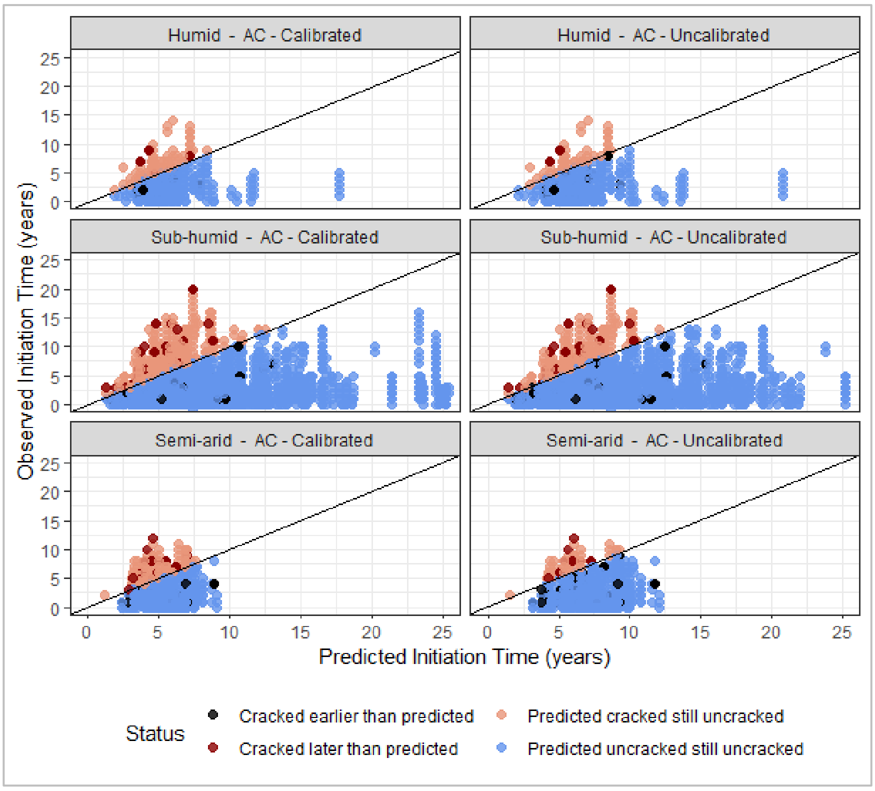

Figure 4. Predicted vs. observed crack initiation (MEAS)

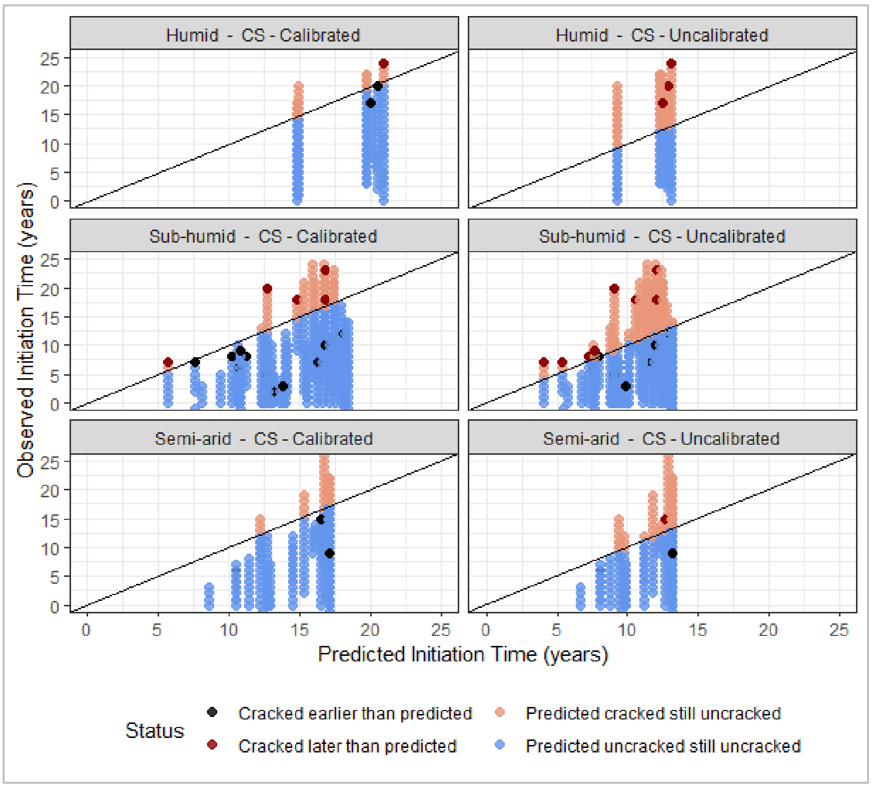

Figure 5. Predicted vs. observed crack initiation (MECS)

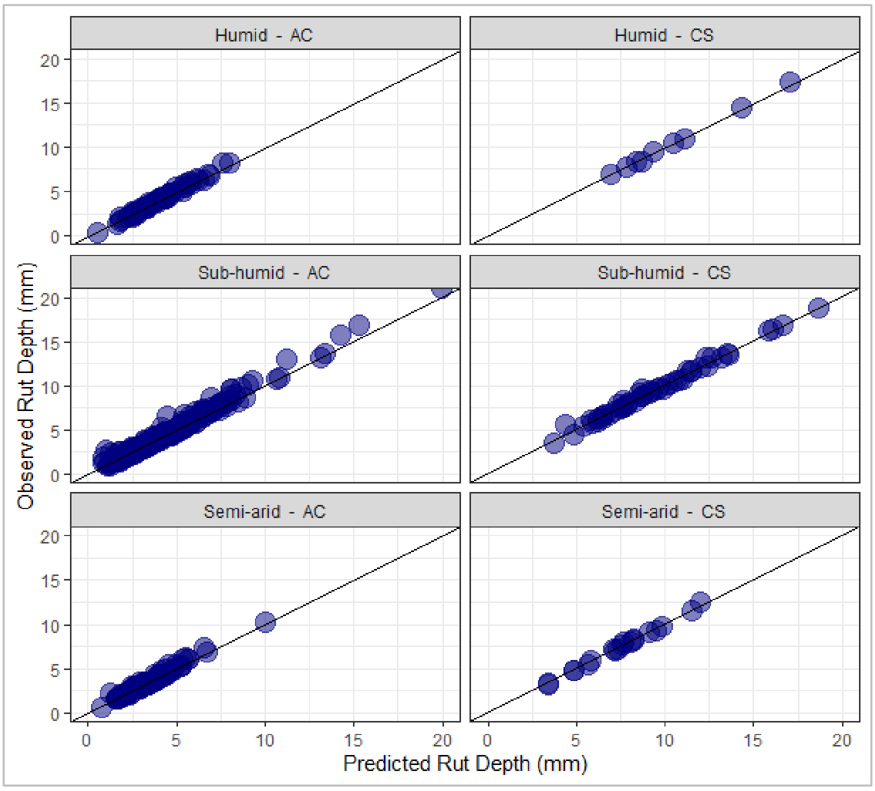

Figure 6. Predicted vs. observed rutting (MEAS and MECS)

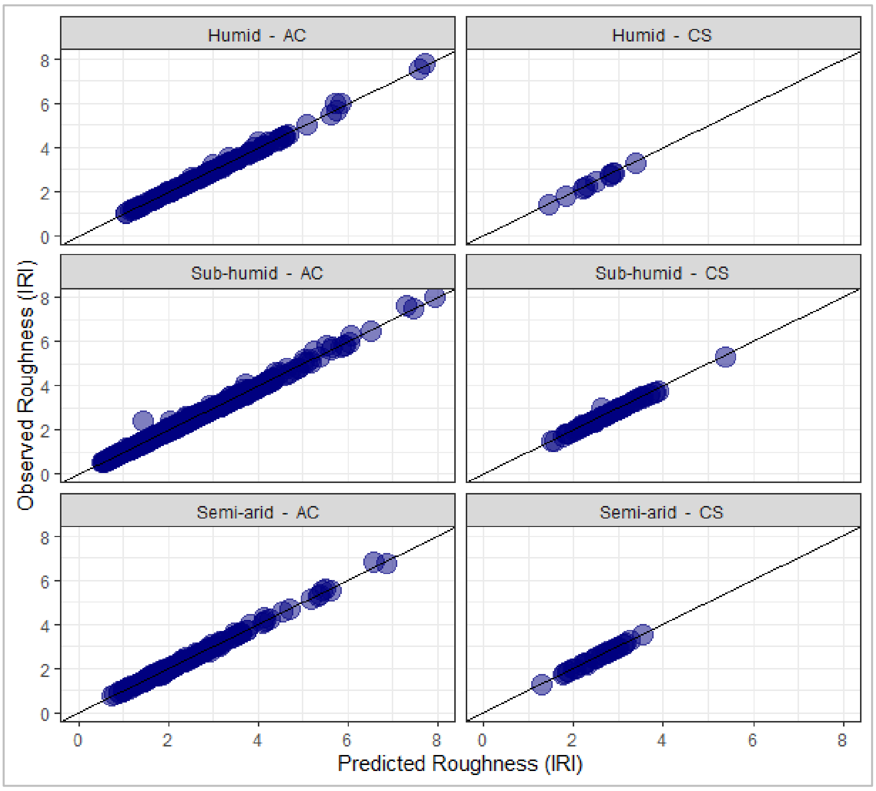

Figure 7. Predicted vs. observed roughness (MEAS and MECS)

4.1.2.7 Relative performance shift and corresponding calibration factors

Through comparison of the performance of traditional AC and MEAS and traditional CS and MECS surfacings, performance ratios between the conventional bitumen and the epoxy modified surface options were determined. These are shown in Table 4.

Table 4. Epoxy modified surface performance ratios

Performance measure	Relative performance ratios	
	Asphalt surfaces to MEAS	Chip seals to MECS
Crack initiation	4	4
Crack progression	0.25	0.25
Roughness progression (general)	5	2
Rutting progression	5	1

Based on the performance ratios presented in Table 4, the New Zealand HDM-4 models were back-analysed to yield the appropriate calibration coefficients that would result in the shift in performance shift indicated in Table 4, above. The resulting calibration factors for MEAS and MECS are shown in Table 5 and Table 6 respectively.

Table 5. HDM-4 Calibration factors for MEAS in NZ

Coefficient	Description	Humid	Sub-humid	Semi-arid
K_{cia}	Crack initiation	3.4	3.4	3
K_{cpa}	Crack progression	0.29	0.29	0.33
K_{gm}	Roughness progression (environmental)	1.09	0.87	0.43
K_{gp}	Roughness progression (general)	0.196	0.2	0.2
K_{rp}	Rutting progression	0.2	0.206	0.206

Table 6. HDM-4 Calibration factors for MECS in NZ

Coefficient	Description	Humid	Sub-humid	Semi-arid
K_{cia}	Crack initiation	6.4	5.6	5.2
K_{cpa}	Crack progression	0.16	0.18	0.19
K_{gm}	Roughness progression (environmental)	1.09	0.87	0.43
K_{gp}	Roughness progression (general)	0.485	0.5	0.495
K_{rp}	Rutting progression	1	1.01	1

4.1.3 Ethiopia

4.1.3.1 Calibration factors for Ethiopia

In order to demonstrate how the shift factors developed can be applied to calibrate the HDM-4 models in Ethiopian conditions, data was obtained from the literature on the Addis-Modjo-Awasa road. This road is predominantly a high volume, asphalt concrete road constructed on a granular base and is situated in a sub-humid/tropical climatic zone. Table 7 shows the Ethiopia case study calibration factors for the traditional asphalt surfaces, the MEAS performance ratios and the resulting MEAS calibration factors.

Table 7. HDM-4 Calibration factors for MEAS in Ethiopia

Factor	Description	HDM-4 calibration factors for traditional materials	Performance ratio	MEAS calibration factor
K_{cia}	Crack initiation	1.49	4	5.96
K_{cpa}	Crack progression	0.67	0.25	0.17
K_{gm}	Roughness progression (environmental)	1.41	-	1.41
K_{gp}	Roughness progression (general)	1.15	5	0.23
K_{rp}	Rutting progression	1.06	5	0.21

4.1.3.2 Demonstration of model outcomes

The results of applying the HDM-4 model calibration parameters given in Table 7 for an example new road section in Ethiopia provided in Kassa (22) are shown in Figure 8. The modelled pavement had a 100 mm asphaltic concrete surface, carried traffic of 2.94 million equivalent standard axles (MESAs) per year and an SNP of 5. No maintenance was modelled.

The results shown were for a 40-year period using the original calibration factors provided by Kassa (22) (labelled 'Control' in the following plots); MEAS calibration factors were determined by applying the performance ratios given in Table 7 to the HDM-4 calibration factors for traditional surfacings provided by Kassa (22). Three condition outputs are shown: cracking (ACA – percentage of cracked area), roughness (international roughness index [IRI] measured in m/km) and rutting (Rut – mean rut depth in mm). It is apparent from Figure 8 that the effect of the calibration exercise is to greatly reduce the percentage area of cracked road pavement (from 100% after 20 years to 50% after 40 years) and to greatly reduce the rates of roughness and rutting progression (from 22% to 12% after 40 years and from 17% to 5% after 40 years, respectively).

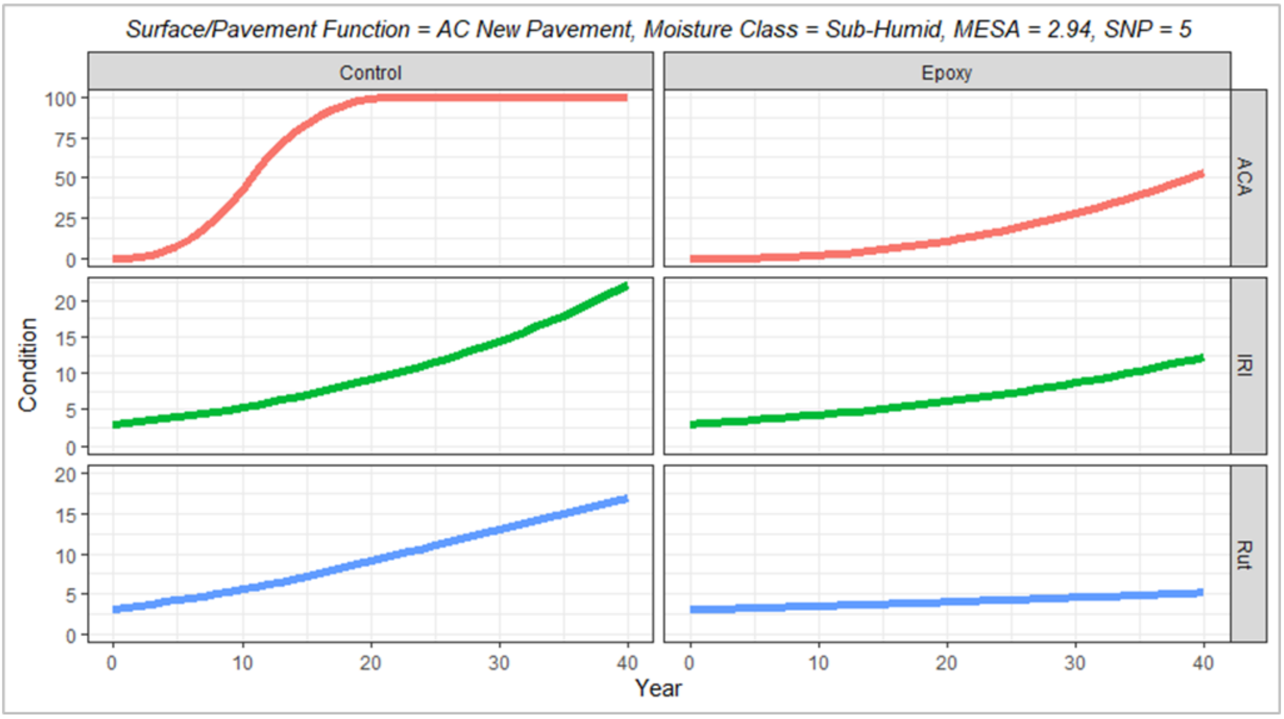

Figure 8. Comparison of HDM-4 outputs between traditional asphalt and MEAS

ACA: percentage of cracked area; IRI: international roughness index; Rut: rut depth

4.1.4 Conclusions

Estimations of the performance ratios and corresponding calibration coefficients for MECS surfaces in NZ were largely based on laboratory, accelerated testing and some early life network data. For EMOGPA, network data was used and there is therefore more confidence in the results obtained for these surfaces. Given the consistency between the outcomes from these data sources, there is sufficient confidence in the performance ratios between traditional and epoxy modified bitumen surfaces in NZ.

However, while the NZ performance ratios enable estimates of the potential economic suitability of epoxy modified surfacings in Ethiopia compared with traditionally used surfacings to be determined using HDM-4, it should be recognised that this is not a substitution for undertaking long-term performance trials in Ethiopia. Therefore, while trials in Ethiopia are undertaken, their performance should be closely monitored and adjustments made to the calibration factors based on country-specific evidence. In addition, although significant research and trials have been undertaken in NZ on epoxy modified surfacings, the oldest in-service pavements were only constructed in 2016. Therefore, much is still to be learned in NZ about their long-term, in-service performance.

Where appropriate data was not available, engineering judgement was employed. Such judgements tended to err on the side of caution and the calibration factors based on the evidence to date can therefore be considered as conservative. However, the calibration should be revisited as new data becomes available.

The estimated calibrated factors should not be used for other applications before being validated against local in-service conditions. Although the estimated calibration ratios are appropriate for relative economic comparison between traditional and epoxy modified surfaces, using these factors for maintenance and renewal programmes – where an absolute performance outcome is assumed – would not be appropriate.

4.2 Life cycle analysis

4.2.1 Introduction

The WS2 research focused on the use of the World Bank's HDM-4 model for undertaking life cycle analysis on the existing traditional bituminous surfacings in Ethiopia (asphalt concrete and double bituminous surface treatment) and on both the long-life epoxy modified bituminous surfacings and the fibre mastic asphalt. The life cycle analysis helped to identify the engineering and economic advantages of the CRISPS project trialled surfacings over the existing traditional surfacing pavements in Ethiopia.

Long-life epoxy road surfacing technologies (i.e. MECS and MEAS) and fibre reinforced asphalt (e.g. FMA) have been used worldwide for a number of years. For example, in NZ the former two surfacings (the latter in the form of EMOGPA) are now in routine use (1; 2; 3; 4), as is FMA in Malaysia (4; 5; 6).

The climate resilience of the surfacings has been reported extensively (e.g. (2; 4; 1; 3; 6; 5; 7; 8; 9). EMOGPA was developed to reduce age-related embrittlement, specifically that due to oxidation (6; 7). Porous asphalts in general, and MECS in particular, have been found to reduce the potentially destabilising impact of increased water pressure on the road surface under wheel loads compared with impermeable surfaces (i.e. the water hammer effect) (8; 9). Epoxy modified asphalts were developed to perform in the very high temperature environments of military airport pavements (2).

Given the above, and that the aim of the project was to provide further information for decision makers to strategically assess the viability of the surfacings, the LCA work focused on quantifying the engineering performance of the technologies, and economic costs and benefits of the surfacings, compared with surfacings routinely used.

To aid decision making, the LCA was carried out under a variety of budget scenarios and considered variability in construction quality (and thereby also corruption) and vehicle overloading.

4.2.2 HDM-4

HDM-4 was chosen for the study because it is the preeminent tool for road investment appraisal, is the World Bank's de facto standard for road investment appraisal and is used in over 100 countries worldwide.

HDM-4 utilises four interrelated modules to predict the life cycle performance of road pavements including road agency costs (RAC) and road user costs (RUC) as a function of traffic levels and composition, climate and user-defined road maintenance standards (i.e. strategies). These modules concern road deterioration (RD), road works effects (RWE), road user effects (RUE) and socio-economic and environmental effects (SEE). HDM-4 calculates the economic benefit of each strategy in terms of standard economic decision rules, including the net present value (NPV). The RD module contains equations that can be calibrated to simulate the deterioration, according to a number of distress types, of any type of road pavement. The distress types simulated by HDM-4 are cracking, edge wear, potholing, ravelling, roughness, rutting and skid resistance (23). The RWE module determines the implications of maintenance strategies on road condition, whereas the RUE module considers the impact of these strategies on RUCs. RUCs concern vehicle operating costs (VOC), travel time and road accidents. The SEE model is to do with vehicle energy consumption and emissions (23).

4.2.3 Representative road sections

For the strategic LCA work carried out, the Ethiopian major road network was modelled in terms of representative road sections. These were chosen to represent the performance of the entire road network, simplifying the analysis. Representative road sections are homogenous in terms of the attributes that are likely to affect road deterioration, and thereby road agency and road user costs. These attributes include construction type, traffic levels and composition, maintenance standards, geometry and climate. The 18 representative road sections (i.e. six pavement types in three climate zones) used for the LCA work are summarised in Table 8.

Table 8. Representative road sections

Ethiopian conventional road pavement			Project pavement surfacings		
Representative road section	**Climate zones**	**Acronym**	**Representative road sections**	**Climate zones**	**Acronym**
High traffic road ERA design manual for flexible pavements, asphalt concrete (AC) surfacing. Chart D1, T10, S3 (24) (i.e. design traffic 50-80 MESA)	Tropical humid, sub-humid and semi-arid	HTAC	**High traffic road** ERA design manual for flexible pavements, MEAS surfacing. Chart D1, T10, S3 (24) (i.e. design traffic 50-80 MESA)	Tropical humid, sub-humid and semi-arid	HTMEAS
Medium traffic road ERA design manual for flexible pavements, Double bituminous surface treatment (DBST) surfacing Chart A1, T6, S3 (24) (i.e. design traffic 6-10 mesa)	Tropical humid, sub-humid and semi-arid	MTDBST	**Medium traffic road** ERA design manual for flexible pavements, MECS surfacing Chart A1, T6, S3 (24) (i.e. design traffic 6-10 MESA)	Tropical humid, sub-humid and semi-arid	MTMECS
Overlay (50mm HMA) on a medium traffic road ERA design manual for flexible pavements, Chart C1, T6, S3 (24). (design traffic 6-10 MESA)	Tropical humid, sub-humid and semi-arid	MTACO	**Overlay (50mm FMA) on a medium traffic road** ERA design manual for flexible pavements, Chart C1, T6, S3 (24) (design traffic 6-10 MESA)	Tropical humid, sub-humid and semi-arid	MTFMAO

4.2.4 Configuration and calibration of the HDM-4 models

To improve the accuracy of the default HDM-4 relationships used in the RD, RWE, RUE and SEE models, the models were configured and calibrated to local conditions as described in the WS2's life cycle analysis report (11).

4.2.5 Scenarios modelled

The performance of the three surfacing technologies were modelled under three different scenarios for a 50-year period of analysis, as follows:

- Budget constraints:

  Mindful of the challenges faced by road agencies worldwide to obtain sufficient road maintenance funds, and considering that MEAS, MECS and FMA are thought to significantly improve the strength, durability and resilience of the pavements, the LCAs were conducted over a 50-year analysis period with the following budgets:

  - Unconstrained budget;
  - Unconstrained budget less 25%;
  - Unconstrained budget less 50%.

- Imperfect construction / corruption:

  HDM-4 enables imperfect construction practices through a number of indicators. For this research, the value of the construction defects indicator for bituminous surfacing was varied from its default value to represent brittle surfacing due to substandard design of the binder content. Similarly, variations in grading of the road base material, aggregate shape and compaction were simulated through the construction defects indicator for the road base.

- Corruption:

  Corruption was modelled by assuming that unscrupulous contractors would use sub-standard quality and quantities of materials and sub-standard construction techniques. These impacts were investigated using the same procedure as described above to investigate poor construction practices.

- Vehicle overloading:

  Illegal vehicle overloading is a particular problem in developing countries that do not have sufficient resources to police the practice. As road pavement damage is related to vehicle axle loads to approximately the fourth power, the overloading of heavy vehicles contributes greatly to accelerated road pavement damage. To account for vehicle overloading, analyses were carried out by increasing the axle loads carried by heavy vehicles by 25%.

4.2.6 Findings

4.2.6.1 Road condition for high traffic representative road sections

The high traffic HTMEAS representative road sections in all three climate zones demonstrated lower rates of deterioration, in terms of road roughness, and required less frequent periodic treatment than the HTAC sections. The differences in frequency of periodic treatment were above 60% for all three climate zones; the greatest difference was in the semi-arid climate zone, where the modelling showed that no periodic maintenance was required (see Figure 9).

Road roughness progression in HDM-4 is modelled as a function of cracking, rutting, ravelling, potholing, structural deformation and environmentally induced deterioration. The deterioration modelling part of the research (WS1) and the review conducted in the LCA aspect of the project (WS2) found that MEAS had rates of cracking, ravelling, rutting and potholing initiation and progression that were four to six times lower than traditional surfacings. Further, the structural number for MEAS is greater than that of traditional surfacings because the resilient modulus of MEAS is about three times higher than traditional surfacings. This improved performance of MEAS compared with traditional surfacings was reflected in the appropriate calibration of the HDM-4 distress models. Consequently, it would be expected that the HDM-4 modelled roughness progression would be less for MEAS compared with the conventional surface for the same climate type, as indicated above.

The variation in roughness progression between climates for a given road surfacing is controlled by calibrating the environmentally induced roughness calibration factor. For the level 1 calibration of the HDM-4 distress models used here, this calibration factor is only a function of the climate (and not the surface type). Accordingly, for the representative road sections surfaced with either material type, the rates of deterioration were higher in the tropical humid zone, than in the sub-humid and semi-arid zones.

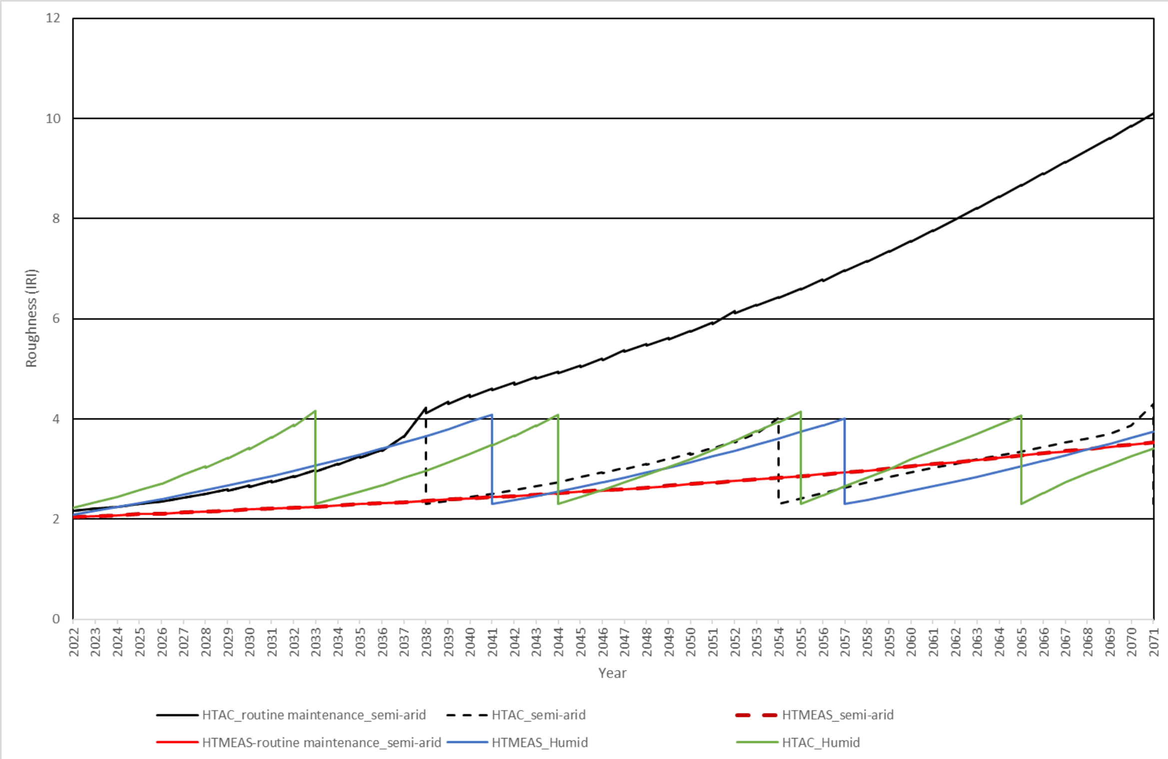

Figure 9. Predicted deterioration of the high traffic representative sections in the semi-arid and tropical humid climates

4.2.6.2 Road condition for medium traffic representative road sections

For the medium traffic representative road sections in all three climate zones, the MTMECS sections had lower roughness deterioration rates and required less frequent periodic treatment than their MTDBST counterparts. The differences in the frequencies of periodic maintenance treatment were 120%, 75% and 63% for the semi-arid, sub-humid and tropical humid climate zones respectively.

For the high-volume sections, the differences in rates of roughness progression between MECS and DBST are because of the values used for the calibration parameters of the HDM-4 rutting, cracking, ravelling, potholing and structural distress models.

Similarly, because of the values used for the calibration of the roughness environmental distress model, the modelled rates of deterioration were higher in the tropical humid zone than in the sub-humid and sub-arid zones (see Figure 10).

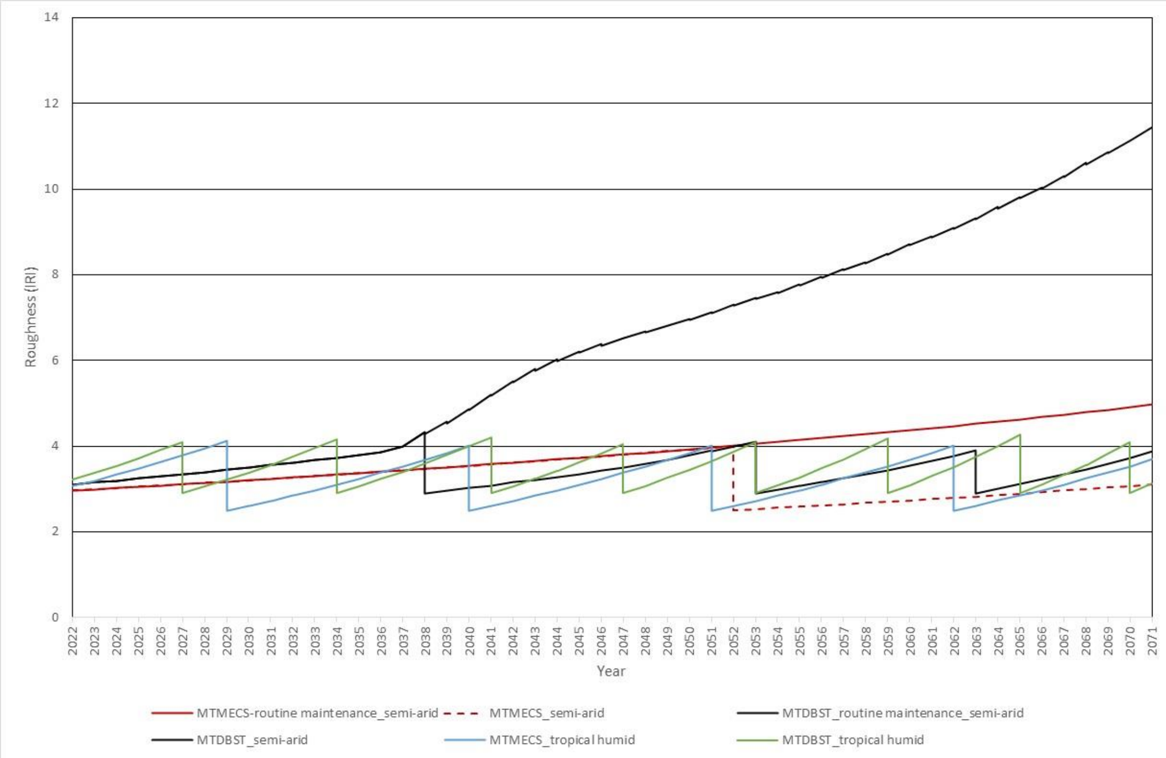

Figure 10. Predicted deterioration of the medium traffic representative sections in the semi-arid and tropical humid climates

4.2.6.3 Road condition for overlaid representative road sections

The medium traffic representative road sections, overlaid with 50 mm of conventional AC or FMA, showed similar rates of roughness deterioration and required a similar frequency of additional overlays. The frequencies of periodic maintenance were between 5% and 14% lower for the FMA sections compared to with the AC overlaid sections, depending on the climate zone (the greatest difference was for the tropical humid zone). The reason for the slightly lower rates of road roughness progression of the FMA overlay compared with AC, is because FMA has a higher resilient modulus value and therefore a higher structural number than AC. This is related to a structural component of roughness progression being less for the FMA compared with the AC overlay.

For the representative road sections surfaced with either material, the rates of deterioration were higher in the tropical humid zone than the sub-humid and sub-arid zones (see Figure 11). For the other surfacings investigated, the value of the calibration factor for the environmental component of roughness was the same for both materials, but the deterioration was correctly modelled as a function of the climate.

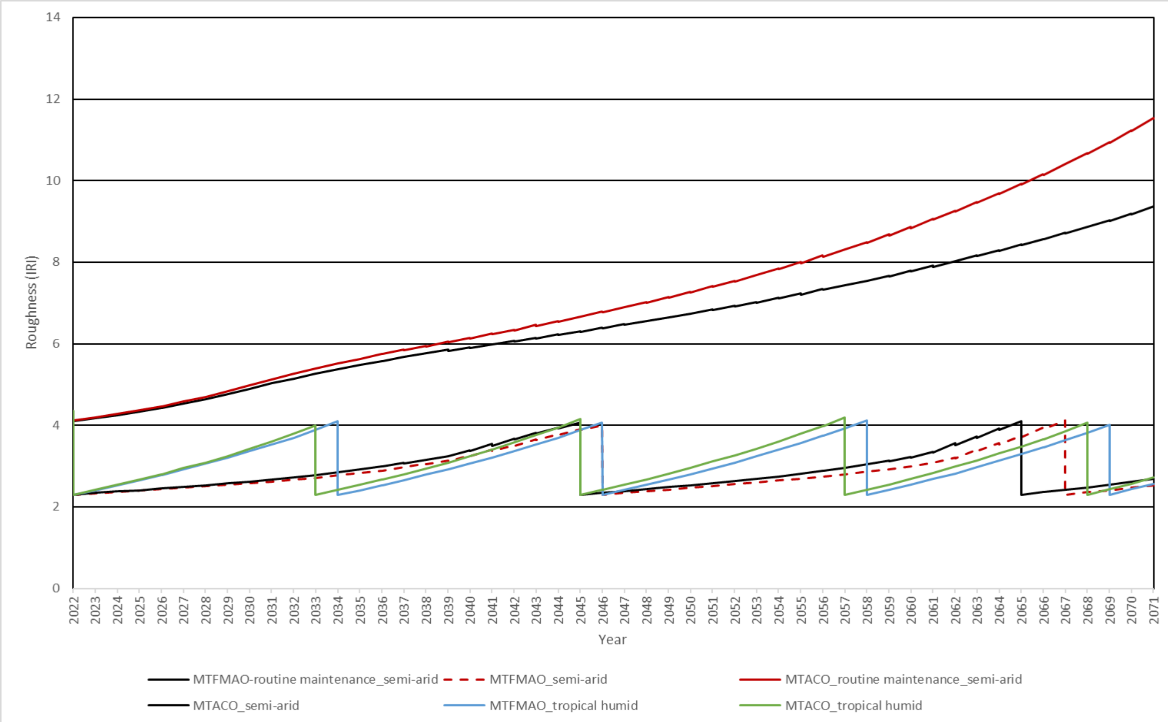

Figure 11. Predicted deterioration of the overlaid representative sections in the semi-arid and tropical humid climates

4.2.7 Budget constraints

As shown in Figure 9, budget constraints greatly influence the average roughness values of all the representative road sections, except for the HTMEAS section in a semi-arid climate, which did not require periodic maintenance. As a result of higher average road roughness values, budget constraints were found to have a large impact on road user costs for all vehicle types for all the representative road sections: see Figure 12, which plot average (over all climates) road roughness and RUCs against time for the HTMEAS and HTAC representative road sections.

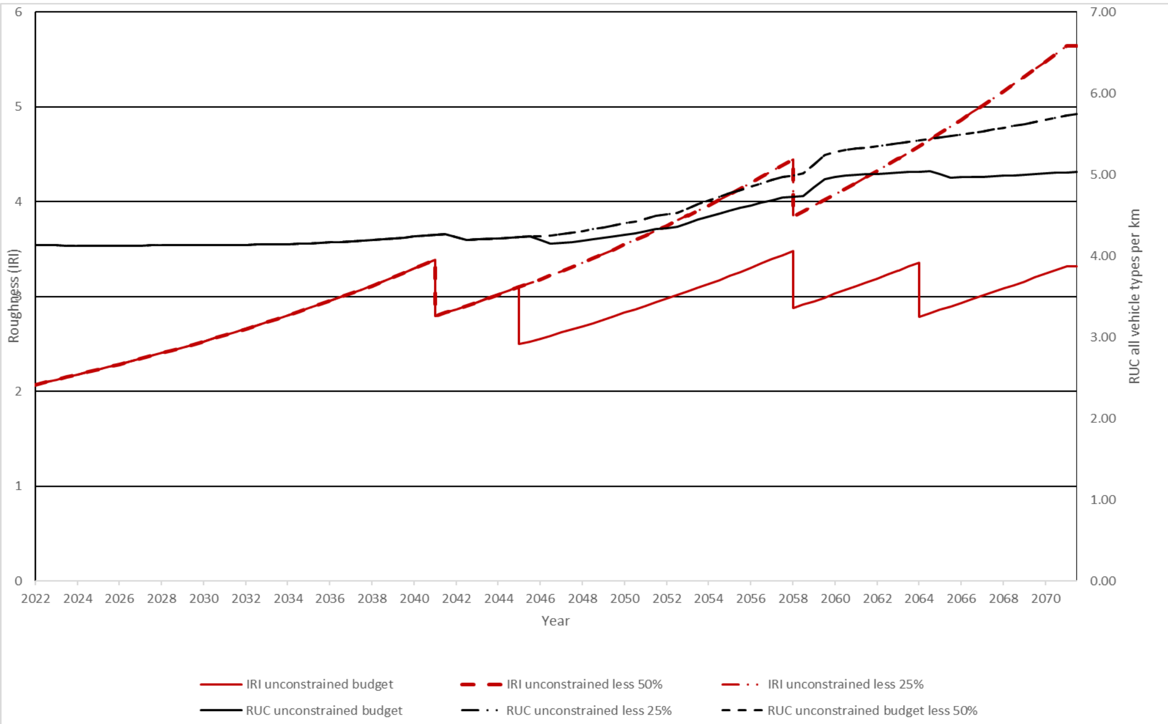

Figure 12. Average roughness and RUCs for the HTMEAS sections (average for all climates)

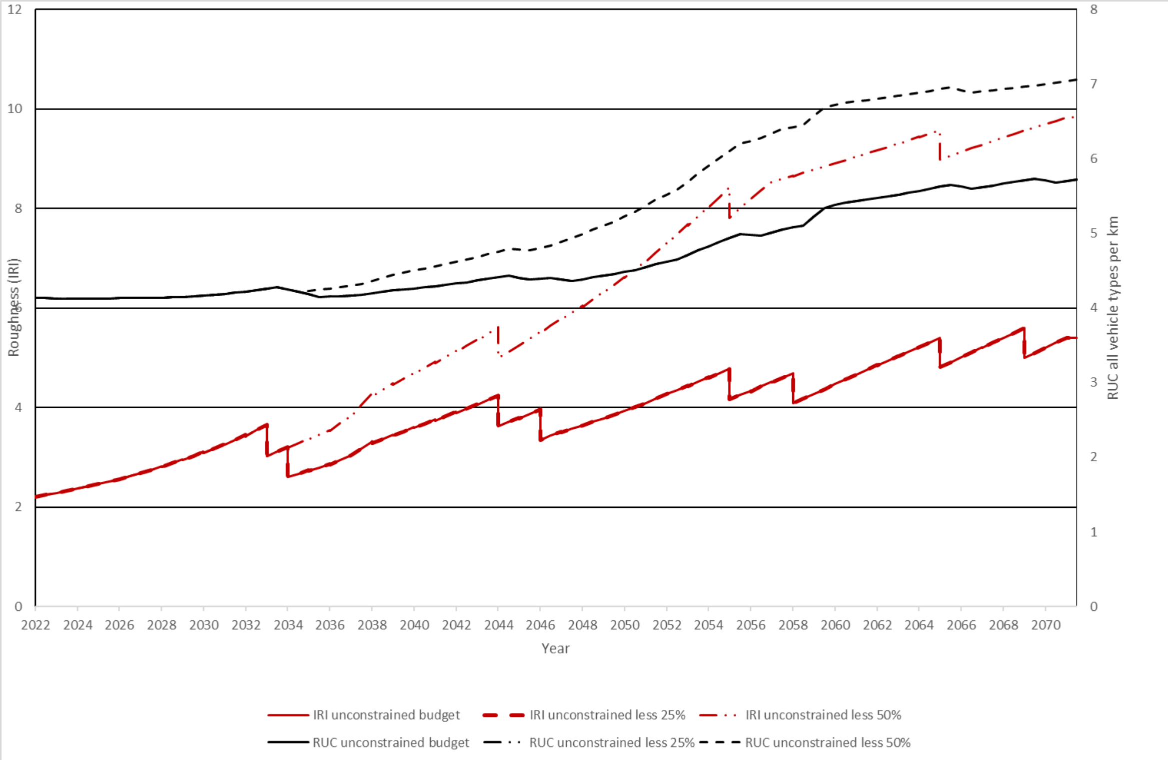

Figure 13. Average roughness and RUCs for the HTAC sections (average for all climates)

4.2.8 Poor maintenance practices and corruption

Corruption and/or poor construction practices were simulated by reducing the quality of the construction of the bituminous and the base layers of the representative road sections. It was found that, in general, this increased the rates of deterioration of the surfacing types considered. However, the effect of corruption in terms of roughness deterioration was less for the epoxy modified and FMA representative road sections than for their ERA counterparts.

4.2.9 Vehicle overloading

Vehicle overloading, which was simulated by increasing the axle loads of heavy vehicles by 25% in the vehicle fleet, increased the rates of roughness deterioration for all representative road sections. The impact of overloading was less in terms of rates of pavement deterioration and frequency of recommended period treatments for the HTMEAS, MTMECS and MTFMAO representative road sections than for their ERA counterparts.

4.3 Economic analysis

4.3.1 Road user costs

The HTMEAS representative road sections have lower RUCs than the HTAC sections (see Figure 12 and Figure 13). As explained above, this is because the average roughness values over the period of analysis of the HTMEAS surfaced roads are lower than their HTAC equivalents. The differences in roughness performance of the two surfaces reflect the lower rates of surface wear and better structural performance of the MEAS surfaces compared with AC ones, as mentioned in section 4.2.6.1.

The RUCs of the HTMEAS and HTAC representative road sections were, as expected, found to be higher for the constrained budget scenarios and the RUCs for "unconstrained budget less 25%" are slightly lower than for the "50% of the unconstrained budget" option.

Comparing the MTDBST and MTMECS representative road sections, the latter were found to have lower RUCs than the former. This is because the average roughness values over the period of analysis of roads surfaced with MECS were lower than those surfaced with DBST (see section 4.2.6.3).

For the MTDBST and MTMECS representative road sections, as expected the VOCs are higher for the constrained budget scenarios. However, for all MTDBST and MTMECS representative road sections, the RUCs for the two constrained budgets (i.e. "unconstrained budget less 25%" and "unconstrained budget less 50%" respectively) are the same. This is because for these two budget scenarios, the HDM-4 optimisation process specifies the same treatment options for the given budgets.

Concerning the MTACO and MTFMAO representative road sections, the RUCs were lower on average for the latter than the former because the average roughness values over the period of analysis of roads overlaid with FMA were found to be lower than those overlaid with AC. The differences in roughness performance of the two surfaces is due to the MTFMAO sections being modelled as having a higher resilient modulus, and therefore structural number, than the MTACO sections. This results in the structural component of roughness of the MTFMAO sections, and therefore average overall roughness, being less than for the MTACO sections (see section 4.2.6.3).

The RUCs of the MTACO and MTFMAO representative road sections are, as expected, higher for the constrained budget scenarios, and the RUCs for the "unconstrained budget less 25%" are lower than the "50% of the unconstrained budget" scenario.

4.3.2 Economic indicators

4.3.2.1 Standard conditions

The economic benefits of the three project surfacing technologies relative to conventional surfacings were demonstrated by determining the NPVs of the three project surfacings compared with the conventional ERA ones.

As can be seen from Figure 14, when comparing HTMEAS with HTAC, in the first 10 years for all three climates, the NPVs are negative. However, thereafter the NPVs are positive. This suggests that for a short analysis period of 10 years, HTAC is more economically viable than HTMEAS. This is because the higher construction costs for HTMEAS compared HTAC have not been offset during the first 10 years of the analysis by savings in road agency maintenance costs and savings in RUC. A similar finding occurs for the when comparing MECS vs with DBST comparison in a tropical humid climate.

As the length of the analysis period increases, the economic benefits of the three surfacings investigated in the project exceed the benefits of conventional surfacings by between $131,000 per km and $304,000 per km for MEAS, between $1,800 per km and $61,000 per km for MECS and between $16,000 per km and $36,000 per km for FMAO. Generally, the NPV values of MEAS exceed those for FMAO, which in turn exceed those for MECS. This is because MEAS sections cost more to construct and maintain, and carry higher levels of traffic, compared with the FMAO and MECS sections.

For the two epoxy surfaced roads (MEAS and MECS), the findings are consistent with the higher construction costs but lower life cycle capital costs and lower rates of roughness progression (and therefore lower RUCs) associated with the epoxy surfacings compared with their ERA counterparts.

Concerning the overlays, the improved life cycle performance of FMAO compared with ACO can be attributed to the lower costs of the FMA surfacing and its slightly greater resilience to deformation (i.e. FMAO has a higher resilient modulus, and thereby structural number, compared with ACO).

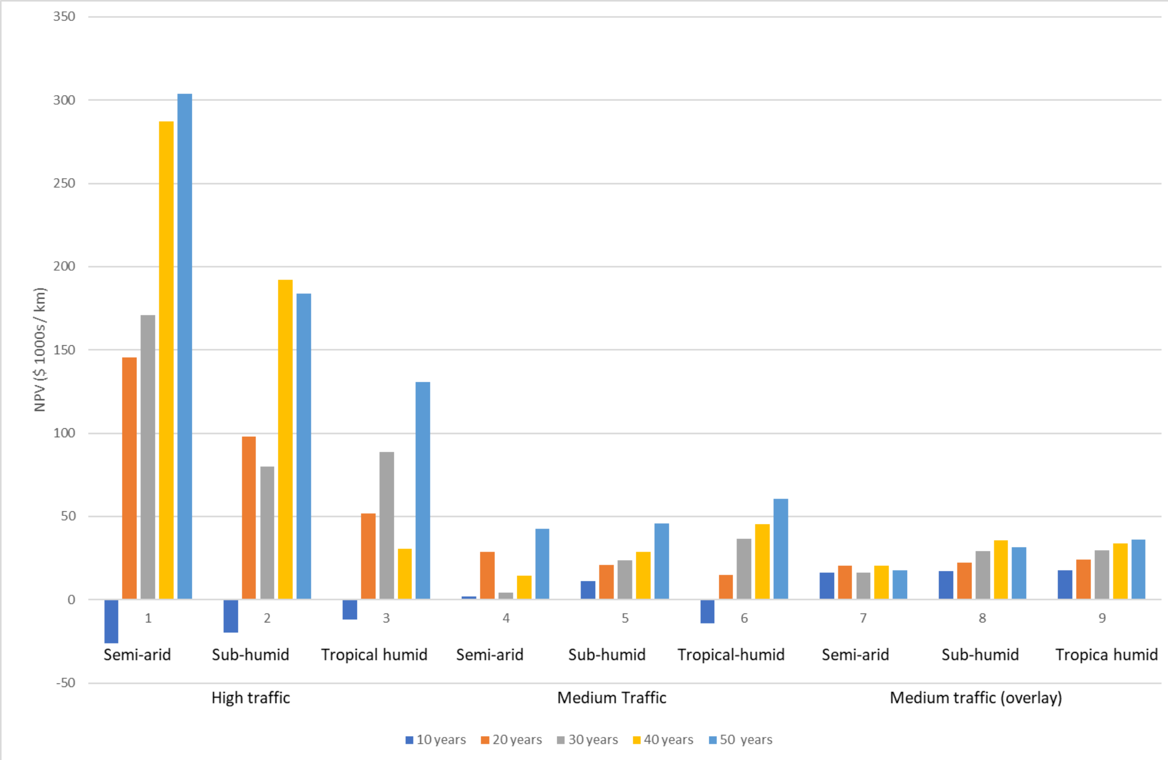

Figure 14. NPV values of project surfacings compared with ERA surfacings

4.3.2.2 Corruption and overloading

The impacts of corruption/poor construction and overloading in terms of NPVs for the representative road sections in a tropical humid climate are shown in Figure 15. Generally, the NPV values of the three project surfacings under the modelled conditions of corruption/poor construction and overloading are greater than under standard conditions. This suggests that the MEAS, MECS and FMA surfacings will perform even better in economic terms, then their conventional counterparts when maintenance and traffic loading conditions are not as designed. The greatest difference can be seen when comparing HTMEAS with HTAC, and particularly so in the case of corruption/poor construction. The increased NPV values of the HTMEAS vs HTAC comparison when corruption/poor construction is modelled compared to standard conditions of construction is due to the greater RACs required for the HTAC representative sections, compared to the HTMEAS representative sections, to remedy initial poor construction.

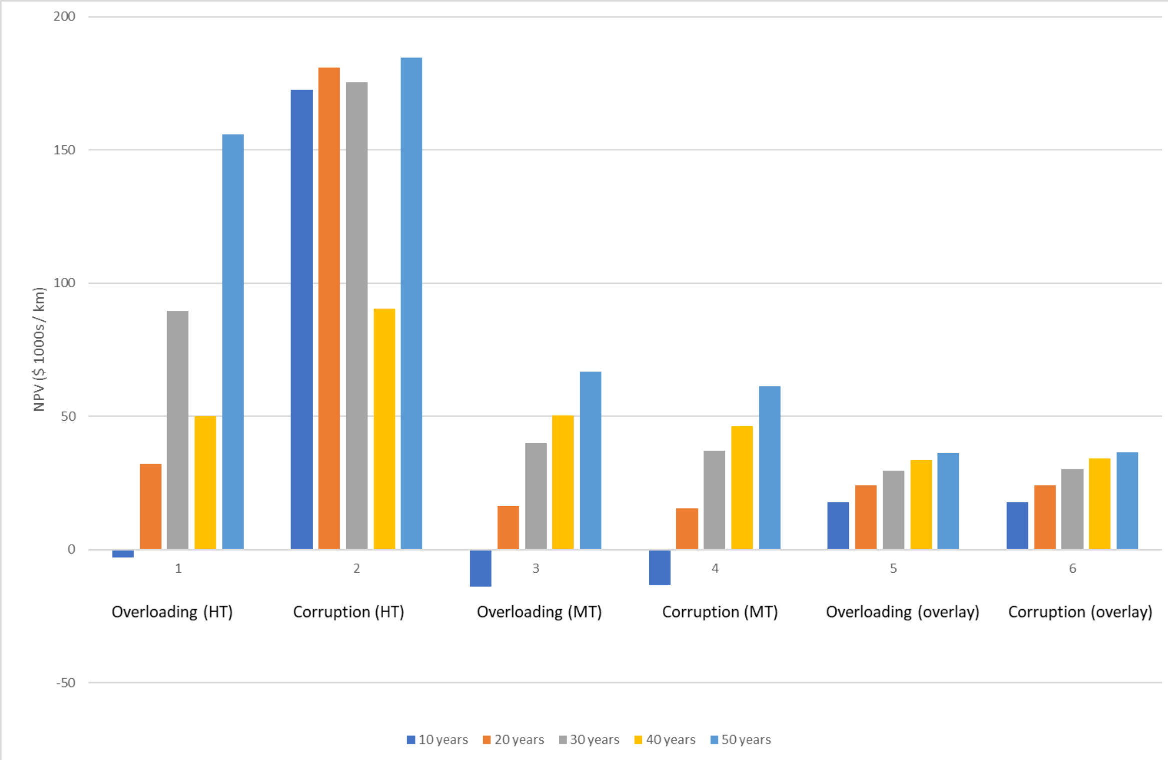

Figure 15. NPV values of project surfacings compared with ERA surfacings for the overloading and corruption scenarios (tropical humid climate)

4.3.3 Conclusions

According to the LCA work undertaken, the economic benefits of constructing and maintaining roads using the three surfacings considered in the research (MEAS, MECS and FMA) over the medium to long term (i.e. more than 10 years) are greater than those for the conventional technologies currently used in Ethiopia. These benefits are even greater under non-ideal conditions i.e. budget constraints, poor construction and traffic overloading.

4.4 A Robust System to Prevent Fraud

4.4.1 Introduction

The WS3 research focused on the development of a robust system to prevent fraud during the construction of long-life epoxy modified bitumen surfacings (MECS and MEAS). The approach adopted was to undertake a holistic review of the necessary quality assessment and quality control measures appropriate for construction of MECS, MEAS and FMA. More importantly, the utilisation of the Fourier Transform Infrared spectroscopy (FTIR) to control the quality of mixes designs for epoxy modified surfacing materials.

In order to prevent fraud, simple tests need to be utilised to ensure the quality of the individual materials and the correct mix-design has been implemented.

Appropriate QC methodology is essential to assess if the content of epoxy in the epoxy bitumen mix agrees with the mixing ratios of epoxy components – Part A or epoxy resins and Part B or hardener. This is particularly important as the epoxy is normally diluted with bitumen and an inappropriate mixture, which is likely to have a higher concentration of bitumen, can lead to lower durability and hence a higher lifecycle cost. Diluting bitumen with epoxy risks to negatively impact the road performance. However, the right portion of epoxy/bitumen has shown not to have a negative impact on the road performance (25). It should be noted that the price of epoxy is normally higher than bitumen and hence there might be an incentive to add more bitumen to the mix.

Controlling the quality of the supplied epoxy prior to the mixing stage is a vital step because using low quality epoxy in the mixture can significantly increase the lifecycle cost, even when all other steps are conducted appropriately. Furthermore, while the other aspects of the QC process are similar to standard procedures for other asphalt paving technologies, there is very little literature on the control of epoxy asphalt bitumen content. This is of particular importance as there are only a few suppliers of the material globally and the viability of MEAS and MECS surfacing technologies in LIC will certainly drive demand.

The Fourier transform infrared spectroscopy (FTIR) proved to be an efficient method for controlling epoxy content in the mixes. It is also both simple, available, and cost effective and therefore suitable for LICs. However, other robust technologies to control the ratios of epoxy components can be used, such as the fast neutron activation analysis (FNAA), but these would be most suited for HICs, given the complexity and highly expensive facility needs.

4.4.2 Existing QC systems for road pavement materials

A framework was developed for QC of pavement management systems Figure 16.) (26). The developed framework incorporates validation of QC data and statistical tests for data associated with pavement inventory, condition assessment and pavement performance modelling. However, the framework seems not to be straightforward but rather a cycle of activities and decisions, which makes it more complex. It goes beyond material and construction stages for the pavement and includes social, economic and environmental factors affecting the condition of the pavement over its lifetime.

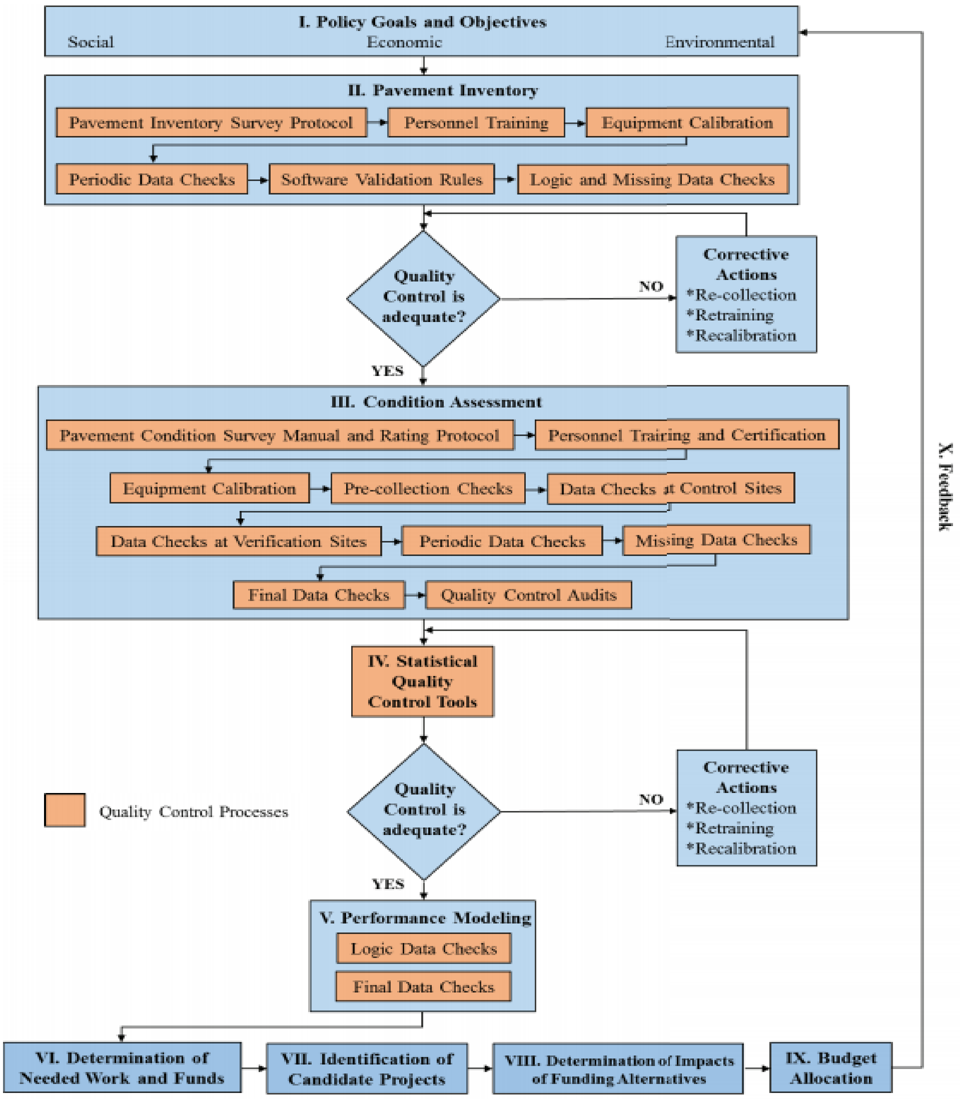

Figure 16. A developed quality control (QC) framework in pavement management systems

Similarly, Petkevičius and Christauskas (27) visualised the quality assurance (QA) processes in asphaltic road construction in a nine steps below:

- Quality of raw aggregate materials
- Mix designs
- Control of the processing of raw aggregates
- Moving asphalt plant to the project
- Mix components testing on continual basis
- Monitoring and recording plant operations
- Checking the mic properties before the mix goes on to the road
- Monitoring the road operation for mix density and smoothness.

Unlike the QC suggested by Valasquez (26), the QA is a one-directional process illustrating elements that need to be looked at to ensure a specified quality is achieved in the construction of the road and importantly only focuses on material selection and handling, design of the mixture and its placement during construction activities.

4.4.3 Proposed QC framework

After investigating the existing QA and QC methods currently in use in the construction of bituminous surfacings, a new generic framework for controlling the quality of an epoxy bitumen asphalt was proposed during the CRISPS project. The developed QC framework for epoxy modified bituminous surfacing technologies is shown in Figure 17 below. The overall QC activities could be categorised into two sub-sections:

1. Control of materials (epoxy bitumen content, strength, durability) and methods (compaction procedure, asphalt laying procedure).
2. Control of the end-product or road surface (smoothness and skidding resistance).

Both categories are vital to ensure an effective QC measure is in place. While checking the quality of material and methods should result in a high-quality road surface, post-construction quality checking of the road surface is also important to confirm this. Control of the end-product ensures that the road complies with the standards, is safe to be used and will last for the expected life. Conducting the two QC categories will also ensure that the involved parties would be responsible for the quality of their parts and the final product – road infrastructure. There are surely various road defects that are used to evaluate the functionality and serviceability of the pavement. However, the proposed QC framework only focuses on the quality control during and immediately after construction and therefore the assessment of the road during the rest of its lifetime was not the main focus of the study.

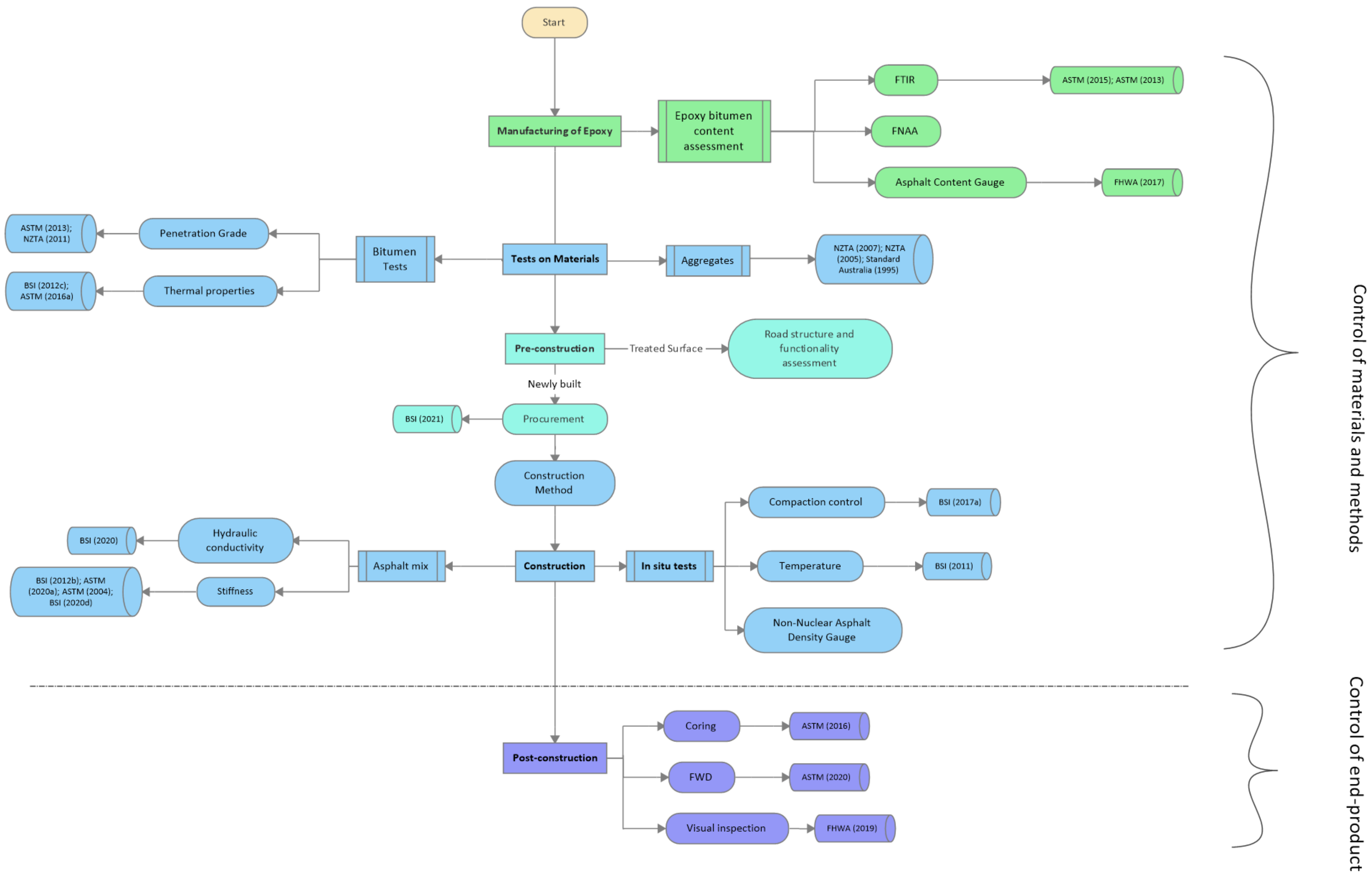

Figure 17. Adopted framework for QC of epoxy bitumen surfacings

4.4.4 Fourier transform infrared spectroscopy (FTIR)

Control of road construction material is normally done through various in situ and/or laboratory tests, as have been discussed in sections 4.4.2 and 4.4.3. The control procedure for the methods normally involves checklists and specifications. Usually, the first stage of the material controls starts with the ones provided by suppliers. CRISPS project involved epoxy bitumen as a road surfacing material, a relatively complex material and hence requiring rigorous measures to control its quality.

The FTIR method is used as a standard test to determine the composition of binder, including its components, based on the unique absorption of energy by various molecules (28). Although there is no specific standard for bitumen analysis, ASTM discusses the use of FTIR for material testing (29; 30). In infrared spectroscopy (IR), radiation is passed through a sample. Some of the infrared radiation is absorbed by the sample and some of it passes through (transmitted). The resulting spectrum represents the molecular absorption and transmission, creating a molecular fingerprint of the sample. FTIR measurements can be extremely accurate and reproducible, making it a reliable technique for sample identification. The high sensitivity enables the identification of contaminants or changes in the sample's composition.

In this project FTIR equipped with Attenuated Total Reflectance (ATR) was used with advantages of small samples, but also being effective in testing both solid, viscous, and liquid samples such as bitumen without any additional and special sample preparation. The penetration depth of the IR beam is only 1-2 µm and heterogeneous samples, leading to different spectra of IR absorption for analysis [13].

FTIR method is based on its ability to absorb/transmit IR light, due to differences in chemical composition of materials. This was successfully demonstrated by other researchers. Some of them have focused on the impact of modifiers such as epoxy on the bitumen chemistry and rheology (28; 31; 32; 33), oxidation, i.e. determining the content of oxidants H_2O_2 and HNO_3 (34; 35; 36; 37) and fatigue and healing properties (38). Weigel and Stephan (28) investigated the application of FTIR for determining physical and chemical properties of bitumen. They were able to determine the bitumen content, softening point, penetration factor and shear modulus of the bituminous binder at various temperatures. Xing et al. (39) combined the atomic force microscopy (AFM) method with infrared spectroscopy to analysis bitumen chemical composition and aging behaviours. Wang et al. (40) successfully employed FTIR to investigate the swelling of rubber in crumb rubber modified bitumen surfacing. The effect of laboratory induced aging on the chemistry and rheology of crumb rubber modified bitumen was also investigated (41).

However, although the FTIR methodology has become the standard approach for assessing bitumen content of the sample, for epoxy bitumen it has a number of drawbacks, including being labour intensive compared with the FNAA method. Furthermore, while the FTIR method measured non-reactive chemical groups in the epoxy materials, investigation of the procedure showed that the results could be affected by the extent of curing or the temperatures during short-term ageing of the epoxy bitumen (42). It should be noted that ageing of bitumen can be split into two phases; the short-term ageing occurring during production, transport and compaction of bitumen when temperatures are higher (approximately 130°C), and the oxidation rate is high due to easy uptake of oxygen into the bitumen; and the long-term ageing due to pavement exposure to both traffic and climatic conditions. As mentioned above, it is critically important to determine as precisely as possible the asphalt bitumen content and therefore this research investigates whether there may be a more viable approach than the standard FTIR approach which was developed for pavement mixes in general.

4.4.4.1 FTIR laboratory tests

FTIR preliminary tests were undertaken at the University of Birmingham, while an extensive testing programme was conducted at Aston University's Energy and Bioproducts Research Institute (EBRI), using the ultraviolet visible (UV-Vis) infrared spectrometer equipped with attenuated total reflectance (ATR). Samples of approximately 100 g or 200 g were prepared, with epoxy contents of 0%, 15%, 20%, 25%, 27.5%, 30% and 35%. The analysis was based on the FTIR-ATR spectra. Testing followed the guide provided by the NZTA to determine the concentration of epoxy modified bitumen (% mass) and its components in the binder used to manufacture epoxy modified open graded porous asphalt. Based on the heights and areas of the peaks from the spectra, percentages of epoxy components in the mixes from both 60/70 and 80/100 bitumen were determined. Also, a correction was made for effects due to curing of the epoxy components between sampling and measurement.

4.4.4.2 FTIR equipment

Figure 18 shows the UV-Vis infrared spectrometer equipped with ATR and the computer that houses the OMNIC™ software used for both collecting and analysing the spectra. The spectrometer was capable of measuring samples over a range of 500 to 4500 cm^{-1} at a resolution of 4 cm^{-1}. Also used were a balance with capacity of 1200 g and readability of 0.001 g, and an oven and a hotplate both able to maintain a temperature of 125°C ± 5°C. The Figure 10 shows the samples prepared by mixing epoxy with bitumen according to the supplier's recommendations, while Figure 11 shows a specimen of the sample fixed on the ATR's crystal for recording of the spectrum.

A specimen of the sample fixed on ATR

Figure 18. FTIR tests set up at EBRI

4.4.4.3 Results and discussion

The analysis of FTIR spectra used a semi-quantitative approach that considered the heights and areas of the spectra corresponding to the carbonyl and sulfoxides molecules that significantly affect the hardening and curing of the epoxy modified bitumen. Both epoxy concentration and curing curves were developed, and based on the curves, calculations for the epoxy components in the mixture were performed.

When compared with the standard mixing ratios recommended by the suppliers, it was found that FTIR results could fall in the range of ±3.5%. This shows that FTIR could be an acceptable and reliable approach for determining the components of epoxy (in mass percentage) in the epoxy modified bitumen blend. Furthermore, the result of the FTIR tests agrees with the results found by the NZTA, which provided the guide followed for testing. However, as there is no standard boundary of the acceptable deviation from epoxy supplier's mixing ratios, and the fact that a few errors could occur during the weighing and mixing of components, suggesting there is a need for a recognised standard for determination of epoxy modified bitumen components using FTIR.

Typical spectra for analysis were collected. For example, Figure 19 shows the spectra for modified epoxy bitumen with epoxy content equal to 25% and the control bitumen grade 60/70. Figure 20 shows the spectra for modified epoxy bitumen with epoxy content equal to 25% and the control bitumen grade 80/100. Figure 21 shows variations at the functional groups (carbonyl and sulfoxide) when a mixture of bitumen grade 60/70 and 25% epoxy content is heated at 105^{0}C for 60 minutes, which allows to calibrate the mixtures for curing during the analysis. Details of the analysis process were provided in the WS3's Anti-fraud report (43).

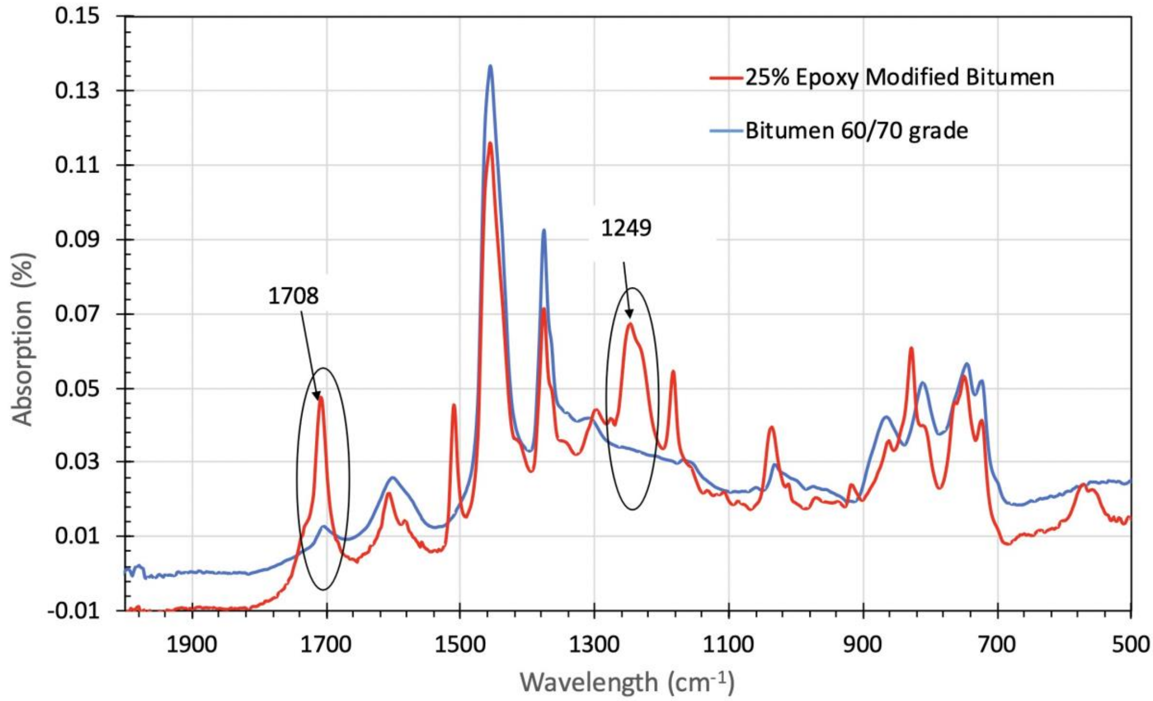

Figure 19. Spectra for bitumen 60/70 grade and 25% epoxy modified bitumen 60/70 grade

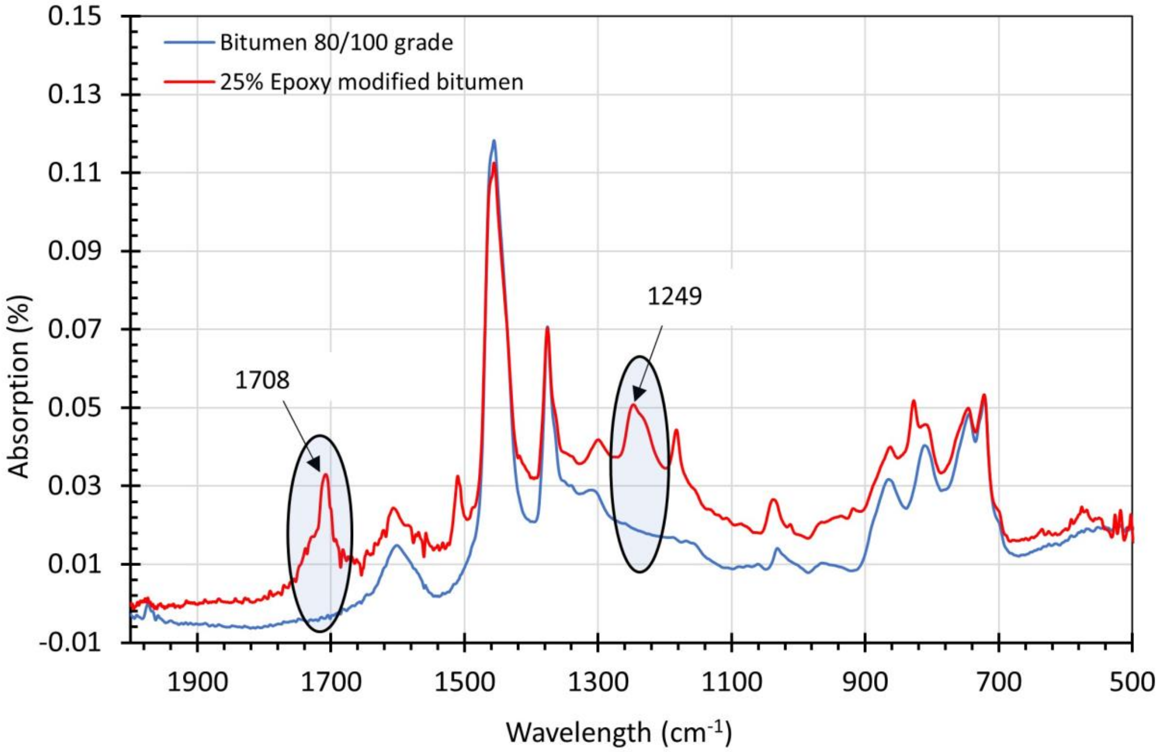

Figure 20. Spectra for bitumen 80/100 grade and 25% epoxy modified bitumen 80/100 grade

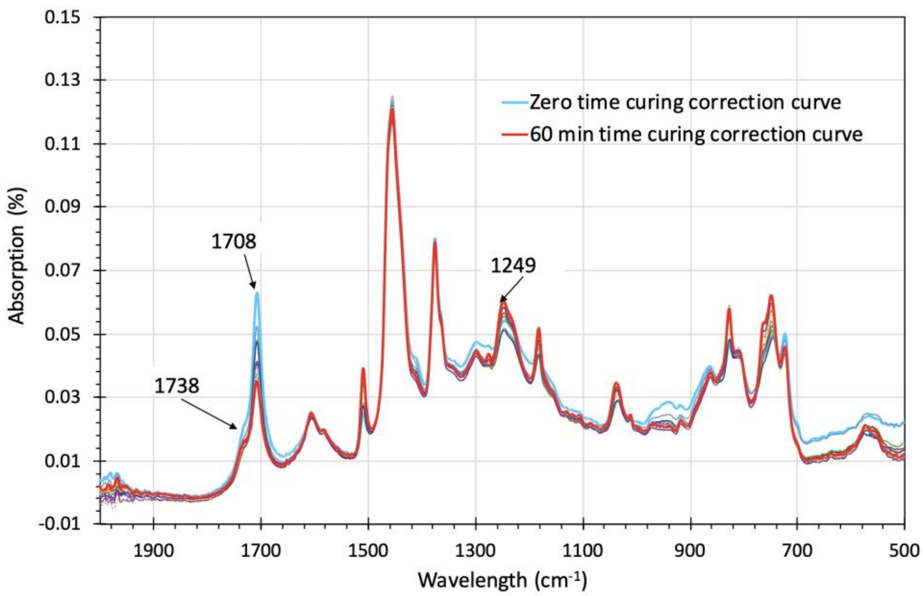

Figure 21. Curing correction curves for 25% epoxy modified bitumen 60/70 grade

The results of the analysis significantly showed that FTIR can control the content of epoxy in the modified epoxy bitumen mixes to help ensure quality control at the mix plants and therefore ensure the quality of the end results – long-life MEAS and MECS pavement surfacings. Figure 22 and Figure 23 show the comparison of epoxy contents measured during the preparation of samples and determined using FTIR, respectively for 60/70 and 80/100 bitumen grades, with indication that the differences were very small between the two measures and with strong correlations between them.

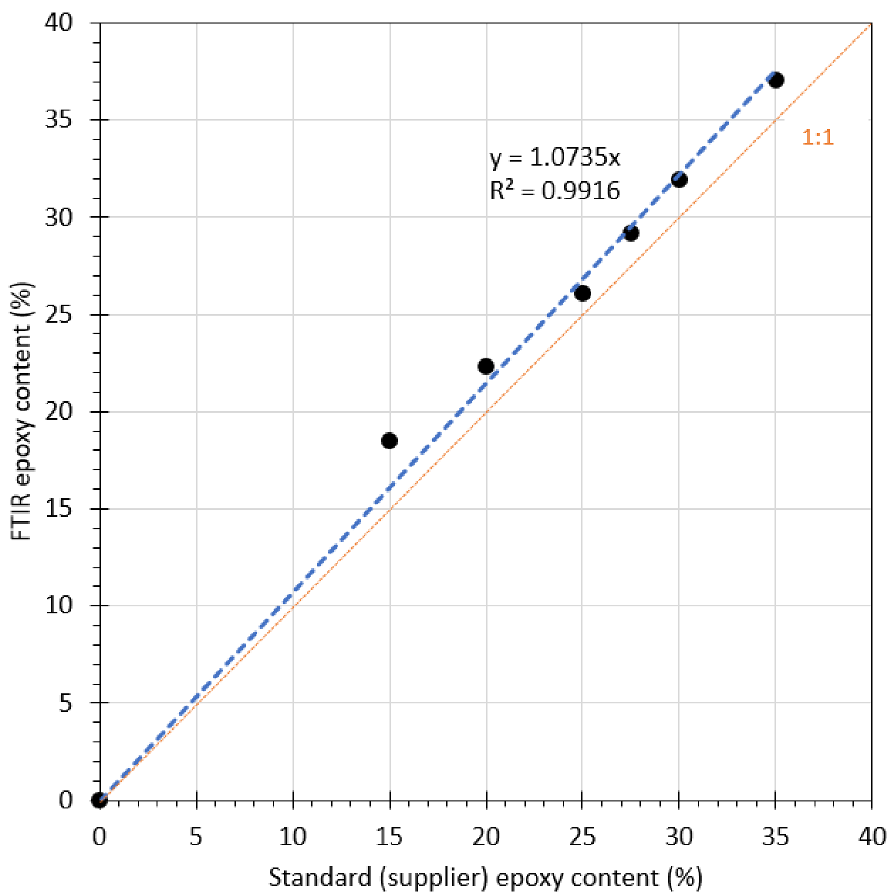

Figure 22. Correlation between FTIR and standard (supplier) epoxy content in 60/70 bitumen mixtures

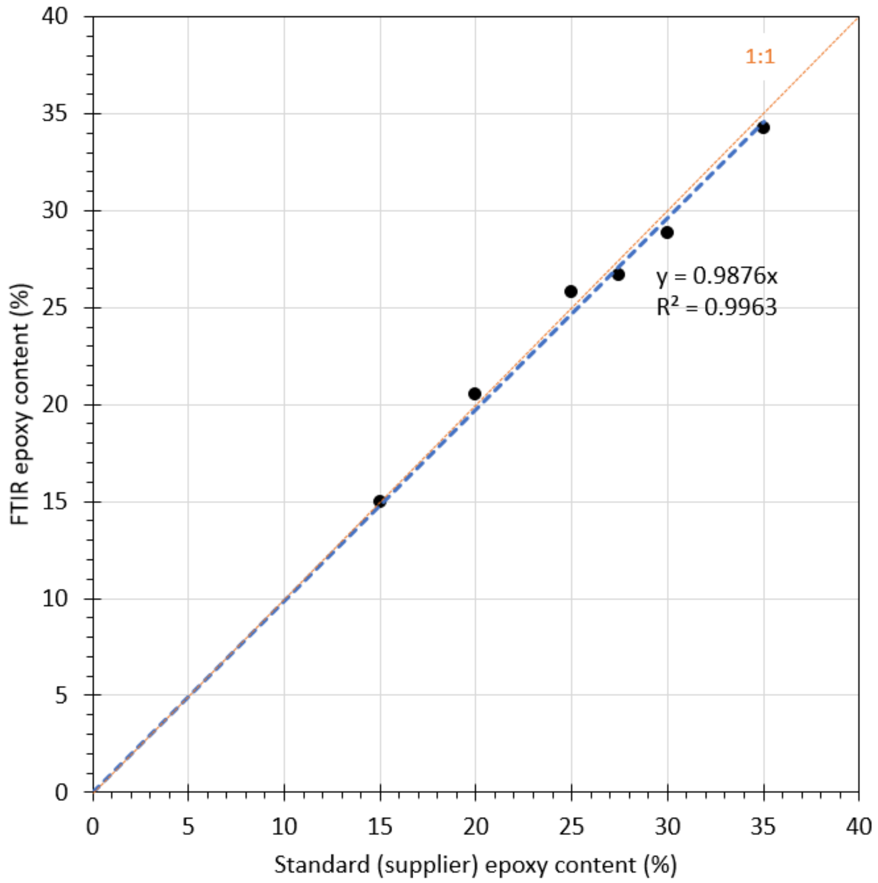

Figure 23. Correlation between FTIR and standard (supplier) epoxy content in 80/100 bitumen mixtures

4.4.4.4 Conclusions

Anti-fraud approach is extremely important during construction of epoxy modified surfacings (MEAS and MECS). This is because epoxy material is very expensive when compared to bitumen, and both sensitive and difficult to handle. Mistakes and errors in proportioning of materials, in particular proportioning of epoxy, will result in the surfacing mixture with less binding capabilities leading to less durable and less climate resilient surfacings.

Quality control of the raw material must be conducted by competent technicians or engineers before being used or mixed up for road surfacing using modified epoxy chip seals (MECS) and modified epoxy asphalt surface (MEAS). This include the quality of aggregates, bitumen, and then the quality epoxy.

To check the quality and prevent fraud of epoxy, FTIR tests on the epoxy components (epoxy resins and curing agent). FTIR spectra must be compared to the spectra of the epoxy components provided in the WS3's Anti-Fraud report (43) to ensure that they have the same chemical composition. Other properties such as penetration and softening point are usually provided by the supplier, but according to NZTA (44) and ASTM (45), epoxy's softening point should range from 60°C - 80°C, while the viscosity at 165°C should be < 200MPa. The specific gravity at 23°C ranges from 1.16 - 1.17 for Part A and 0.98 - 1.02 for Part B. However, it should be noted that the safe handling temperature is approximately 150°C, the short-term storage (less than 5 days) temperatures range from 125°C - 130°C, and long-term storage (more than 5 days) temperatures should be < 100°C, while the mixing temperatures are also between 125°C and 130°C. The minimum compaction temperature is 80°C.

For the mixtures of epoxy modified bitumen, FTIR tests should be carried out to ensure that epoxy-bitumen has the same spectrum as determined by the laboratory tests prior to confirming the appropriate mix design for the project. If the same spectra are obtained, it confirms that the right proportions of bitumen and epoxy were used (bitumen and epoxy components) at the mix plant.

During the tests undertaken for the CRISPS project, FTIR proved to an effective and nearly accurate equipment to prevent fraud. For example, for the target mix with a 25% epoxy content (by weight), the absorption peak was approximately 0.07% and 0.05%, respectively for the sulfoxide and carbonyl groups of the mix containing 60/70 bitumen grade. Similarly, the absorption peak was approximately 0.05% and 0.03%, respectively for the sulfoxide and carbonyl groups of the mix containing 80/100 bitumen grade. For the 25% modified epoxy bitumen, the ratio of the area of the sulfoxide group's peak to the area of the carbonyl group's peak (A_{1249}/A_{1725}) was found to be approximately 0.76 and 0.72 for the mix containing 60/70 and 80/100 bitumen grade respectively. The spectra of the mixes were similar to those obtained in NZ, irrespective of both epoxy and bitumen being supplied from the UK while the NZTA used epoxy supplied from the US. Tests should be undertaken using FTIR spectroscopy with Attenuated Total Reflectance, capable of producing spectra in the range of 400 to 2000 cm^{-1}, use a resolution of 4 cm^{-1} and 24 scans or more for each sample tested. A triplicate of spectra should be recorded for each sample and averages considered for determination of heights and areas of peaks.

Therefore, FTIR laboratory testing results showed that the method is reliable, simple and feasible in the context of LICs as it is easily available ad cost effective for controlling the quality of fresh epoxy bitumen mixture; ensuring prevention of possible fraud related to materials at the mix plants, which, if it happens, can contribute to substandard pavement MEAS and MECS surfacings.

4.5 Constructability Trials

4.5.1 Introduction

The Work Stream 4 was dedicated to the constructability of trial sections of MECS, MEAS and FMA surfacing technologies in Ethiopia. Constructability, in this case, is defined as the ease of constructing the surfacings using the plant and equipment typically available to a LIC road agency, or its contractors, such as the Ethiopia and many other African and Asian countries. The reasons for the selection of Ethiopia for the constructability trials include:

i. Ethiopia's strategic road network is subject to a variety of environments and traffic levels which can be representative of many LICs.
ii. An assessment of potential partner countries in Part 1 of the HVT programme found that Ethiopia was ranked in the top three LICs in Sub-Saharan Africa and was well placed to support and benefit from Part 2 research.
iii. The University of Birmingham's (UoB) Roads Group has established close research links with the Ethiopian Roads Administration (ERA) over several years, including undertaking a five-year research and capacity building programme for ERA to improve the resilience of Ethiopia's roads and, ERA agreed to support the constructability trials in its letter supporting the UoB's project application.

4.5.2 Constructability trials - sites selection

Since the purpose of this phase of the research was to demonstrate the constructability of the three technologies (and not in-service performance), a pragmatic approach was taken for the selection of the trial sites, whereby site selection was based on ease of access from ERA's Road Research Centre (RRC), located in Kality, Addis Ababa. The suitability of the roads to be used for trials constructability also was checked using the guidance published in COTO (46). For the MEAS and FMA technologies it was necessary to choose sites adjacent to road sections where ERA had planned to undertake major periodic maintenance during the project's time frame as two of the technologies required the use of a mobile surfacing batching plant, which is both expensive and time consuming to arrange and move to site. Accordingly, it was decided to consider building both technologies on adjacent sections on the Awash - Meiso road (A10 - Trunk Road). Trial section for the application of MECS was selected along the Link Road connecting the towns Modjo and Edjere (B51). Mean monthly rainfall in both the areas is about 70 mm and maximum temperature is 37 °C and 28 °C respectively for the Awash-Meiso and Modjo- Edjere sections. The coordinates of the location of the trial sections are shown in Table 9 whereas temperature, rainfall and traffic data are given in Table 10. The control sections, designed and built in accordance with the ERA design manual for flexible pavements (24), were built adjacent to the trial construction sections. Locations of the road sections are shown in Figure 24.

Since MEAS, MECS and FMA surfacings are more durable compared to conventional asphalt it was necessary to record the details of the existing pavement construction, undertake road and drainage surveys (in both wet and dry seasons) prior to surfacing works. However, properties of the road construction materials used in the construction of the Awash – Meiso road were not known. Therefore, an intrusive ground investigation, which included determinations of particle size distribution, compaction characteristics, Atterberg limits, linear shrinkage, CBR, Specific gravity and water absorption characteristics of the various materials, was undertaken in the sections of roads identified for trial construction. The characteristics of the more recently completed Modjo-Edjere road were already known, so an investigation was required. The thicknesses of the pavement layers of the two roads shown in Table 11.

Both the trial sections are generally at grade or small embankments. The two drainage surveys showed that the roadside drainage was generally well maintained and in good condition. The road condition survey showed that both the roads were in good condition with minimal failures and with few areas where rut depths exceeded 5 mm.

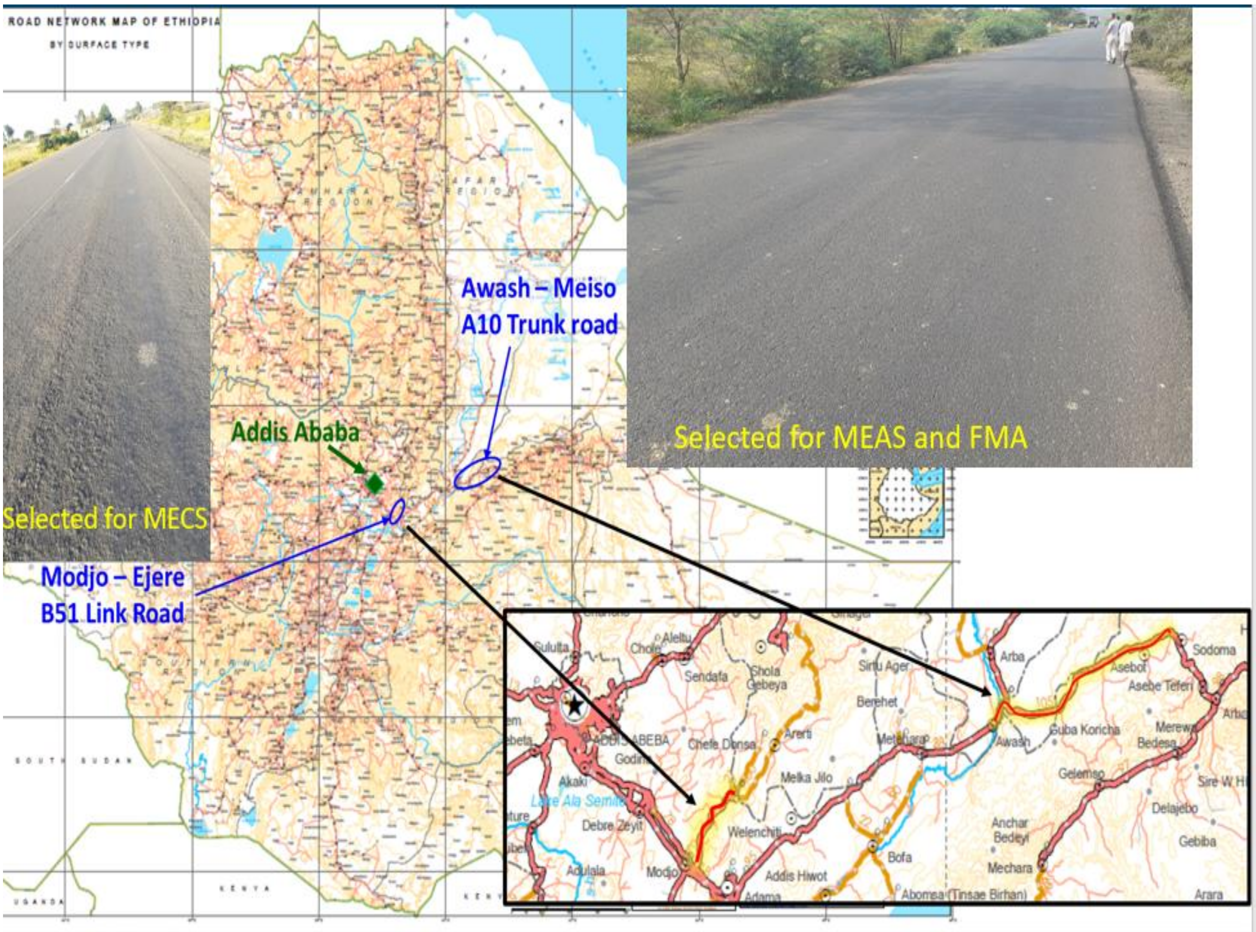

Figure 24. Location of the roads for trial sections

Table 9. Locations of Awash-Meiso - trial section

Road segment	Location of the trial section from Awash/Mojo-Edjere	Location of the trial section from Addis Ababa	Remark
Awash - Meiso	31+100 - 31+200	256+100 - 256+200	FMA trial section
	31+400 - 31+500	256+400 - 256+500	Control section
	31+650 - 31+750	256+650 - 256+750	MEAS trial section
Modjo – Edjere - Arerti	12+050-12+150	87+050 - 87+150	Control section
	12+200-12+300	87+200 - 87+300	MECS trial section

Table 10. Temperature, rainfall and traffic data for the Awash-Meiso and Modjo-Edjere roads

Road Segment	Mean daily maximum/minimum temperature (°C)	Annual rainfall (mm)	Traffic
Awash – Meiso (Trunk Road)	37/4	70	>30 million – 15 years ESAL
Modjo – Edjere (Link Road)	28/11	70	84708 (ELV per lane)

ELV = Equivalent Light Vehicles

Table 11. Existing road thicknesses

Road Segment	Technology application	Pavement layer	Layer material	Thickness (mm)
Awash – Meiso (Trunk road)	MEAS and FMA	Surfacing (AC)	Asphalt concrete	120
		Base course	Crushed aggregate	150
		Subbase	Natural gravel	100 - 150
		Capping	Natural gravel	>250
Modjo – Edjere (Link road)	MECS	Surfacing (AC)	Triple surface treatment	25- 30
		Base course	Crushed aggregate	100 - 225
		Subbase	Natural gravel (Cinder)	240 - 80
		Capping	Natural gravel	≥250

4.5.3 Construction of trials

The constituent materials of all three technologies were obtained, and the trial sites identified and specifications for the design and construction of all three technologies were formulated, as detailed in the WS4's Trials Constructability report (47). As noted previous, constructability of MECS and FMA surfacings were undertaken. Detailed information on constructability of both MECS and FMA is given in WS4 report (48). Main features of constructability are described here.

4.5.3.1 Construction of MECS and chipseal control sections

This surfacings course essentially comprises single size aggregate and a two-part epoxy binder: Part A is epoxy resin and Part B is essentially hardener and accelerator. The epoxy binder is not currently widely available and was obtained from a recognised supplier in the USA, ChemCo Systems, and shipped to ERA's RRC in Ethiopia.

Since only a 100m section of road, requiring small quantities of binder, was to be constructed a conventional bitumen spray truck used for chip sealing could not be used. A trailer mounted a bitumen spray system was modified to accommodate a second spray tank, pump and a flow control system. The two parts were pumped through two, 1.75m long spray bars with nozzles set at 15° to the axis of the bar and 15° to vertical such that there two components of the binder mixed by impingement about ¾ distance to the road surface. The MECS trailer set up and the arrangement of the two spray bars is shown in Figure 25.

The two-part epoxy binder was applied at a rate of 1.2l /m^2 (Part A 0.3l/m^2 and Part B 1.0l/m^2). Part A was heated to a temperature of 78°C and Part B was heated to 160°C. Road surface temperature before application of the epoxy binder was 37°C and the ambient air temperature was 26°C. Application of both epoxy and bitumen binder is shown in Figure 25.

Figure 25. Set up of the MECS plant and the spray bars.

Figure 26. Epoxy binder application for MECS

80/100 penetration grade bitumen was applied at an application rate of 0.78l/m^2 at a temperature of 175°C (range 165°C - 190°C) for the control section. The pavement surface temperature was 40°C and the ambient air temperature was 28°C when the control section was constructed. Binder application for the control section is shown in Figure 27.

Figure 27. Application of binder for the control section.

10 mm chippings were applied at the rate of 10 kg/m^2 for both MECS and the control section. Chips were rolled with 4 passes of the steel wheel roller followed by 8 passes of the pneumatic tyre roller.

The MECS and the control sections was closed for 6 days to allow curing of the binders before opening to traffic.

4.5.3.2 Construction of FMA and asphalt concrete control sections

The FMA requires the addition of fibres extracted from the waste generated from the oil palm tree and whilst it may be feasible to source fibres of similar characteristics locally in Ethiopia, the fibres need to be processed using a precise methodology. Consequently, and given the time frame of the project, it was decided to de-risk the trial and obtain the processed fibre from the Malaysian supplier, NOVAPAVE SDN BHD, who manufactures the material on behalf of the Malaysian Ministry of Transport for its use in Malaysian roads.

FMA was designed as an overlay and compared to an AC overlay. The former was designed in accordance with the guidance provided during the project by the University of Putra Malaysia, which are detailed in the WS4 report (47). Details of the materials, plant and the methodology used in the construction of both the FMA and asphalt surfacing overlay used in the control sections are described WS4 report (47).

Although much work had been undertaken on FMA in Malaysia leading to its inclusion in their specifications, it was deemed necessary to undertake a laboratory investigation in Ethiopia to confirm the design. Extensive laboratory study was undertaken to firm up the design. Aim was to use the aggregate sizes normally used by ERA in the asphalt concrete, however significant laboratory work was required to confirm the design that complied with that suggested by University of Putra, Malaysia. The final design required the inclusion of an additional screen (9.5mm) to the hot bins, giving four hot aggregate bins with contains aggregate in the following size ranges: 19-12.5mm, 12.5 to 9.5mm, 9.5 to 4.75mm and 4.75 to 0.075mm. Aggregate from the four bins were mixed in specific ratios together with inert filler and active filler (Portland cement) could be missed with 5% bitumen binder to give the required mix. The final design gradation of the coarse aggregate is shown in Figure 28 and the specifications of FMA and the final design (measured) values are shown in Table 12.

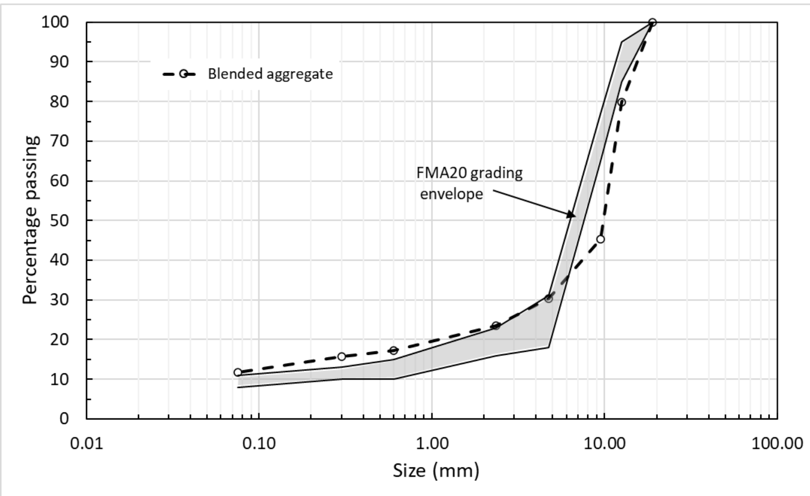

Figure 28. Mix parameters at the design bitumen content

Table 12. Summary of FMA mix design properties based on 5% bitumen content

Mix Parameter	Stability (kN)	Flow (mm)	G_{mb}	VIM (%)	VMA (%)	VFA (%)	G_{mm}
Specification	8.0	2-4	-	3-5	17 (minimum)	65-80	
Measured value	9.0	3.6	2.455	5	16.4	66.6	2.622

Where:

G_{mb} - Bulk specific gravity of the mix
VIM Voids in the mix
VMA - Void in mineral aggregate
VFA- Void filled with asphalt
G_{mm} - Maximum Specific Gravity

ERA used YLB-700 mobile asphalt batching plant, which was owned by their contractor (Yonab Construction, Ethiopia) to manufacture the FMA. It can manufacture 700kg per batch and has a capacity of 60 t/hr. It has three cold bins and three bins for hot aggregate and an additional hot bin for fine aggregate. Key parts of the plant are shown in Figure 29.

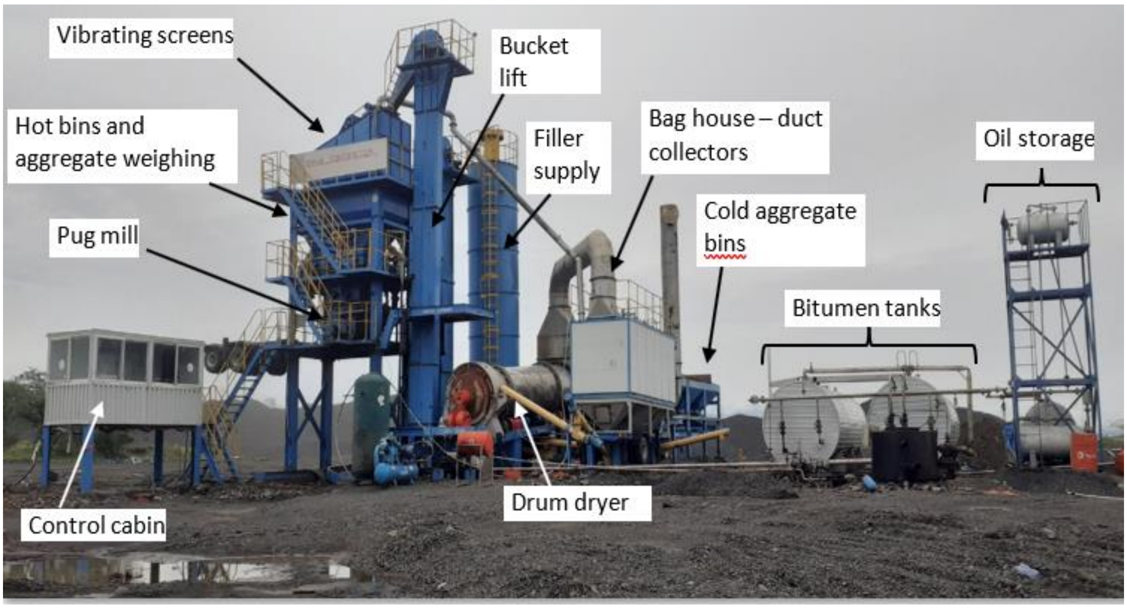

Figure 29. The TLB700 Mobile Asphalt Batching plant

A conceptual diagram of manufacture FMA is shown in Figure 30.

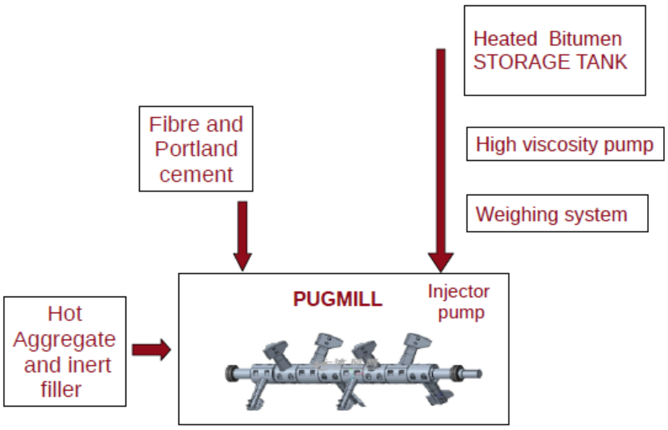

Figure 30. Conceptual diagram of manufacture of FMA.

Although the project aim was to undertake minimal modification to plant, it was deemed necessary to make two modifications to the asphalt plant to manufacture FMA complying with the design.

a. An access port was added to the top of the pugmill to add fibre pellets and Portland cement to the pugmill.
b. Add an additional screen (9.5mm) for hot bins so that hot coarse aggregate could be stored in 4 hot bins (19-12.5mm, 12.5 to 9.5mm, 9.5 to 4.75mm and 4.75 to 0.075mm).

Detailed guidance and specification of the manufacture and construction of FMA are also included in the WS4 report (47).

The trial site was about 5.6km (12-minute journey) from the asphalt batching plant. Both the FMA and control sections were constructed between 8th and 10th April 2023. Both the sections were both 70m long and 3.5 m wide. Both materials were placed in accordance with ERA's standard procedures, with no modifications. In line with ERA's standard practice. RC-70 tack coat was applied to the cleaned road surface before construction the overlay layer.

A summary of the FMA construction trial is shown in Table 13.

Table 13. Summary of the FMA construction trial

Description	Values and Remarks
Aggregate temperature when input into pug mill (°C)	210
Time for dry mix with fibre (sec)	35
Time for wet mix (sec)	40
Temperature of FMA when discharged into truck (°C)	160
Distance and time to site (km)	5.6 (12 minute journey)
Road surface temperature(°C)	45
Laydown temperature(°C)	150
Mat thickness (mm)	65
Thickness of compacted FMA (mm)	50
Density of compacted FMA (Mg/m^3)	2.39
Road surface temperature when opened to traffic	Opened to traffic after 5 days. Pavement temperature at the time was about 43°C.

Construction of the FMA surfacing is shown in Figure 31.

Figure 31. Construction of FMA surfacing

4.5.4 Conclusions

From the research undertaken by the team and observations from trials constructability, the following can be concluded:

1. MEAS Trial Constructability – although the MEAS was not constructed, based on the work undertaken the following conclusions were drawn:
    - For MEAS, the critical part of the process is to ensure correct mix ratios of Parts A and B are essential to ensure a strong yet economical binder.
    - Maintaining temperatures within certain limits is essential for Part A and Part B, during manufacture.
    - Transport and haulage distances must be checked against temperature losses to ensure that MEAS is laid down at the correct temperature.
    - Placement and compaction of MEAS is as for usual asphalt. Compaction should be carried out within the recommended ranges.
    - Opening the road section to the traffic must not be rushed and is only acceptable when the MEAS surfacing is 50°C or less.
    - Significant modifications were required for the YLB-700 type mobile asphalt plant to manufacture MEAS. The plant could be used to manufacture normal asphalt even after the modifications.
2. MECS Trial Constructability:

   - Temperature control for both parts of the epoxy binder is critical.
   - Ensure that the parts A and B are mixed in the correct proportions.
   - Correct choice of the chips is essential as it has significant impact on the rates of application of the binder and on the costs of the project.
   - Whilst it was possible to modify the existing spray truck for the trial project, it would have resulted in much wastage for small projects. The small towed trailer mounted spraying system developed by ERA for this project was adequate.
3. FMA Trial Constructability:
   - Temperatures control is essential for the manufacture, transport and both placement and compaction of FMA.
   - It is possible to manufacture FMA with minimal alterations of mobile asphalt batching plant such as YLB-700 used in this study.
   - Appropriate and verified proportions of materials must be used.

4.5.5 Lessons learned from constructability trials

The Constructability Trial work stream of the CRISPS project was a complex undertaking requiring the application of new technology in a developing country. It was new to the engineers and operatives at all levels in ERA and required modifications to both plant and their existing practices. A number of the activities undertaken proved more challenging than envisaged. In addition to this overseas experts' input could only be provided remotely. In addition to the above the constructability trial for the FMA was undertaken on a Trunk road, which made it imperative to ensure that both the mix design and the construction methods adopted would negate the possibility of premature failure of the surface. Key lessons learned from the Work Stream 4 of the CRISPS project are described below.

- <u>Planning for unforeseen circumstances:</u> It was difficult to plan for events such as COVID-19, which resulted in delays in transporting materials to Ethiopia, bureaucracy and construction plant breakdown. The impact of COVID-19 on travel restrictions also meant that all the capacity building work was done remotely via video links, except one workshop that took place in Ethiopia. This, at times, was very challenging as internet access in the field was difficult.
- Information about in-country resources: Information about the asphalt plant and the chipseal equipment was not readily available for various reasons, including changes in contractors' personnel and lack of expert input from the plant supplier as was the case with the asphalt batch plant. This resulted in a delay in getting the required information to assess the extent of modifications required. The plant supplier and their contractor were slow to respond to ERA's requests for information about the performance and capability of their plant.
- <u>Cost of capacity building and construction</u>: As full details of the work required in Ethiopia could not be determined at the start of the project, it was difficult to cost it. At the end of the project, ERA contribution was estimated to be about $50k.

5. Research Uptake and Capacity Building

5.1 Introduction

The research uptake and capacity building adopted the strategy that involves communications, dissemination, and skills transfer. The research uptake and capacity building formed a cross-cutting work stream (CCWS) where all the other work streams (WS) were involved.

5.1.1 Communications

Effective means of communication were used during the implementation of the project to ensure meaningful engagement from LIC stakeholders. These included a mixture of traditional, social media platforms, email communication and direct engagement with individuals and via organizations. To this end, some examples of effective communication can be listed:

- A website for the project was created on the University of Birmingham's platform to improve the visibility of the project in the research community (https://more.bham.ac.uk/hvt-crisps/about-the-project/). On the website, the interested public could easily access information about the project research team, background and progress of the project, and major events ahead about the project.
- Other University of Birmingham's websites for promoting research and education (e.g. https://www.birmingham.ac.uk/news/2023/connecting-communities-climate-resilient-transport-infrastructure-in-an-increasingly-complex-world).
- A LinkedIn group was created and effectively used to communicate major events such as webinars and workshops about the project as well as sharing and exchanging ideas with global researchers (https://www.linkedin.com/groups/13920510/?lipi=urn%3Ali%3Apage%3Ad_flagship3_groups_index%3BuQoTH6BGSxGBc62zlAxcsA%3D%3D).
- Webpages describing the project activities were be hosted through the IRF's knowledge Centre –i.e., The Global Transport Knowledge Practice (gTKP) www.gtkp.com). The examples of these activities include webinars (e.g. https://irfnet.ch/event/crisps-policy-dialogue-supporting-the-development-of-climate-resilient-road-infrastructure-an-agenda-for-change/), reading packs (e.g. https://irfnet.ch/wp-content/uploads/2022/02/CRISPS-Reading-Pack-03-Quality-Control-Methods-03-02-22-1.pdf ; https://irfnet.ch/wp-content/uploads/2022/02/CRISPS-Reading-Pack-04-Fourier-transform-infrared-spectroscopy-Final.pdf) and newsletters (e.g. https://irfnet.ch/2022/03/23/crisps-newsletter-march-2022/).
- ASCE's website (e.g. https://www.asce.org/publications-and-news/civil-engineering-source/civil-engineering-magazine/article/2022/03/established-road-surfacing-technologies-being-tested-in-ethiopia).
- Transportation Sciences Network's website (e.g. https://www.transportationsciencesnetwork.org/event/new-technology-road-surfacing-constructability-trials-ethiopia-planning-and-setting).
- World Highways' website (e.g., http://www.worldhighways.com/wh6/feature/epoxy-resins-resilient-roads-ethiopia).
- The UoB's School of Engineering and the IRF's Twitter accounts.

5.1.2 Disseminations

5.1.2.1 Journal papers

Three journal papers have been written to completion or under preparation. These are:

1. E. Ngezahayo, M. Burrow, N. Metje, M. Eskandari Torbaghan, G. Ghataora, T. Henning, R. Muniandy and Y. Desalegn. Investigating the Effectiveness of Fourier Transform Infrared spectroscopy (FTIR) as an Anti-Fraud Approach for Modified Epoxy Asphalt Mixes in Developing Countries. Sustainability J., Special Issue: Sustainable Road Pavements, 2023. (100% complete).
2. M. Burrow, E. Ngezahayo, G. Ghataora, N. Metje, M. Eskandari Torbaghan, and T. Henning. Life cycle analysis of epoxy modified surfacings in Ethiopia – More Engineering and economic benefits than thought. Sustainability J., Special Issue: Sustainable Road Pavements, 2023. (75% complete).

3. G. Ghataora, M. Burrow, R. Muniandy, E. Ngezahayo, N. Metje, M. Eskandari Torbaghan, T. Henning, Y. Desalegn and H. Tse. Construction of Fibre Mastic Asphalt Trial Road Surface in Ethiopia – a case study. Journal of the South African Institution of Civil Engineering. (25% complete).

5.1.2.2 Conference papers

Two conference papers were presented during the PIARC/SARF Africa Regional Conference in South Africa:

1. G. Mathieson, T.F.P. Henning, S.B. Costello, M.E. Torbaghan, N. Metje and M.P.N Burrow. Climate resilient and sustainable road pavement surfacing for developing countries. PIARC/SARF conference, 2022
2. M. Burrow, G.S. Ghataora, Y. Desalegn, H. Tse, R. Muniandy, N. Metje, M.E Torbaghan, E. Ngezahayo, and T. Henning. Constructability of Epoxy Asphalt and Fibre Mastic Asphalt Surfacings in Ethiopia. PIARC/SARF Conference, 2022.

5.1.2.3 Newsletters

Three newsletters were published via IRF's Centre for Global Knowledge Transfer:

1. E. Ngezahayo. Development of an Anti-fraud and Quality Control Method for MEAS and MECS Mix Designs. CRISPS Newsletter – March 2022.https://irfnet.ch/2022/03/23/crisps-newsletter-march-2022.
2. G. Mathieson. Deterioration Model Development. CRISPS Newsletter – February 2022. https://irfnet.ch/2022/02/10/crisps-newsletter-february-2022.

5.1.2.4 Reading packs

Six reading packs were availed and usually a reading pack for each webinar, except the third webinar that was accompanied by two reading packs.

1. CRISPS 5th Webinar: New Technology Road Surfacing Constructability Trials in Ethiopia: Planning and Setting Up. Reading pack (https://irfnet.ch/wp-content/uploads/2022/04/CRISPS-Reading-Pack-05-Constructability-Trials-FINAL.pdf). May 5, 2022.
2. CRISPS 4th Webinar: Developing a Quality Control Framework for Epoxy Bitumen – From Theory to Practice. Reading packs (https://irfnet.ch/wp-content/uploads/2022/02/CRISPS-Reading-Pack-03-Quality-Control-Methods-03-02-22-1.pdf; https://irfnet.ch/wp-content/uploads/2022/02/CRISPS-Reading-Pack-04-Fourier-transform-infrared-spectroscopy-Final.pdf). March 1, 2022.
3. CRISPS 3rd Webinar: Epoxy Modified Bitumen – Performance from Laboratory Test, Trials and Applications to Date. Reading pack (https://irfnet.ch/wp-content/uploads/2021/12/CRISPS-Reading-Pack-02-Epoxy-Surfaces.pdf). December 14, 2021.
4. CRISPS 2nd Webinar: Fibre Mastic Asphalt Technology – A Novel Material for More Resilient Roads. April 15, 2021.
5. CRISPS 1st Webinar – Introducing the Climate resilient sustainable road pavement surfacings. Presentations (https://irfnet.ch/wp-content/uploads/2020/12/0-CRISPSWebinarOpeningSlidesDissemination.pdf; https://irfnet.ch/wp-content/uploads/2020/12/1-Obika_IntroductiontoHVT.pdf; https://irfnet.ch/wp-content/uploads/2020/12/2-Burrow_CRISPSPresentation_Webinar1_Burrow.pdf; https://irfnet.ch/wp-content/uploads/2020/12/3-HenningCRISPSPresentation.pdf; https://irfnet.ch/wp-content/uploads/2020/12/5-GathaoraCRISPSPresentation_Webinar1_Ghataora.pdf). December 10, 2020.

5.1.2.5 Webinars

The five webinars were attended satisfactorily by attendees from academia, civil societies, donors, governments, private sectors and others globally. Figure 32 to Figure 37 describe the distribution of attendees for each of the webinar. Also Figure 3 gives the average distribution of the participants to the webinars while Figure 38 shows the geographical location of participants by countries.

- CRISPS 1st Webinar – Introducing the Climate resilient sustainable road pavement surfacings. Presentations: 169 from 47 countries.

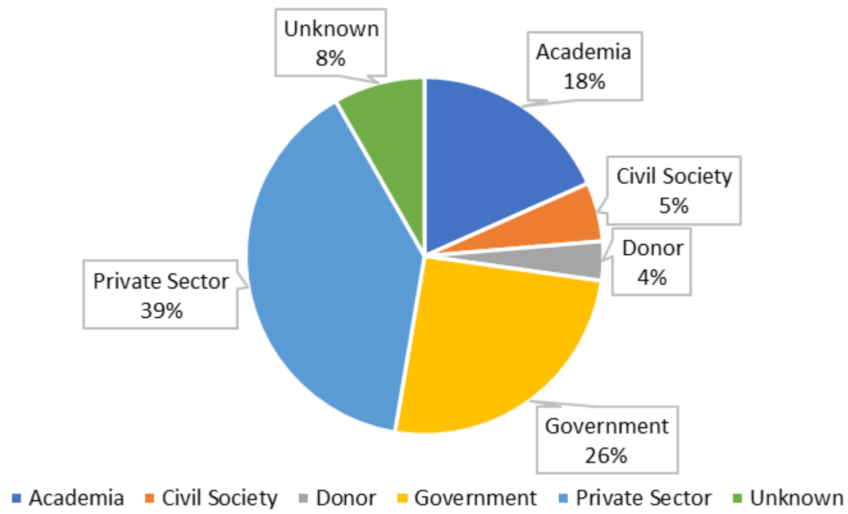

Figure 32. The 1st CRISPS webinar: Distribution of participants

- CRISPS 2nd Webinar: Fibre Mastic Asphalt Technology – A Novel Material for More Resilient Roads: 142 attendees from 53 countries

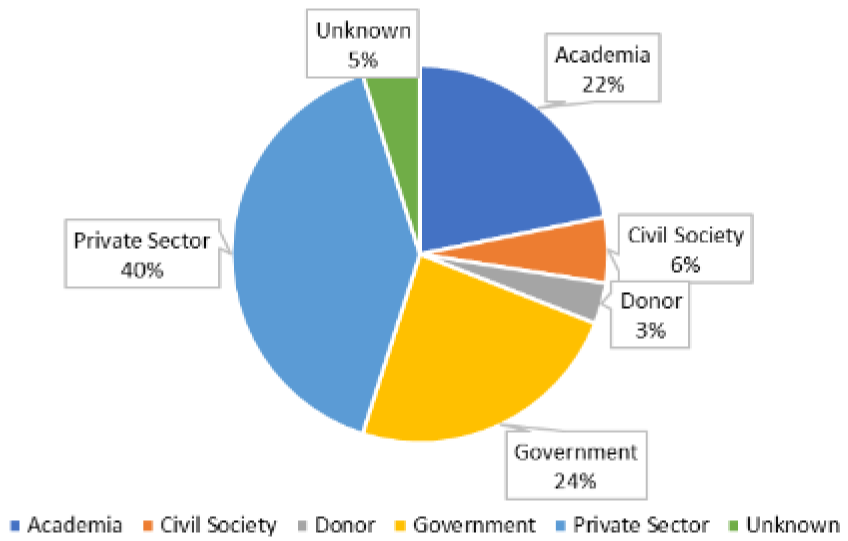

Figure 33. The 2nd CRISPS webinar: Distribution of participants

- CRISPS 3rd Webinar: Epoxy Modified Bitumen – Performance from Laboratory Test, Trials and Applications to Date: 40 attendees from 19 countries.

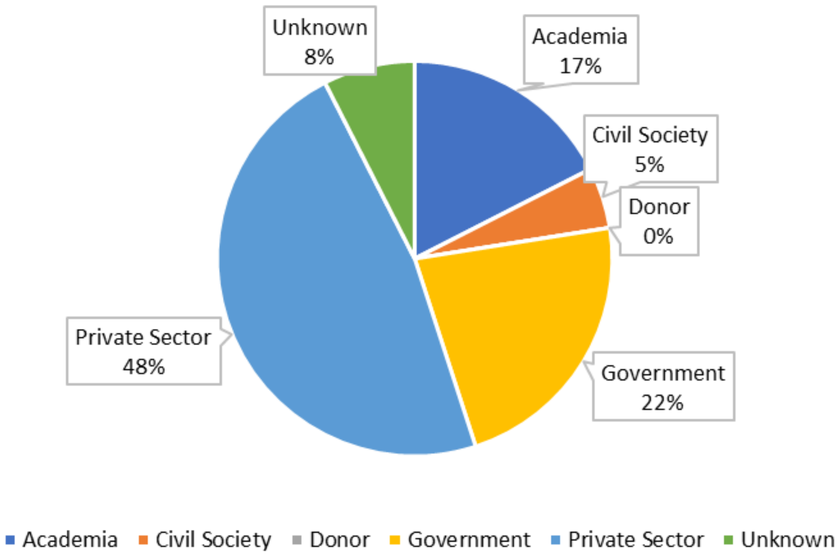

Figure 34. The 3rd CRISPS webinar: Distribution of participants

- CRISPS 4th Webinar: Developing a Quality Control Framework for Epoxy Bitumen – From Theory to Practice: 62 attendees from 28 countries.

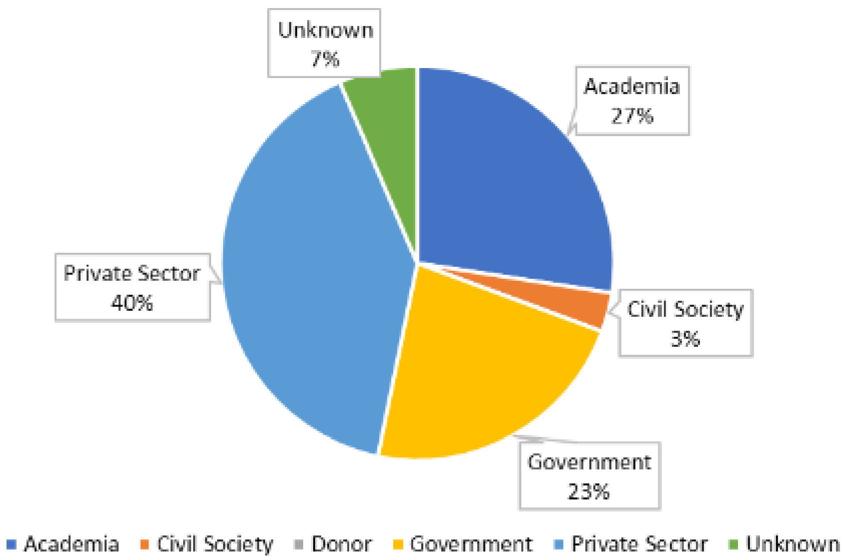

Figure 35. The 4th CRISPS webinar: Distribution of participants

- CRISPS 5th Webinar: New Technology Road Surfacing Constructability Trials in Ethiopia: Planning and Setting Up: 51 attendees from 27 countries.

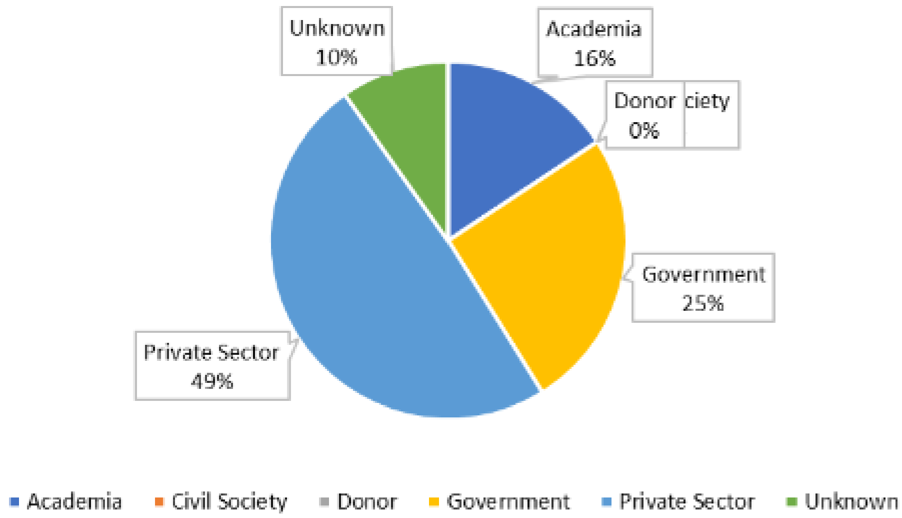

Figure 36. The 5th CRISPS webinar: Distribution of participants

- All the five CRISPS webinars: 464 attendees from 76 countries.

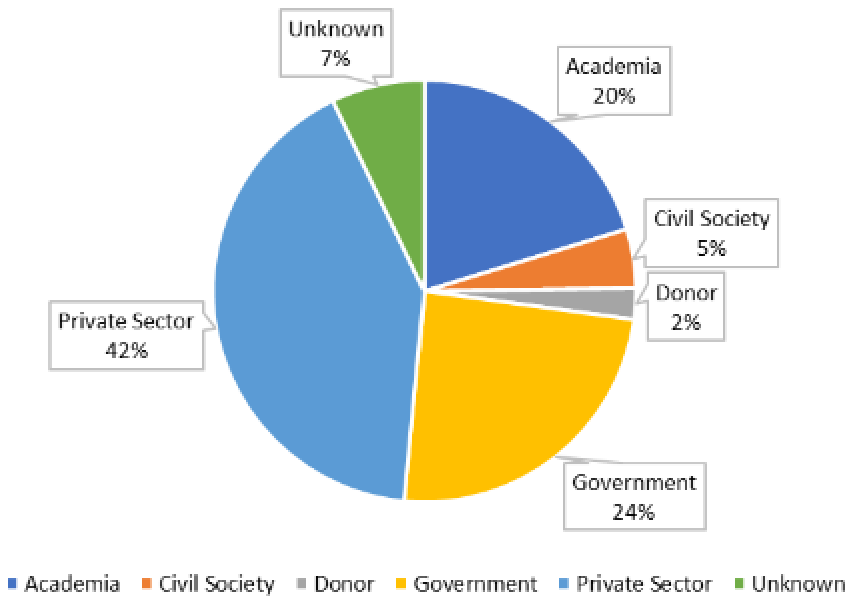

Figure 37. All the five CRISPS webinars: Distribution of participants

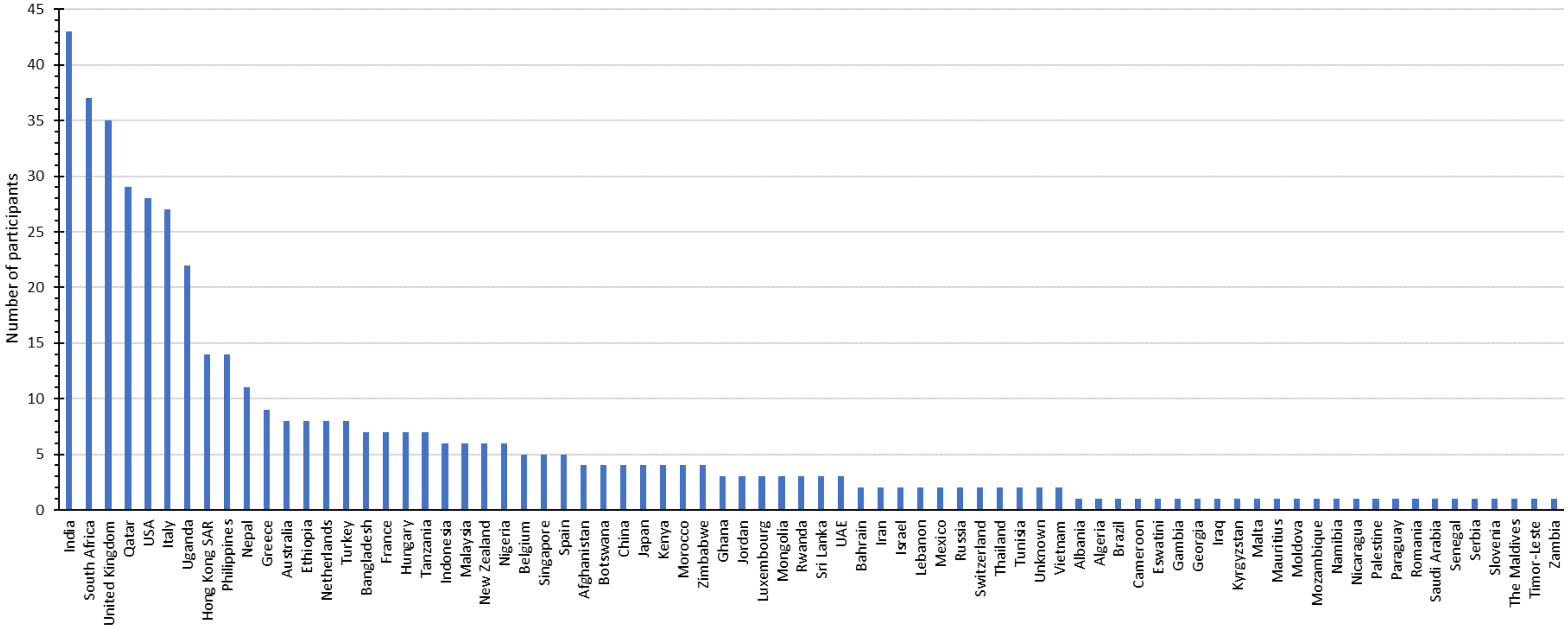

Figure 38. Distribution of participants to all the five CRISPS webinars by country

5.1.2.6 Policy Dialogue and Workshop

Policy Dialogue

The 6th CRISPS Webinar was on Policy Dialogue, with a theme of "Supporting the Development of Climate Resilient Road Infrastructure – an Agenda for Change" and took place on February 28, 2023. It was supported by a brief content (https://irfnet.ch/wp-content/uploads/2023/02/CRISPS-Policy-Dialogue-Briefing-Note-21-02-23.pdf). The policy dialogue was moderated by invited audience of 14 experts and attracted a registration of 356 participants globally.

The major reflections from the policy dialogue were:

- Reform of procurement processes can incentivise innovation, often road construction is undertaken using traditional approaches and materials. Technology may facilitate some change, the organisations that deliver change must also adapt to these changes.
- Research projects such as CRISPS are experimenting with technologies currently not applied in low-income countries. This project demonstrates the viability of these approaches but a longer duration project where we can monitor how these roads performed.
- The University of Birmingham is working closely with ERA during construction of trials, and ERA will ensure the monitoring these sections of roads for longer time, which may lead to some modification of the available information in the future.
- Trialling and adopting new technologies take time, and in the same time it does require investment, and collaboration.
- More coordination needs to happen between different agencies and development banks so that innovative projects such as this can be embedded in funding calls.
- In south-east Asia, there exists close collaboration between research programs looking at servicing trials, World bank projects looking to finance those findings from the research projects. There can be better collaboration between specific international financing institutions for projects and these research programs.
- More emphasis needs to be placed on local design and construction industry. Local design at times, is not good enough in order to address climate issues. Basic drainage, for example, is just not designed in to most roads. There is need to spend more time building the capacity of local design industry in order to create a local industry that is capable of implementing research findings.
- There needs also to be more funding to support the sharing of knowledge, facilitate collaboration and enable the dissemination of research through different partnerships. This kind of collaborative approach needs to be institutionalised through sustainable funding.
- Research teams must spend more time communicating with road authorities and outlining research funding in a collaborative and critical way. This may support the uptake of findings from once setting into another.

Workshop

The workshop took place in Capital Hotel and Spa, Addis Ababa, Ethiopia on December 8th, 2022 and gathered 30 engineers working in road sector in different roles, including those from academia. The aim of the workshop was to disseminate and discuss the findings of the CRISPS research project. The timetable for the workshop is given in and the activities under each element in the timetable are elaborated below. The key findings from each of the Work Streams' deliverables were highlighted. Figure 39 gives the picture of attendees following the workshop discussion. Table 15 gives the timetable followed, with key moderators.

Figure 39. Participants during the workshop

Table 14. Workshop moderators and timetable

Time Ethiopia	Session Title	Participants
09:00-09:30	Welcome and Introductions	Chair: Mr Yitagesu Intro Comments: The CRISPS Project (Dr Avis) Discussion and Questions (Dr Avis and ERA)
09:30-10:15	Session 1: Work Package 1 - Deterioration model development	Chair: Mr Yitagesu Intro Video: Deterioration model development Discussion and Questions (Dr Henning and ERA)
10:15-11:00	Session 2: Work Package 2 Life cycle analysis	Chair: Mr Yitagesu Intro Video: Life cycle analysis Discussion and Questions (Dr Burrow and ERA)
11:00- 11:30	Break	
11:30-12:15	Session 3: Work Package 3 Anti-fraud system	Chair: Mr Yitagesu Intro Video: Developing an Anti-Fraud System Discussion and Questions (Dr Torbaghan and ERA)
12:15-13:00	Session 4: Work Package 4 Constructability trials	Chair: Mr Yitagesu Intro Video: From Theory to Practice – Constructability Trials Discussion and Questions (Dr Ghataora and ERA)
13:00-13:30	Supporting the Development of Climate Resilient Road Infrastructure – an Agenda for Change	Chair: Mr Yitagesu (ERA) Reflections: Dr Burrow (UoB) Reflections: Ms Zammarato (IRF) Reflections: Mr Worku (ERA)

After long discussions on the findings of the deliverables, the workshop participants appreciated the following on each of the WS's deliverables:

- The participants appreciated that the deterioration models showed less deterioration rates for the trialled technologies when compared to existing or conventional surfacings.
- The participants were convinced and happy that the trialled surfacing technologies provide better economic benefits than conventional surfacings, particularly in longer time which can ease the pressure for road maintenance from LICs.
- The participants appreciated the use of FTIR for anti-fraud during manufacturing of epoxy modified bituminous surfacings, and recommended the approach to be regularly considered for quality control of bituminous surfacings in all projects. This can again reduce fraud and corruption associated with materials during road construction in LICs.
- The participants appreciated the progress made, such as the development of specifications for different trialled surfacing technologies and the innovation and creativity for modifying and adjusting the equipment to suit the materials.

5.1.3 Skills transfer

The CRISPS project has contributed to knowledge transfer through supporting research students at both PhD and Masters levels as well as during taught programmes at both undergraduate and postgraduate programmes, and at different Universities in different countries.

PhD students

- Ms Abeba B Demessie recently completed a PhD in Civil Engineering at the University of Birmingham. Her data helped during the calibration of the World Bank's HDM-4 to undertake life cycle analysis of the CRISPS surfacings technologies.

- Mr Yitagesu Desalegn is in the final year of his PhD in Civil Engineering at the University of Birmingham and will incorporate data related to Trials Constructability.

MSc projects

At least fifteen MSc projects have been given to students of the MSc programme in Road Management and Engineering at the University of Birmingham. The examples of those projects are:

- Effect of corruption and poor construction on deterioration of epoxy surfacings
- Investigation of roughness progression in epoxy surfacings

MSc and undergraduate taught programmes teaching materials

The findings of the life cycle analysis of the CRISPS technologies were integrated into the teaching and learning materials for the Road Asset Management module of the UoB's MSc in RME. Moreover, findings of the deterioration modelling of the CRISPS technologies have been integrated into the teaching and learning materials for MSc in Transportation Engineering at the University of Auckland in New Zealand. Deterioration modelling for FMA surfacing has been integrated in undergraduate taught modules at the Univerisiti Putra Malaysia.

6. Contributions from Ethiopian Roads Administration

The Ethiopian Roads Administration made significant contribution to the project, estimated to approximately 45,515.74 GBP, as detailed in Table 16 below.

Table 15. Contribution of ERA to the project

Climate Resilient Sustainable Road Pavement Surfacings (CRISPS) Project					
Costs of the project expended by the Ethiopian Roads Administration - Road Research Center					
Item No.	Description	Unit	Quantity	Cost/unit	Amount (ETB)
1	MEAS				
1.1	Asphalt concrete	m^2	400.00	1,090.88	436,352.00
1. 2	Oil/Paint	LS			5,000.00
1. 3	Lime	Qtl.	12.00	1,800.00	21,600.00
2	Labour				
2.1	Permanent staff salary	month	12.00	60,000.00	720,000.00
2.2	Allowance	day	300.00	800.00	240,000.00
3	Equipment				
3.1	Vehicle (rental)	day	75.00	3,667.00	275,025.00
3.2	Fuel cost	Lit	1,252.50	69.00	86,422.50
3.3	Tools (laboratory equipment)	LS			50,000.00
	Sub Total (A)				1,834,399.50
4	MECS				
4.1	Chips seal surfacing	m^2	400.00	1,090.88	436,352.00
4.1	Oil/Paint	LS			5,000.00
5	Labour				
5.1	Allowance	m	40.00	800.00	32,000.00
5.2	Equipment				
5.3	Vehicle (rental)	day	10.00	3,667.00	36,670.00
5.4	Fuel cost	Lit	167.00	69.00	11,523.00
5.5	Tools (laboratory equipment)	LS			25,000.00
	Sub Total (B)				546,545.00
6	Others				
6.1	Tax	LS			150,000.00
	Sub Total (C)				150,000.00
7	Others (Miscellaneous)				200,000.00
	Total project cost (ETB)				2,730,944.50
	Total project cost (GBP)				45,515.74
Assumptions: Fibre Mastic Asphalt (FMA), 50m trial and 50m control section at a width of 4m, road marking (oil paint), vehicle assigned for the field works, other tools, salary of the two experts assigned in a permanent basis, Allowances for field works.					

7. Conclusions and Recommendations

7.1 Conclusions

The following conclusions can be drawn from the CRISPS project:

- **The deterioration model development**: the key findings are that MEAS, MECS and FMA surfaces from a period performance perspective can last potentially four to six times longer than traditional surface methods (AC and DBST). With an initial cost increase of between three to five times for MEAS, MECS and FMA surfaces when compared to AC and DBST, there is confidence that the surfaces trialled during the project will be cost efficient and this was confirmed by the economic analysis factors determined during the life cycle analysis of the surfacings. Deterioration modelling findings suggest that epoxy surfaces are more resilient to climate impacts, which is particularly relevant in those countries that experience temperature increases. Typically, bitumen does not last long in hot climate conditions. It oxidizes quickly, and becomes brittle, and it cracks. Epoxy surfaces show promise by using epoxy within bitumen thus is will last longer. A secondary benefit is that when less bitumen is used over the life of the road due to less requirements in maintenance, there is a possibility to capitalise on savings in carbon emissions from the construction process and from the use of the material.
- **The life cycle analysis**: it is well known that roads stimulate economic development and the project demonstrated that first of all, epoxy and FMA materials perform better than existing surfacings under the same traffic loadings and climatic conditions. Secondly, trialled materials proved to last longer than existing materials. The project highlighted that such materials have a higher upfront cost but that over a period of, say, 30, 40, 50 years, these pavements are superior in terms of economic costs. This was shown by a discounted economic benefit analysis and even more importantly than that, the cost to the road user of using these roads is less. In other words, over the life cycle, not only is it less expensive for the road agency to use or to implement these technologies, but also for the road user the cost of driving on the road is less because the average condition over time is better.
- **The anti-fraud system**: FTIR is a relatively available method whilst FNA is not easily available. FTIR provided acceptable results determining different parts of the epoxy bitumen that were used during the CRISPS project. Given the cost and the positive results stemming from FTIR, it is recommended that FTIR be used in low-income countries, because it is affordable, and provides accurate results.
- **The constructability trials**: the key finding from this work stream is that construction using epoxy and FMA is possible in Ethiopia with minimal changes to existing plant infrastructure. When it comes to fibre mastic asphalt, fibre is imported into the country and can be added to the plant with little or no change to existing equipment or procedures.
  In terms of epoxy materials, there is a requirement to purchase a few components and for these to be added to existing plants which is feasible. For example, in terms of chip seals, it is necessary to buy specific nozzles and other fittings.
- **Research uplift and capacity building**: research uplift was well achieved through publications of journal and conference papers, newsletters, reading packs and articles in websites, presentations in webinars and workshops. Similarly, capacity building was achieved through training of PhD and both postgraduate and undergraduate students as well as engaging stakeholders in a policy dialogue.

7.2 Recommendations

The recommendations, based on the findings of this research, are essentially the need to support the development of climate resilient road infrastructure**.** Climate change is one of, if not the, most significant challenge to achieving long-term sustainable, including economic growth and development. Climate change is both a long-term issue and a contemporary challenge, it entails uncertainties for policy makers trying to shape the future. Policy makers all over the world are facing similar challenges. While we know that the climate will change, there is uncertainty as to what the local or regional impacts will be and what the impacts on societies and economies will be. For example, in Ethiopia, it is expected that there will be an increased frequency and intensity of extreme weather events, changes in season's duration and seasonal precipitation, and increased temperatures.

To enable transportation infrastructure to adapt to climate change and minimise the impact of extreme weather events, it is important to understand how roads are planned and managed and to identify weaknesses and strengths in dealing with climate change. Transportation systems have historically been designed and planned in response to past climate records. However, due to climate change, historical climate patterns are no longer a reliable predictor of the future risks. As most transportation infrastructure is expected to last for decades, it is important to understand how future climate might affect investments in the coming years. It is imperative that decision-makers appropriately consider and account for current and future extreme weather conditions during the planning, design and construction phase of the road network. There are a number of ways to better cope with these conditions, including improved climatic and design modelling, the use of more resilient materials, appropriate technical specifications and improved construction techniques.

Road authorities and administrations will need to make the case for increased cost outlay in the short term in order to deliver medium to long-term savings. This can be difficult given budget constraints and the need to demonstrate value for money. Road authorities in many settings must also work within political cycles which are often short i.e., 4-5 years between elections. That being said, the CRISPS project provides much needed evidence to support these discussions and to advocate for higher upfront costs to deliver savings in years to come. A number of key themes have been explored throughout the policy-dialogue workshop and are central to supporting the development of climate resilient road Infrastructure:

- It is imperative to build capacity at all levels and facilitate multi-stakeholder partnerships that are able to support the development of climate resilient road infrastructure.
- Such partnerships are better able to provide the human, technical and financial resources to deliver change in contexts where such resources may be limited.

Finally, to deliver on the change required, there is need to:

- Identify best practice and innovation in pavement surfacing development from across the global north and south through robust and rigorous assessment. Support partnerships and capacity building between the private and public sector built on trust and knowledge exchange. Best practice can only be transferred when supported by sufficient technical, human and financial resources in place.
- Provide platforms that facilitate knowledge sharing and transfer.

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The University of Birmingham
School of Engineering
Department of Civil Engineering
Edgbaston Campus
Birmingham B15 2TT
Website: https://www.birmingham.ac.uk/index.aspx