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EARN

Final report on effects of using reclaimed asphalt and/or lower temperature asphalt on the road network

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EARN

Effects on Availability of Road Network

Final report on effects of using reclaimed asphalt and/or lower temperature asphalt on the road network

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Executive summary

This report is the final output of the Effects on Availability of Road Network (EARN) project. The EARN project was undertaken under CEDR Call2012: Recycling: Road construction in a post-fossil fuel society in order to investigate the effects of using reclaimed asphalt (RA) and/or lower temperature asphalt on the road network.

The work consisted of a review of existing data on service lifetime and availability of road materials and structures, a site trial to evaluate varying proportions of RA, experimental evaluation of moisture damage and ageing in asphalt mixtures and development of an impact assessment model. Each of these activities has been undertaken in a co-ordinated manner.

The review of existing data showed that no databases exist to identify the influence of the use of recycled construction materials or secondary by-products on the durability of the road pavements. The application of RA in HMA can reduce the expected service life but the evaluation showed a large scatter. Furthermore, international literature shows that the use of RA in new HMA mixtures results in adequate material durability performance most of the time. However, feasible laboratory conditioning procedures are needed that can represent the long-term effects of incorporating additives and/or recycled materials into the mixture in order to allow the estimation of durability during the mix design process. It was also found that paving during adverse weather conditions will slightly increase the risk from insufficient compaction and poor interlaying bonding and the splitting of larger construction sites into smaller patches, which may be required in order to undertake maintenance during times of low traffic volume, will increase the disadvantage of an increased number of joints.

The site trial, where four different mixtures containing varying proportions of RA and warm mix additive were used, found that the site quality testing of international roughness index (IRI), mean profile depth (MPD) and corrected SCRIM Coefficient (SC) showed good asphalt material performance, although the MPD values were slightly lower than the usual national value for Ireland of 1.4 mm. Laboratory tests showed good material performance throughout a 12 month test period although the stiffness of the mixtures containing RA did decrease over the monitoring period, which may represent a cause for concern in the long term. The material resistance to water damage was good, with ITSR values above the required 80 % threshold. The mixture containing 30 % RA and warm mix additive at 12 months saw an improvement in its wet ITS value that resulted in an ITSR value above 100 % while the ITSR value for the mixture containing 40 % RA and warm mix additive decreased by 4.6 % between months 6 and 12.

The laboratory sensitivity testing showed that the inclusion of RA has an effect on mixture tensile strength with the ITS values increasing with increasing RA content; the rate of strength degradation due to moisture damage reduced for mixtures containing RA compared to control mixtures; and the use of warm mix additive increasing the resistance to moisture damage induced both by bath conditioning alone and by combined bath-MIST conditioning. Also, a change in the amount of RA content, from 30 % to 40 % did not change the dry and wet ITS and ITSR values significantly. The TSR values of the RA mixtures, with and without WMA additive, improved for the field-aged mixtures, indicating that the asphalt underwent a curing process that increased the strength with time and enhanced the response to moisture damage. The use of warm mix additive was found to increase the resistance to moisture damage induced both by bath and bath-MIST conditioning. It is recommended that ageing is considered when validating a mix design with respect to moisture damage susceptibility.

The impact assessment modelling found that generally, an appreciable CO_2e and cost savings can be observed for the novel asphalt mixtures to a greater or lesser degree with the CO_2e savings being derived from both energy savings at the plant (the lower heating and drying energy of the LTA asphalt mixtures) and the recycled content that was incorporated. Direct comparisons were possible for the surface course materials which both had a recycled content of 28.6 %; in relation to these mixtures a saving of 13 % could be attributed to lower plant energy consumption and a further 5 % saving due to the recycled content. In order to maximise energy efficiency during production of asphalt, operations should be carefully planned to avoid repeatedly switching between HMA and LTA mixtures. Overall, the carbon footprint calculation indicates a cradle-to-gate CO_2e saving in the region of 13 % to 16 % associated with the use of LTA materials over their conventional HMA alternatives.

The resulting main findings from the research are:

- The use of LTA systems, RA, secondary by-products and/or binder additives can have an effect on the durability of flexible pavements, but that affect is not always adverse and may not be great.
- The effect of using lower temperature asphalt systems, RA, secondary by-products and/or binder additives can be modelled in the expected service life of mixtures.
- Data on the effect of each specific components and the extent to which they are incorporated into the mixture needs to be collected in order to make the model more accurate.
- The MIST procedure is suitable for standardisation as an asphalt conditioning procedure in the EN 12697 series.

1 Introduction

1.1 Background

Reclaimed and secondary materials are being used evermore widely in the production of paving mixtures, primarily on the grounds of their reduced environmental impact. Similarly, hot mix asphalt (HMA) is starting to be replaced by lower temperature asphalts (LTAs) (which can be subdivided into warm mix asphalt [WMA], half warm mix asphalt [HWMA] and cold mix asphalt [CMA]) in order to lower the temperatures at which the material is produced and placed on the road. However, the assumption that their use will actually reduce the environmental impact in the longer term is rarely tested, even when that use has an adverse effect on the durability of the mixture. As a simple example, the use of 50 % reclaimed asphalt (RA) will reduce the need for fresh aggregate by half, but this advantage will be wiped out if the durability is reduced by a third and the other aspects of construction would mean that such a use of RA had a negative effect on sustainability.

In order to allow the true benefits of lowering mixture temperatures or of using reclaimed and secondary component materials in pavement mixtures to be understood, a simple methodology to analyse the true cost, environmentally and financially, is required. For such a model to be precise, it will require reliable data about the durability of the pavement with different component materials, which currently is not readily available. In the absence of such data, estimates of the durability will be needed from material test results. However, such a model could still be used with even limited data in sensitivity analyses to understand what changes in durability will do to the effectiveness of the reputably sustainable changes to construction techniques.

Some research had previously been undertaken on the durability of pavements constructed with RA, including the European Re-Road project, and the use of WMA, including the US Federal Highway Administration's International Technology Scanning Program study tour, but the data on both is limited. In the Re-Road project, the in-service durability of surface asphalt courses prepared with considerably high rates of RA were evaluated by monitoring several existing trial sites. Some of the so-far elaborated results indicate that the addition of high amounts of RA in HMA may reduce the service lifetime compared to fully new materials (Kalman, 2011). During the Direct-Mat Project (www.direct-mat.eu), a data base was established containing details on road construction projects applying various kinds of recycling techniques. Although a high number of projects were considered, generally the information on the actual long-term performance reached by the partly innovative recycling procedures is still missing. The incorporated literature review indicated several applications of RA in new HMA, but the comparable material performance is in terms of rutting and crack resistance. Nevertheless, some existing results did indicate a decreased resistance against fatigue, for mixtures containing high proportions of RA (Table 1-1).

The problem with obtaining details of the life of materials is that those materials have to have been in service for longer than their expected service lives.

Table 1-1: Experience of performance of HMA containing RA compared to control sections
(Mollenhauer *et al*., 2011)

Mixture type		HMA with x % RA has the same or better properties than comparable mixture without RA		HMA with x % RA has worse properties than comparable mixture without RA	
		Laboratory study	**Full-scale study**	**Laboratory study**	**Full-scale study**
Surface course asphalt	AC	20 5 (DRF 4.2) 40 % (DRF 4.6) 50 % (DRF 4.1)	–	–	–
	SMA	20 % (DRF 4.162) 30 % (DRF 4.14) 30 % (DRF 4.51)	–	30 % (DRF 4.162)[3]	–
	ACTL	–	30 % (DRF 4.229)	–	–
Binder course asphalt	AC	25 % (DRF 4.2) 30 % (DRF 4.15) 30 % (DRF 4.155)	–	30 % (DRF 4.155)[1]	–
Base asphalt	AC	30 % (DRF 4.12) 15 % (DRF 4.154)	–	–	–
	HRA	–	–	–	–
General HMA		30 % (DRF 4.222) 30 % (DRF 4.224) 35 % (DRF 4.160) 40 % (DRF 4.163) 50 % (DRF 4.225) 50 % (DRF 4.51) 70 % (DRF 4.181) 70 % (DRF 4.223) 100 % (DRF 4.228)	45 % (DRF 4.159)	30 % (DRF 4.222)[3] 70 % (DRF 4.223)[3] 50 % (DRF 4.225)[4]	45 % (DRF 4.159)[2]
Life cycle analysis/ Pavement performance		–	(DRF 4.161) 30 % (DRF 4.164) 20 % (DRF 4.165)	–	–

1 Higher moisture content
2 More cracking
3 Reduced fatigue resistance
4 reduced rutting resistance

1.2 Project summary

This is the final report from the EARN project. The EARN project was designed to address the durability of road structures, layers and materials containing high proportions of reclaimed road materials. In order to model the availability of the road network and the consequences for maintenance needs, traffic congestion due to construction sites and relevant model parameters were identified from the durability of road materials and structures as influenced by mix design and material composition, conditions during road works (season, day/night, weather conditions) and environmental effects.

There is a need for engineers, particularly the client's engineers, to understand the full implications of using reclaimed and secondary materials. Whilst efforts to make highway construction more sustainable are laudable, they must be effective over the longer-term and not be just reduced cost and/or environmental impact on the construction phase alone. If the use of such components in the mixtures does affect the serviceability or durability of the mixture, then any savings may be transitory.

The project built upon existing knowledge, supplemented by limited site and laboratory studies, to develop a specific model to look at this issue and to provide indicatory values for use in the model. The existing knowledge has been extended with an extensive literature search on the times for construction and the relevant effects that determine the service lifetime of the different pavement layers. The site trial looked at mixtures with and without RA, but had to assess their durability from early-life properties. The laboratory trials concentrated on combined effect of ageing and moisture damage on the performance of selected asphalt mixtures containing different proportions of RA. All three strands fed into life-cycle analysis models to customise them for the effect of using alternative component materials on the availability of the network and their overall financial and environmental cost.

2 Existing data

2.1 Work Package 1

Work Package 1 of the EARN project looked at the information currently available on the relevant parameters influencing the service life of pavements are defined. In particular, it sought suitable input values for these parameters to be used in the life-cycle assessment (LCA) and life-cycle cost assessment (LCCA) models in Work Package 4.

The results of the investigation into existing data on the effects of constituent materials, recycled and secondary sources materials and construction conditions on pavements durability are given in the Work Package deliverable (Mollenhauer *et al*., 2014) with a synopsis of these findings in Sections 2.2 to 2.4.

2.2 Durability

Asphalt pavement durability is a key factor in determining the performance of a pavement material and, as such, the pavement service life together with the pavement maintenance requirements during that service life. Therefore, it plays an important role regarding the environmental life-cycle of the road structure.

The durability of a pavement involves many relevant parameters that can be categorised as:

- The effects from traffic and weather as well as environment and sub-base soil conditions.
- The parameters for unbound base layers, hydraulically bound base layers and bituminous bound base and finally surface layers.

A high number of parameters affect the durability of road materials and the service lifetime of the pavement structure, a summary of potential parameters being given in Table 2-1.

Table 2-1: Parameters affecting the durability of road materials

Categories	Parameters
Environmental effects	Air Temperature, sun exposure, wind speed Sun exposure Frost-Thaw-Cycles Precipitation, humidity High-depth frosting
Traffic loading	Tyre/Axle load; weight and number Traffic Speed (distribution) Axle configuration
Sub-base characteristics	Bearing capacity Sub-base moisture / drainage properties
Pavement type and structure	Type of pavement Number of structural layers Layer thickness Interlayer bonding
Unbound base layers	Composition (type of aggregates, grading) Degree of compaction Moisture Bearing capacity
Hydraulically base layers	Construction type Void content Grading of aggregates Stiffness / Strength Binder type Binder content Construction conditions: Shrinkage / cracking

Categories	Parameters
Bitumen stabilised base layers (Cold recycling mixtures)	Type of mixture (foam or emulsion; site or plant mixed) Aggregate grading Binder content (bitumen) Binder content (cement) Curing conditions Stiffness / Strength Void content
Asphalt layers (hot, half-warm and warm mix asphalts)	Type of mixture Aggregate grading Binder type Binder content Air voids content and volumetric properties Type and content of additives RA type, quality and content Construction conditions Performance properties

However, many data sets are required to evaluate the effect of each parameter on the service lifetime of the pavement. Furthermore, the modelling of a pavement’s service life is only possible if most of the parameters are known; otherwise, it is subjected to a wide range of uncertainty.

In addition, a list of asphalt additives and techniques for LTAs was established showing the high number of various techniques for reducing the energy consumption of asphalt paving works (Appendix A).

2.3 State of the art on durability of pavements

The current state of the art on the durability of pavements should be found in terms of the assumptions used to develop the pavement management system widely used to maintain road networks. The current assumptions for three countries are given in Table 2-2.

In order to improve the prediction quality for pavement management systems on project level (i.e. for specific road sites), results of laboratory performance tests can be introduced into PMS as demonstrated by Wistuba *et al*. (2013) during ERA-Net road project InteMat4PMS. This approach should improve the prediction quality and provide the link between laboratory-assessed road material properties and the predicted service life of the road structure built of the road materials (Figure 2-1). In InteMat4PMS, the approach was demonstrated for the fatigue resistance of asphalt base layer.

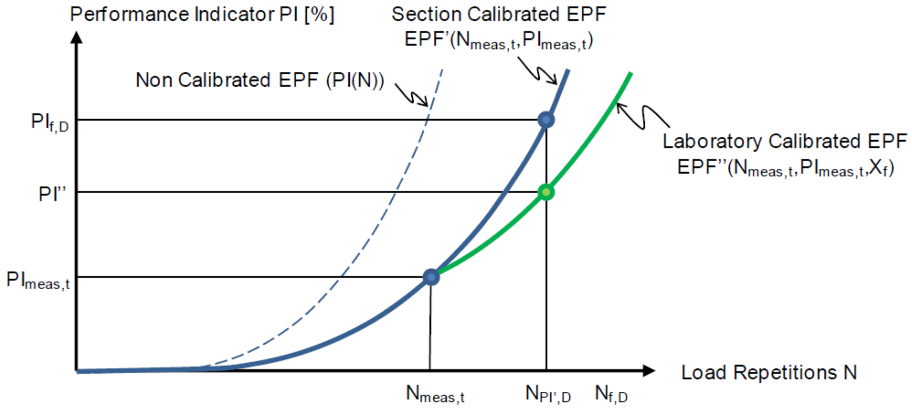


Figure 2-1: Calibration of performance indicator for PMS application based on laboratory material performance tests
(Wistuba *et al*., 2013)

Therefore, the results of laboratory performance tests can be used for estimating the effect of road material composition on the service life of the road structure. This approach has been applied for the analysis of international research projects and additional literature regarding the effects on asphalt material performance of RA use or LTA mixtures.

Table 2-2: General service life assumptions for pavement management systems

Road layer	Pavement material	Germany (FGSV, 2001)		Netherlands (IVON, 2012)		UK (SWEEP Pavements, 2013)	
		≥ 300 ESAL/day	< 300 ESAL/day	Right hand lane	Full width	surface life	structural life
Surface asphalt layers	Asphalt concrete (AC)	12	18	12	18	8	–
	Very thin layer asphalt concrete (BBTM)	–	–	–	–		
	Hot rolled asphalt (HRA)	–	–	–	–		
	Stone mastic asphalt (SMA)	16	22	11	17		
	Mastic asphalt (MA)	19	26	–	–		
	Porous asphalt (PA)	–	–	10	18		
Asphalt base layers	Asphalt concrete (binder layer)	26	30	–	–	–	20
	Asphalt concrete (base layer)	55	75	*	*		
	Other base layers						
	Hydraulically bound base layer	60	80	*	*		
	Unbound base layer	55	75	*	*		
Rigid pavement	Concrete surface layer	26	30	*	*	10	40
	Hydraulically bound base layer	55	70	*	*		
	Asphalt concrete base layer	50	65	*	*		
	Unbound base layer	45	60	*	*		
Maintenance materials	Slurry surfacing	6	8	–	–	8	–
	Micro-surfacing	5	8	–	–		
	Thin HMA layer on sealing	8	10	–	–		

* Highway maintenance in the Netherlands aims at timely strengthening the asphalt base layers and (sub)bases and thus, never has to be replaced.

2.4 Data review

Data from both literature and site were sought. The site data found was UK data on service lifetime of road structures (HAPMS), German data on asphalt material composition and pavement surface condition and the Dutch perpetual pavements study.

Some of the parameters that affect durability can be controlled by material and pavement engineering (e.g. mix design, raw material selection, and pavement design) while others are ancillary conditions which cannot be modified during road design and construction (e.g. weather conditions). Because of its effects on the frequency and extent on maintenance road works, the durability plays an important role on the environmental life-cycle performance of the road structure as well as on its life-cycle costs.

For evaluating additional effects on service lifetime not yet considered in life-cycle assessment (LCA) and life-cycle cost assessment (LCCA), European databases on structural and performance properties of the road network were assessed in detail. Unfortunately, due to lack of reliable structural data on road network databases and the inhomogeneity of locality referencing with the detailed material databases, no conclusions could be drawn about the effect of including recycled materials or secondary materials on the service lifetime of the road structure.

What has been shown from international literature is that the use of RA in new HMA results in adequate material durability performance in most of the cases. However, some researchers have also identified reduced durability for mixtures containing RA. Altogether, the application of RA in new HMA inhibits additional procedures in mix design as well as asphalt mixture production on an industrial scale. Because the sole number of production steps increases, which individually affect the durability properties of the resulting asphalt mixture, the risk of reduced durability will increase in general. When all procedures were conducted in high quality (as is usually the case in laboratory research as well as test section studies), no adverse durability effects were observed in most publications. Nevertheless, if there is any general adverse long-term performance, as indicated by database analysis in every-day paving industry, the higher risk will result in reduced durability for some of the projects. The increased use of various additives will further increase this development due to additional risks (e.g. incompatibilities to specific binders).

When considering the durability effect of asphalt mixture composition as well as the use of additives and or recycled materials, feasible laboratory conditioning procedures is needed in order to allow the estimation of long-term properties during mix design. Based on these results, durability effects can be implemented into LCA and LCCA in comparison to traditional asphalt mixtures with known durability properties.

For the effect of construction season, the paving during adverse weather conditions will slightly increase the risk for insufficient compaction and interlaying bonding. These independently occurring effects result in significant reductions of pavement and/or road material service lifetime. The reductions of -1,7 % due to risk of insufficient compaction and -0,5 % due to risk of insufficient interlayer bonding can be summed to produce a service life decrease of -2,2 % for pavements constructed in winter months (October until January).

The splitting of larger construction sites into smaller patches, which may be necessary when using times of low traffic volume for conducting pavement maintenance works, incorporate the disadvantage of an increase in the number of joints. These areas of pavements often exhibit inadequate compaction properties and, therefore, a significantly decreased durability. Based on published research results, the effect of reduced compaction on estimated service lifetime combined with the risk of inadequate joint design could be estimated to a reduced service lifetime of -14,4 %.

3 Site trial to evaluate varying proportions of reclaimed asphalt

3.1 *Work Package 2*

Work Package 2 of the EARN project identified a site where trial stretches using reclaimed asphalt can be incorporated and, in consultation with the NRA and the relevant Local Authorities, developed the mix design and undertook the laying of these trial sections. Visual monitoring, analysis of cored material and evaluation of ride quality was undertaken to provide comparative data between sites during the restricted timescale of the trials. However, the ride quality could not deteriorate in the available timescale of the project and further funding may be sought to monitor the trials after the project has been completed.

The construction and site monitoring of the site trials with varying proportions of RA are given in the Work Package deliverable (Tabaković *et al*., 2014) with a synopsis of these findings in Sections 3.2 to 3.4.

3.2 *Design*

The asphalt mixture investigated in this study was a 10 mm SMA typical of that used in Irish and European practice. The variations of the 10 mm SMA mixture are 0 % RA as control; 30 % RA and no additive; 40 % RA and Cecabase RT 945 warm mix additive; and 30% RA and Cecabase RT 945 warm mix additive. The grading curves for these mixtures are presented in Figure 3-1, illustrating the good agreement between the control mixture grading and those of the mixtures containing RA. Using the control mixture grading as the guideline allowed the best particle distribution for the mix designs, and consequently the best mixture design as illustrated in Table 3-1.

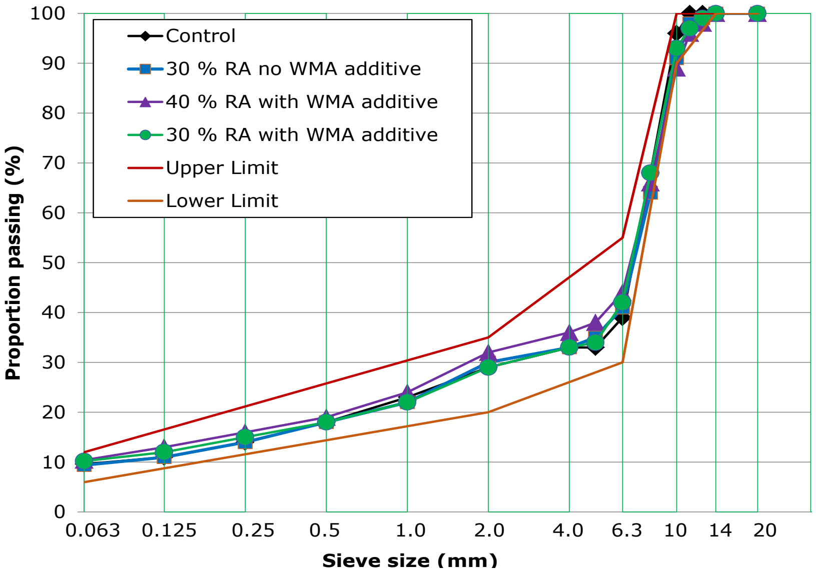


Figure 3-1: Particle size distribution

Table 3-1: Mixture designs

Mixture No.	Proportional content (%)					
	RA	10 mm	CRF *	Filler	Fresh binder	WMA Additive
1	0	65.9	21.8	6.7	5.6	0
2	28.6	43.8	17.0	5.7	4.9	0
3	38.1	34.4	17.1	5.7	4.7	0.5 **
4	28.6	43.8	17.0	5.7	4.9	0.5 **

* Crushed Rock Fines
** Warm mix additive added to Mixtures 3 & 4 at 0.5 % of the total binder content in the mixture.

3.3 Construction

In collaboration with the Irish National Roads Authority, a section of the N3 national road was identified as a suitable road section for the site trial experiment. The site was located between Blanchardstown and Clonee Village, at the outskirts of the Dublin city. The GPS coordinates of the trial site are latitude 53° 24’ 19.35”, longitude -6° 24’ 30.55’’ to latitude = 53° 24’ 6.43’’, longitude = -6° 23’ 59.21’’. The section was chosen because the road section was due for resurfacing, it is close to the asphalt plant (c.60 km) and it is on a main commuter route into Dublin city with an average daily vehicle traffic count, one direction only, of 15,480 vehicles including HGV. Figure 3-2 illustrates a satellite image of the trial section and surrounding area. The road is a dual carriage way with three traffic lanes on each side (bus lane and two traffic lanes). The middle lane was chosen as the test lane because it will be subjected to the most trafficking, particularly from heavy goods vehicles. The traffic direction is towards Dublin city. Figure 3-3 shows a schematic layout of the trial section. The site was split into four sections of varying lengths for the different mixtures.

Figure 3-2: Satellite image of the trial road section

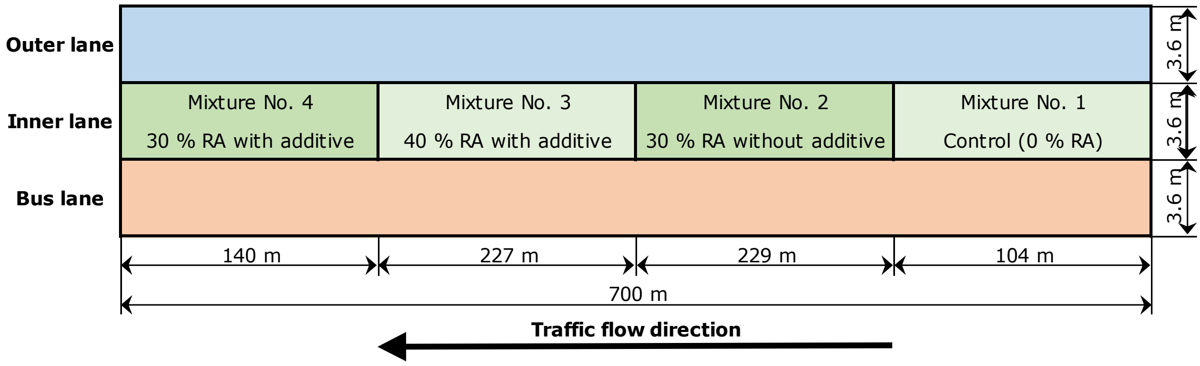


Figure 3-3: Schematic representation of the trail section

To cover the trial section area, it was estimated that just over 230 tonnes of asphalt material was required. The work started with removal of the existing surface course which was milled to a depth of 40 mm. An initial regulating course was then laid to a depth of 20 mm. The outer lane and bus lane (Figure 3-3) were resurfaced with a standard SMA, containing no RA or warm mix additive, to a depth of 40 mm. The test lane was resurfaced with the materials described above.

The paving process started with laying Section 1 (control mixture). The asphalt material was hauled from the plant to the site by truck and unloaded to the material transfer vehicle before it was sent to the paver. The purpose of the material transfer vehicle was to remix the material before sending it to the paver and laying it onto the road. Figure 3-4 shows the paving process. The paving process of the Section 1, passed as expected without any difficulties. However, Section 2 proved to be more difficult because the mixture was cooling down rapidly with the consequential reduction in workability of the mixture. The paving of Sections 3 and 4 passed without much difficulty, highlighting the improved workability of the mixtures incorporating the warm mix additive, with up to 40 % RA. The site work records are summarised in Table 3-2, giving section lengths, temperature and weight of each mixture.

Figure 3-4: Paving process of the trial section

Table 3-2: On-site work record of asphalt material

Mixture No.	RA content (%)	WMA additive	Load No.	Chainage (m)	Discharge temp. (°C)	Rolling temp. (°C)	Weight (Tonnes)
1	0	No	1	0 – 104	150	134	30.00
2	30	No	2	104 – 155	115	105	17.20
			3	155 – 220	130	115	17.20
			4	220 – 333	150	130	28.90
3	40	Yes	5	333 – 385	137	125	30.10
			6	385 – 458	135	125	17.00
			7	458 – 560	134	128	28.80
4	30	Yes	8	560 – 618	125	118	17.00
			9	618 – 672	132	124	17.20
			10	672 – 700	136	128	28.65

The RA feedstock was supplied from a site on the M1 motorway in North County Dublin and is 14 mm porous asphalt derived from a single source. The material was milled and stored in a depot until required on this project. The total amount of RA material supplied was 170 tonnes. The quantity of the processed RA material by size is given in Table 3-3. The visual inspection revealed that the >16 mm material contained binder course material aggregate. Therefore, the >16 mm and <6 mm RA aggregate was screened out and not used for the trial asphalt mixtures.

Table 3-3: The quantity of the processed RA material by size

Size (mm)	>16	16 to 12.5	12.5 to 6	<6
Quantity (T)	40	45	35	50
Proportion (%)	24	26	21	29

The binder content in the RA was determined according to the EN 12697 39. Five samples of RA were taken and weighed. The samples were placed in the oven at 530 °C for 30 min. Once the samples were cooled, they were weighed again and proportion of binder in the mixture calculated. The average binder content was 5.3 %. Following the binder burn off procedure, the material particle size distribution determined following EN 12697 2. The RA material aggregate size distribution/grading is shown in Figure 3-5 and the binder contents were 5.2 %, 5.4 %, 4.8 %, 5.7 % and 5.4 % with an average of 5.3 %.

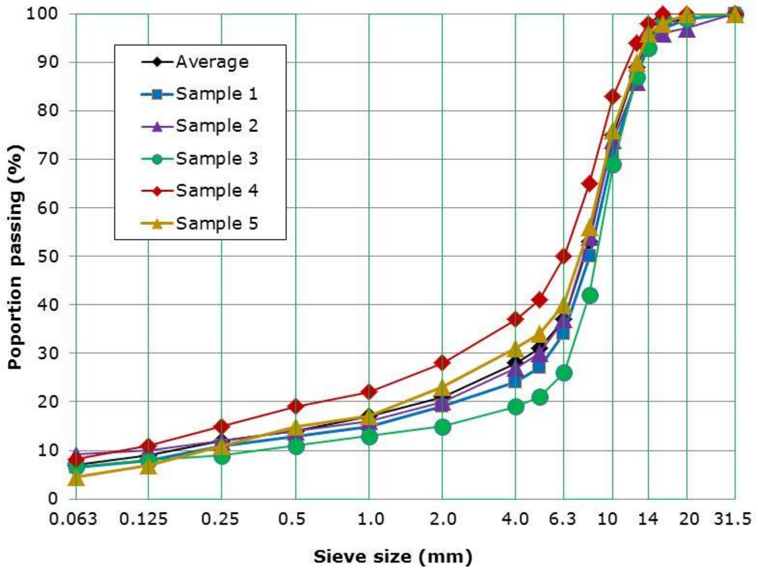


Figure 3-5: RA material grading after the binder removal

3.4 Monitoring

In order to assess the initial performance of the sections, the international roughness index (IRI), mean profile depth (MPD) and skid resistance by SCRIM were measured in accordance with ASTM E950 / E950M (ASTM, 2009), EN ISO 13473-1 (ISO, 2004) and CEN/TS 15901-6 (CEN, 2009), respectively. The skid resistance measures are sideways force coefficient (SFC) and corrected SCRIM Coefficient (SC). Measurements were made initially (except for skid resistance) and then after 6 and 12 months with the results shown in Table 3-4.

Table 3-4: In situ measurements of site performance for first year

Mixture No.	Test period	IRI (m/km)			MPD (mm)	Skid resistance	
		Left	Right	Average		SFC	SC
1	0	1.25	1.23	1.24	0.86	–	–
2		0.96	0.99	0.98	0.76	–	–
3		1.04	1.10	1.07	0.68	–	–
4		1.33	1.43	1.38	0.77	–	–
1	6 months	1.06	1.36	1.21	0.62	0.72	0.50
2		1.17	1.06	1.11	0.61	0.68	0.47
3		1.17	1.13	1.15	0.55	0.64	0.44
4		1.70	1.45	1.58	0.73	0.68	0.46
1	12 months	1.24	1.33	1.29	0.77	0.54	0.49
2		1.18	1.03	1.11	0.64	0.52	0.48
3		1.21	1.12	1.16	0.53	0.49	0.45
4		1.51	1.37	1.44	0.70	0.50	0.46

The average IRI value for each section is < 2 m/km which shows good ride quality of the pavement surface. The average MPD values are below 0.9 mm and above 0.4 mm, which indicates that the surfaces have suitable macro-texture depth for the type of the road (a National road) where the maximum speed limit is 100 km/h. The average SFC and SC value for each section is > 0.3 which shows good friction quality of the pavement surface. These values reassure that MPD values are at safe levels and all sections have a good ride quality and are safe for road users.

The asphalt mixture material was also sampled from the paver as shown in Figure 6a; this material was used for the laboratory evaluation of moisture damage and ageing (Section 0). In addition, a total of 108 cores (27 from each trial section) were taken 24 hours after the construction was completed. The coring procedure is shown in Figure 3-6b & 6c.

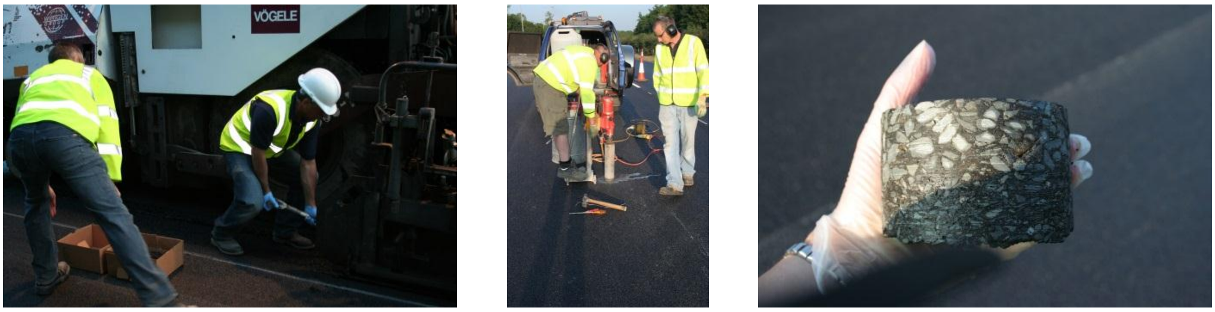

a) Material sampling b) Coring c) A core sample

Figure 3-6: Collection of samples from site

Laboratory testing of the indirect tensile stiffness modulus (ITSM) in accordance with EN 12697-26 (CEN, 2012) and the water sensitivity in accordance with EN 12697-12 (CEN, 2008) were undertaken in order to evaluate the material used on site. The tests were carried out soon after the trial was laid and then after 3 months, 6 months and 12 months of being in service and the results are given in Table 3-5 for ITSM and Figure 3-7 and Figure 3-8 for indirect tensile strength (ITS).

Table 3-5: ITSM test results

Mixture No.	RA content	Warm mix additive?	Stiffness (MPa) at time		
			3 months	6 months	12 months
1	0 %	No	1692.5	1703.2	1620.1
2	30 %	No	2295.3	2237.8	1789.6
3	40 %	Yes	2407.0	2322.5	2005.6
4	30 %	Yes	1898.4	2181.5	1629.9

The mixture stiffness values reduce between test months 3 and 12, with the control mixture having lowest reduction of 4.3 % where the mixture containing 30 % RA and no warm mix additive (Mixture 2) had the highest reduction of 22 %. Mixtures 3 and 4 had stiffness reduction of 16.7% and 14.1% respectively.

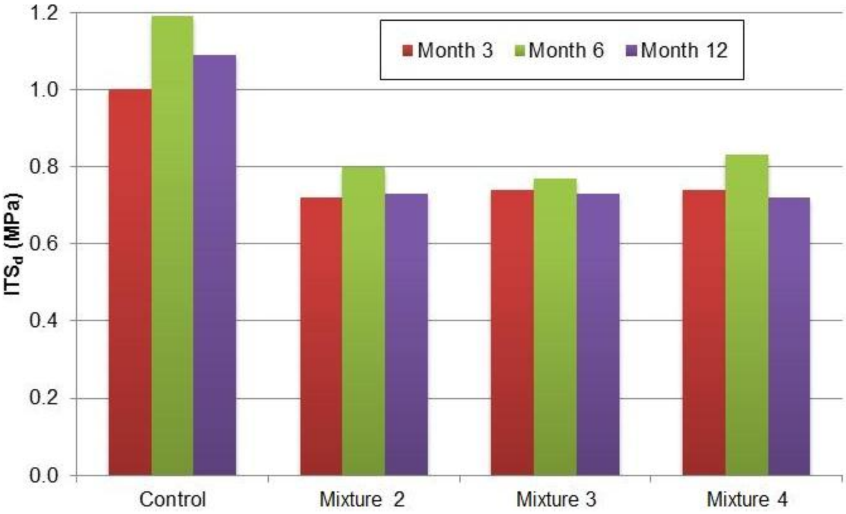


Figure 3-7: ITS results after dry conditioning

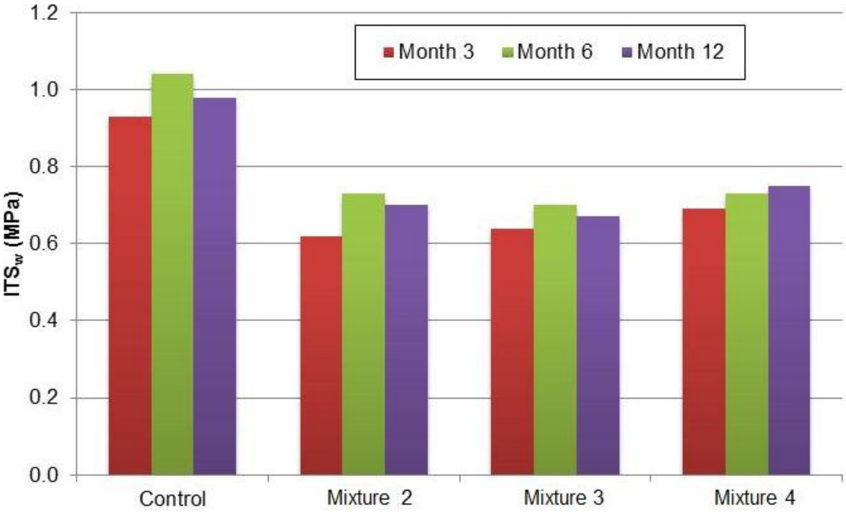


Figure 3-8: ITS results after wet conditioning

The results show good resistance to the moisture damage with all mixtures achieving ITS ratio (ITSR) value about required 80 %. An exception is the control mixture (Mixture 1) whose ITSR value dropped just below 80 % (to 79.3%) at month 12. Results further show improvement in ITSR values in the 12th month for Mixtures 2 and 4. This change is due to the improvement in material wet strength (ITS_w) for both materials.

4 Laboratory evaluation of moisture damage and ageing

4.1 *Work Package 3*

Work Package 3 of the EARN project investigated the combined effect of ageing and moisture damage on the performance of selected asphalt mixtures containing different proportions of reclaimed asphalt. Both fresh and conditioned materials were tested for a comparison of their mechanical response utilising laboratory compacted cylindrical specimens.

The laboratory programme and results are given in the Work Package deliverables (Varveri *et al*., 2014a; Varveri *et al*., 2014b; Varveri *et al*., 2014c) with a synopsis of these findings in Sections 4.2 to 4.5.

4.2 *Objective of laboratory testing*

The objective of laboratory testing was to investigate the combined effect of ageing and moisture damage on the mechanical performance of selected asphalt mixtures containing various proportions of RA. For this study, site trials have been laid of mixtures both without and with RA in Dublin, Ireland, from which cylindrical specimens were cored and utilised for laboratory testing. The coring procedure and the laboratory testing were carried out in two stages; in the first stage, field cores were taken 24 h after the construction of the trial section was completed and were evaluated for their propensity to moisture damage, while in the second stage asphalt cores were taken 12 months later and the same testing programme undertaken. In this manner, apart from the moisture damage susceptibility, the effect of ageing on the mechanical response of the selected mixtures was able to be evaluated.

4.3 *Test protocol*

A total of 27 cores were drilled from each section of the road trial. For each mixture, the specimens were divided into two subsets. The first subset was subjected to moisture conditioning, while the other subset was stored in a climate chamber in dry conditions at 20 °C. In order to address the individual damage mechanisms associated with the two types of damage inducing processes, the moisture conditioning protocol applied is a combination of two different conditioning methods (Figure 4-1): (a) bath conditioning and (b) cyclic water pore pressure application. Cyclic pore pressure generation in the asphalt mixture is achieved by means of the moisture induced sensitivity tester (MIST). The MIST was designed as an accelerated conditioning device for the evaluation of the resistance of an asphalt mixture to stripping by simulating the high pressure fields which develop within an asphalt layer due to traffic loading.

MIST is a self-contained unit, Figure 4-2(a), which includes a hydraulic pump and a piston mechanism that is designed to cyclically apply pressure inside a sample chamber. The test involves placing a 100 mm or 150 mm diameter sample of 25 to 150 mm height inside the sample chamber, filling the chamber with water, closing the sample chamber lid, choosing the preferred conditioning settings and starting the test, Figure 4-2(b-d). The machine then automatically heats the sample to the desired temperature and starts cycling between zero and the selected pressure. Tests can be performed at different pressures and temperatures to replicate different traffic and environmental conditions. Furthermore, the user can specify the desired number of conditioning cycles.

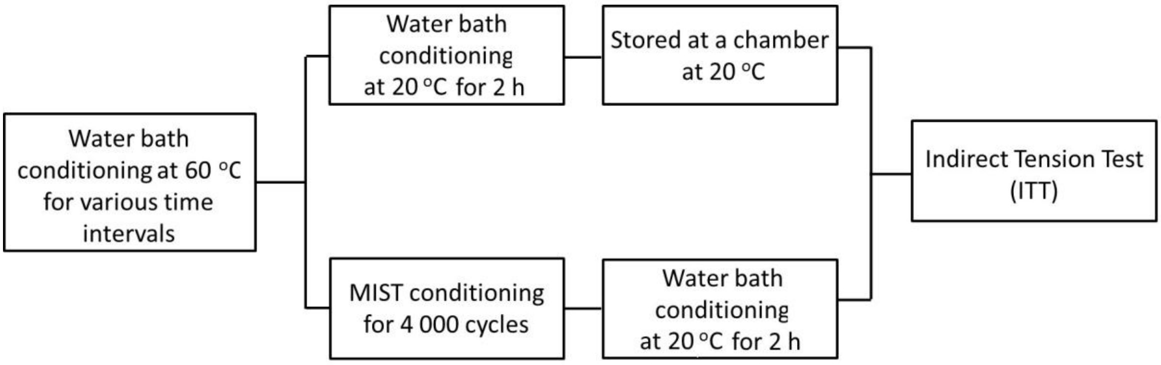


Figure 4-1: Schematic of the applied moisture conditioning protocols

Figure 4-2: **Moisture induced sensitivity tester**

In the applied protocol, the specimens were first subjected to moisture infiltration by placing them in a bath, filled with distilled water at an elevated conditioning temperature of 60°C, in order to facilitate the infiltration of water into the asphalt mixture and, consequently, accelerate the long-term degradation of the material properties. At fixed time intervals of three and six weeks, three specimens per mixture were removed from the bath, placed in a bath at 20 °C for 2 h and then maintained in a climatic chamber at 20 °C until tested for their strength using the indirect tension tester (ITT). An additional three samples per mixture were removed from the bath and further conditioned in the MIST device by applying 3500 cycles of pressure application at a temperature of 60 °C and a pressure of 0.48 MPa. After MIST application, the samples were placed in a water bath, at 20 °C for 2 h. After conditioning, the indirect tensile strength of each of the two subsets is determined in accordance with EN 12697-23 (CEN, 2003). Table 3 shows the number of specimens utilised for each type of conditioning level.

A total of six additional specimens per mixture were stored in a climate chamber at 20 °C, after delivery. These dry specimens were kept in the chamber during the time of conditioning and were tested together with the conditioned specimens at each defined time interval. In this way, any differences in their strength due to age hardening effects were taken into account.

Table 4-1: Testing matrix

Type of conditioning	Mixture No.	Week 0	Week 3	Week 6
Dry conditions	1	6	3	3
	2	6	3	3
	3	6	3	3
	4	6	3	3
Water bath	1	–	3	3
	2	–	3	3
	3	–	3	3
	4	–	3	3
Water bath & MIST	1	3*	3	3
	2	3*	3	3
	3	3*	3	3
	4	3*	3	3

**Only MIST conditioning was applied on the dry subset at week 0.*

4.4 Laboratory tests without ageing

The laboratory tests carried out during the first phase of testing were on samples taken from site soon after laying in order to investigate the effect of RA on the moisture damage susceptibility of asphalt mixtures. Four variants of a typical SMA 10 mixture were prepared. The variations were 0 % RA as control; 30 % RA and no additive; 40 % RA and warm mix additive; and 30% RA and warm mix additive. The Indirect Tensile Strength (ITS) to EN 12697-23 (CEN, 2003) and the Indirect Tensile Strength Ratio (ITSR) to EN 12697-12 (CEN, 2008) were used for the evaluation of moisture damage resistance of the mixtures.

The results showed that the inclusion of RA can affect the strength of the mixtures. ITS values were found to increase with increasing RA content in dry conditions, which can be explained by lower void content due to reduced compaction resistance. However, the rate of strength degradation due to moisture damage was found to be higher for the RA mixtures and increased RA content. The use of warm mix additive was shown to increase the resistance to moisture damage as shown by the MIST results, whereas the conventional test procedure according to EN 12697-12 (CEN, 2008) results in the contrary result. This first observation indicates the importance of the need for better understanding of moisture damage and its consideration in test procedures for durability assessment.

4.5 Laboratory testing after ageing

Figure 4-3 shows the effect of physical hardening on strength with the samples being kept in storage at dry conditions of both unaged and field aged mixtures. The dry tensile strength increases with increasing RA content for all mixtures. In addition, the mixture strength further increases with time, due to physical hardening of the asphalt binder, while the samples were kept in storage. The hardening rates vary for the different mixtures with physical hardening apparently having more of an influence on the mixtures with higher RA content. However, some differences in the ITS values are expected for RA mixtures because the binder from the RA has already undergone oxidation, so the rate of hardening of the RA mixture is slower.

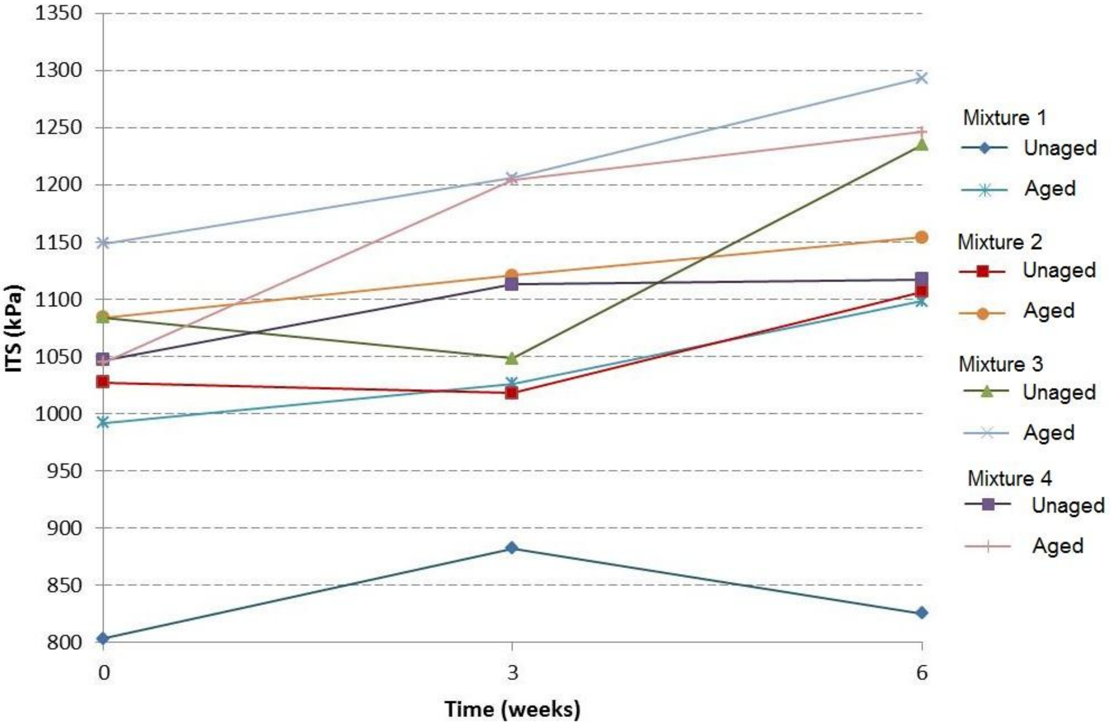


Figure 4-3: Effect of age hardening on indirect tensile strength

The mean ITSR values (from three replicas) for the fresh (unaged) and field-aged samples are shown in Figure 4-4 and Figure 4-5, respectively, with the results presented for both bath and bath-MIST conditioned samples at the each time interval and the coefficient of variation for each mixture shown on the top of the bars. The solid red line represents the threshold value below which an asphalt mixture is considered to be more susceptible to moisture damage according to Dutch (CROW, 2010) and Irish standards. The tensile strength ratios of the RA mixtures, whether or not a WMA additive is added, were lower than the conventional HMA for the unaged mixtures. Nevertheless, the ITSR values of the RA mixtures, after field-ageing, were found to be higher than the control mixture. The results showed that Mixture 4, which had the higher RA content and a WMA additive, performed better against moisture damage compared to other variants.

Overall, the mixtures containing RA had a lower reduction in strength with the different moisture conditioning protocols, both before and after ageing, compared to the control mixture, as shown in Table 4-2. From the results, the contributions of the short- and long-term moisture damage on the strength of the samples were quantified. Specifically, Mixture 1 (0 % RA) had the highest reduction in strength for all conditioning protocols. Mixture 2 (30 % RA; no WMA additive) was found to perform better against moisture damage after only bath conditioning; particularly after it underwent ageing in the field. However, the reduction in strength was significantly higher after the application of the combined protocol. The results showed that, for Mixture 2, the weakening effect of moisture diffusion (through bath conditioning) was more apparent after the first three weeks and resulted in high levels of damage when cyclic pore pressures are applied.

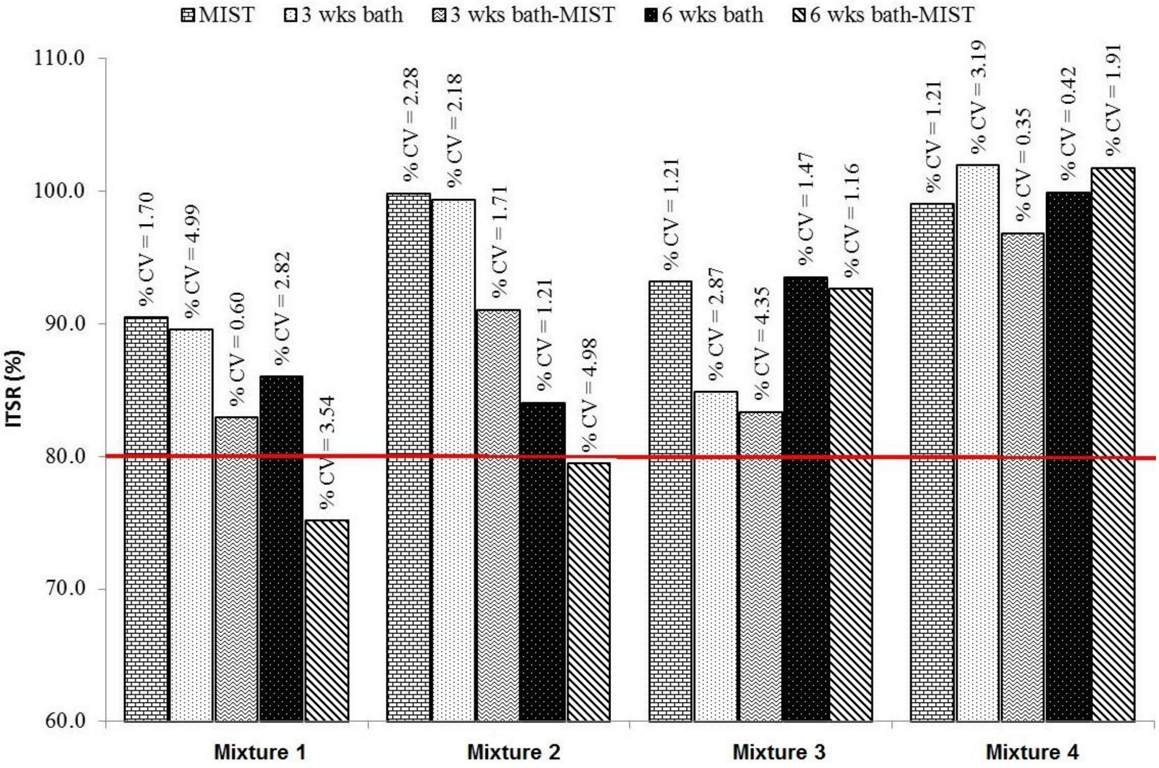


Figure 4-4: **Mean ITSR values for unaged samples**

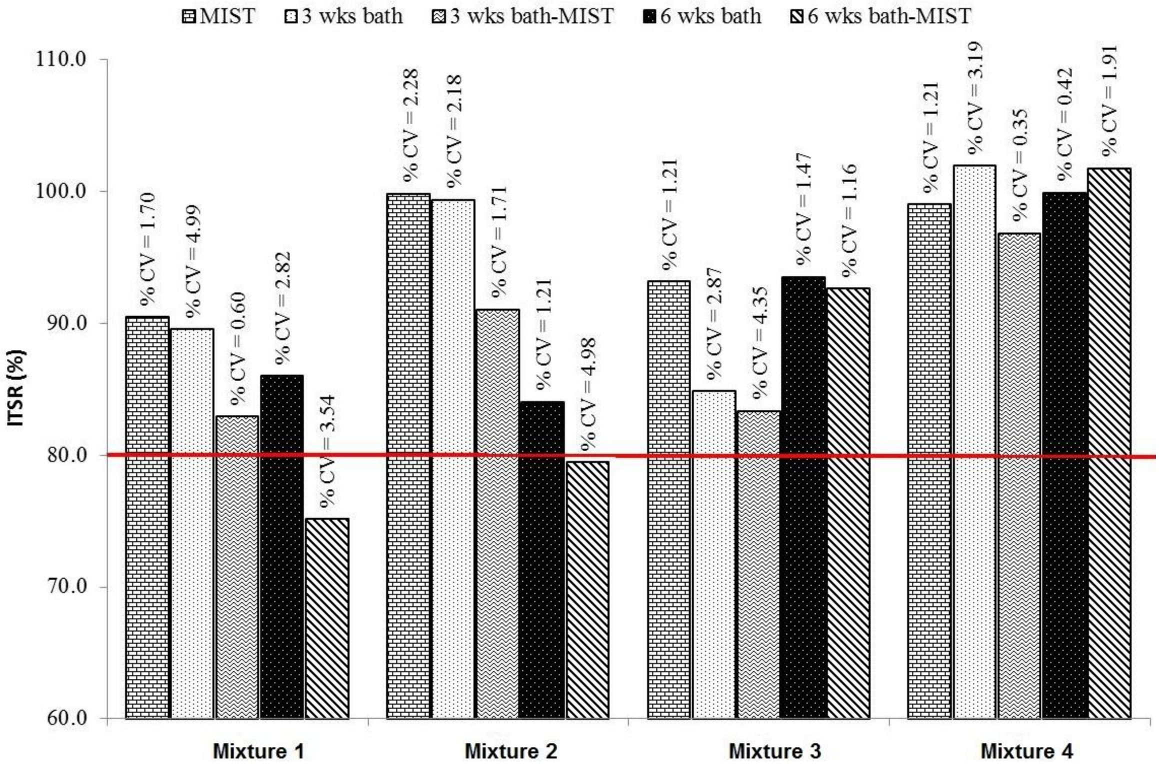


Figure 4-5: **Mean ITSR values for aged samples**

Table 4-2: **Average reduction in strength**

Conditioning method	Time (weeks)	Strength reduction (%)							
		Mixture 1		Mixture 2		Mixture 3		Mixture 4	
		Unaged	Aged	Unaged	Aged	Unaged	Aged	Unaged	Aged
Bath	0	–	–	–	–	–	–	–	–
	3	+1.01	-10.5	-15.75	-0.7	-4.05	-15.2	-7.12	+1.9
	6	-6.08	-14.0	-14.00	-16.0	-13.51	-6.5	-9.01	-0.1
Bath & MIST	0	-4.17	-9.6	+0.21	-0.2	+0.58	-6.8	-1.32	-1.0
	3	-3.92	-17.1	-14.03	-9.0	-3.31	-16.7	-9.68	-3.2
	6	-10.54	-24.9	-27.29	-20.6	-19.32	-7.4	-18.58	+1.7

Furthermore, the results demonstrate that the use of WMA additives improved the moisture susceptibility of unaged and field-aged mixtures. Mixture 3 (30 % RA plus WMA additive) showed a decreasing strength with increasing bath conditioning time; however it appeared to be insensitive to the application of cyclic pressure, indicating that Mixture 3 is more probable to fail cohesively, due to the weakening of the binder, rather than adhesively. This can be attributed to the antistripping effect of the Cecabase RT 945 WMA additive, which seems to improve the adhesion properties of the aggregate-binder systems. Mixture 4 (30 % RA plus WMA additive), exhibited the best performance against moisture damage. The rate of strength degradation was extremely low, particularly after field ageing; comparable strength levels were measured after the various conditioning scenarios.

The results indicate that the performance of the mixtures against moisture damage is improved by the use of warm mix additives. In general, both Mixtures 3 and 4, which contain an additive, show a better behaviour compared to Mixture 2. In particular, because the only variance between Mixtures 2 and 4 is the use of the additive, it is clear that the positive effect additives can have on the ITS. Furthermore, it can be observed that a change in the amount of RA content, from 30 % to 40 %, does not result in major differences in the ITS and ITSR values, mainly for the aged samples.

5 Impact assessment modelling

5.1 *Work Package 4*

Work Package 4 of the EARN project modelled how the inclusion of recycled materials in road pavement materials affects performance in environmental and economic terms. An appropriate modelling approach was established that allowed the impacts of recycling (positive or negative) to be quantified in terms of monetary cost and environmental impact. Both cost and environmental modelling utilised a life cycle based approach. The emphasis was to utilise data and modelling approaches arising from past and complementary on-going research because a plethora of viable research already been produced in this area.

The methodology and results of the impact assessment modelling together with the proposed decision model are given in the Work Package deliverable (Wayman *et al*., 2014) with a synopsis of these findings in Sections 5.2 to 5.5.

5.2 *Modelling approach and data sources*

Carbon-footprinting (CF) and life-cycle costing (LCC) analyses have been conducted based on the EARN site trial of WMA together with a site trial of CMA for the CoRePaSol (Characterization of Advanced Cold-Recycled Bitumen Stabilized Pavement Solutions) project. Direct data collection at the trials and subsequent follow-up were the source of information on the key variables such as mix design recipes, energy consumption during production and cost of components, fuel and transport. Other standard, reputable data sources were utilised to provide emissions factors for fuels, transport and embodied carbon values for constituent materials. The asphalt pavement embodied carbon tool (asPECT) v4.0 was used to conduct the CF analysis, and a bespoke model created to conduct the LCC analysis.

The 2014 update to asPECT included a facility to modify the standard UK emissions factors for when the tool is applied in another geographical region. The emissions factors for electricity, gas oil and diesel were therefore modified using those specific to Ireland (SEAI, 2012) and the 60:40 allocation of recycled content to recyclability benefits, employed by consensus to reflect the specific UK situation, was modified to 100:0 in favour of the recycled content method of allocation. Allocating benefits purely on the basis of only the recycled content will reward recycling in the current mixture at the present time.

Life cycle costs (LCC) are those directly associated with the planning, design, acquisition, disposal and support of an asset (NSW Treasury, 2004). Therefore, LCC incorporates the ongoing operating and maintenance costs rather than the traditional approach of just focusing on the initial capital cost. These costs are distributed over each stage of the assets lifetime, and, for the purpose of this analysis, have been allocated through the full life cycle. The LCC model developed estimates the overall direct and indirect life cycle costs of alternative asphalt mixtures over a 60 year investigation period for a 1 km lane length. The total cost of one intervention is comprised of the individual costs incurred during each lifecycle stage (from material procurement to excavation and disposal). Depending on the lifetime and performance of the asset, there may be multiple interventions over the course of the 60 year investigation period. In this case, the model assumes that precisely the same intervention will be repeated and reapplies the original total cost as many times as is necessary. When the lifetime of the asset exceeds the 60 year period (i.e. an intervention takes place at year 55 with a lifetime of 10 years, leaving 5 additional years of value), the model assumes the residual value using a linear rate of deterioration. This value is then subtracted from the total cost of that intervention in order to allow for an equitable comparison of treatments. The costs are then discounted back to the base year (year 0) of the analysis using a standard net present value (NPV) technique. This process is carried out for both direct and indirect costs for each mixture applying discount rates. It then compares the NPV for each of the asphalt mixtures to indicate which one delivers the most value for money.

Typically, a positive NPV value would indicate a positive investment, and vice versa. In the case of road interventions, where there are no revenues generated by the investment, thus all of the results will be negative. In this case, the highest value (closest to zero) demonstrates the most financially viable option.

5.3 Example for warm mix asphalt

The cradle-to-gate, cradle-to-site and total CO_2e footprints calculated for the works carried out at the trial site are presented in Table 5-1. A breakdown of the contribution of the different life cycle steps is provided in Figure 5-1. Over a 60 year asset life, the contribution of the different materials is presented in Table 5-2, normalised to a 1 km stretch of single lane highway. Here the impact of variations on the service life is indicated, according to design lives specified for the UK, the Netherlands and Germany.

Table 5-1: Calculated CO_2e footprints per tonne for the four mixtures used

Component	Mixture 1 (SMA 0 % RA control)	Mixture 2 (SMA 30 % RA)	Mixture 3 (SMA 40 % RA + additive)	Mixture 4 (SMA 30 % RA + additive)
Cradle-to-gate CO_2e footprint ($kgCO_2e/t$)	49,25	47,64	45,20	43,97
Cradle-to-site CO_2e footprint ($kgCO_2e/t$)	60,83	59,22	56,78	55,54
Total for the EARN trial installation ($kgCO_2e$) including regulating course and tack coat	18,784			

Table 5-2: Calculated CO_2e footprints for a 1 km single lane stretch over 60 years

Cradle-to-grave CO_2e footprint for 1 km over 60 years ($kgCO_2e$), including tack coat	Mixture 1 (SMA 0 % RA control)	Mixture 2 (SMA 30 % RA)	Mixture 3 (SMA 40 % RA + additive)	Mixture 4 (SMA 30 % RA + additive)
UK (8 year service life)	161 493	155 025	148 942	145 927
Netherlands (11 year service life)	117 118	112 413	107 990	105 794
Germany (16 year service life)	80 139	76 903	73 863	72 351

Relevant cost parameters (Wayman *et al*., 2014) have been used to calculate cost in Euro per tonne for each of the four alternative materials in Table 5-3 and the net present value costs over the 60 year asset life in Table 5-4.

Table 5-3: Calculated costs per tonne for the four mixtures used

Component	Mixture 1 (SMA 0 % RA control)	Mixture 2 (SMA 30 % RA)	Mixture 3 (SMA 40 % RA + additive)	Mixture 4 (SMA 30 % RA + additive)
Cradle-to-gate cost (€/t)	66,93	58,63	57,01	59,45
Cradle-to-site cost (€/t)	114,66	106,36	104,74	107,18
Total for the EARN trial installation (kgCO$_2$e) including regulating course and tack coat	72,482			

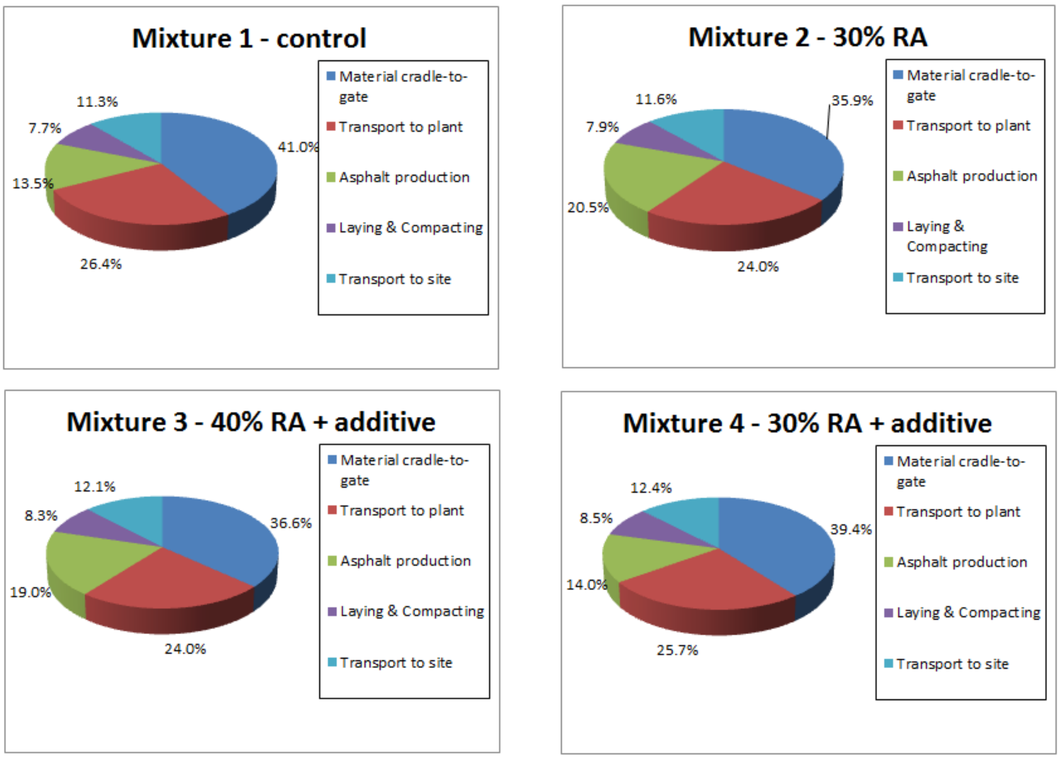


Figure 5-1: Contribution of the life cycle steps to the overall footprints cradle-to-site

Table 5-4: Calculated costs for a 1 km single lane stretch over 60 years

Cradle-to-grave direct costs for 1 km over 60 years (€), including tack coat	Mixture 1 (SMA 0 % RA control)	Mixture 2 (SMA 30 % RA)	Mixture 3 (SMA 40 % RA + additive)	Mixture 4 (SMA 30 % RA + additive)
UK (8 year service life)	-393,804	-378,062	-375,989	-379,120
Netherlands (11 year service life)	-258,616	-247,833	-246,413	-248,557
Germany (16 year service life)	-207,451	-198,545	-197,373	-199,144

In Table 5-5 the results of the exploratory analysis into working window are presented. Interventions with HMA are modelled to last eight hours and those with LTA seven hours. The cumulative cost associated with this difference in working window over a 60 year asset life are indicated based on the anticipated design lifetimes of the UK, Germany and the Netherlands.

Table 5-5: Indirect costs for a 1 km single lane stretch over 60 years

Indirect costs for 1 km over 60 years (€), including tack coat	HMA	LTA
UK (8 year service life)	-40 377	-35,330
Netherlands (11 year service life)	-30 993	-27 119
Germany (16 year service life)	-22 896	-20 034

Clear savings are observed for the novel mix designs (Mixtures 2, 3 and 4) relative to the HMA control mixture (Mixture 1) in terms of both CO_2e and cost. The CO_2e savings range from between 3,3 % to 10,7 % cradle-to-gate and between 2,7 % to 8,7 % cradle-to-site on a per tonne basis. Mixtures 1 and 4 provide the most equitable basis for comparison between a HMA and LTA mixture containing RA. Comparing them, the savings associated with using the HMA would be 10,7 % cradle-to-gate and 8,7 % cradle-to-site respectively.

The total CO_2e footprint for the works as installed is calculated at 19.4 tonnes, including the four mixtures as surface course, the regulating course and the tack coats. If all 334 t of materials used on the works (in both the surface and regulating courses) were Mixture 4, the total footprint would have been 17,8 t CO_2e, relative to 19,5 t for all HMA, a saving of 1,7 t CO_2e.

5.4 Example for cold mix asphalt

The N77 road in Ireland between Henebry's Cross, Kirwans Inch and Ardaloo, was selected by the National Roads Authority as the test site. The GPS coordinates of the trial site are between latitude 52° 43' 9,17", longitude -7° 17' 41,30'' to latitude 52° 42' 22,68'', longitude -7° 16' 21.43''. The section was chosen because the pavement of this single carriageway section of road required rehabilitation, and it is on a main commuter route into Kilkenny city with an average daily vehicle traffic count in excess of 9 000 vehicles including HGVs. The satellite image in Figure 5-2 indicates the approximate location.

Figure 5-2: Approximate location of the CoRePaSol trial section

The trial site was split into three sections where different types of cold mix asphalt would be laid and tested. 2600 m of pavement was reconstructed over a period of nine days between 9 and 19 September 2014. The planned arrangement of the three sections on the road is presented in Figure 5-3.

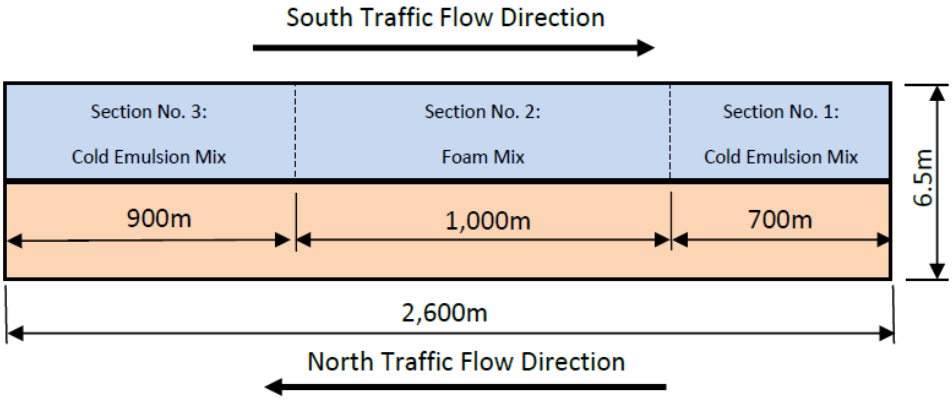


Figure 5-3: Schematic representation of trial section

The carbon footprint results, measured in CO_2e equivalents, for the ten mixtures cradle-to-site are presented in Table 5-6.

Table 5-6: Calculated CO_2e footprints for the ten CoRePaSol cold mixtures installed

Mixture		Site chainage (m)	Cradle-to-site CO_2e footprint (kgCO_2e per t)
Mixture 1	Emulsion mix with cement	0 – 200	21,90
Mixture 2	Emulsion mix with cement	200 – 500	19,08
Mixture 3	Emulsion mix with cement	500 – 700	19,61
Mixture 4	Emulsion mix without cement	1690 – 1800	8,84
Mixture 5	Emulsion mix with cement	1800 – 2020	22,85
Mixture 6	Emulsion mix with cement	2020 – 2450	20,66
Mixture 7	Foam mix with cement	700 – 970	17,67
Mixture 8	Foam mix with cement	970 – 1180	21,68
Mixture 9	Foam mix with cement	1180 – 1400	21,78
Mixture 10	Foam mix with cement	1400 – 1620	20,66

The absence of cement in Mixture 4 makes a significant difference to the overall footprint.

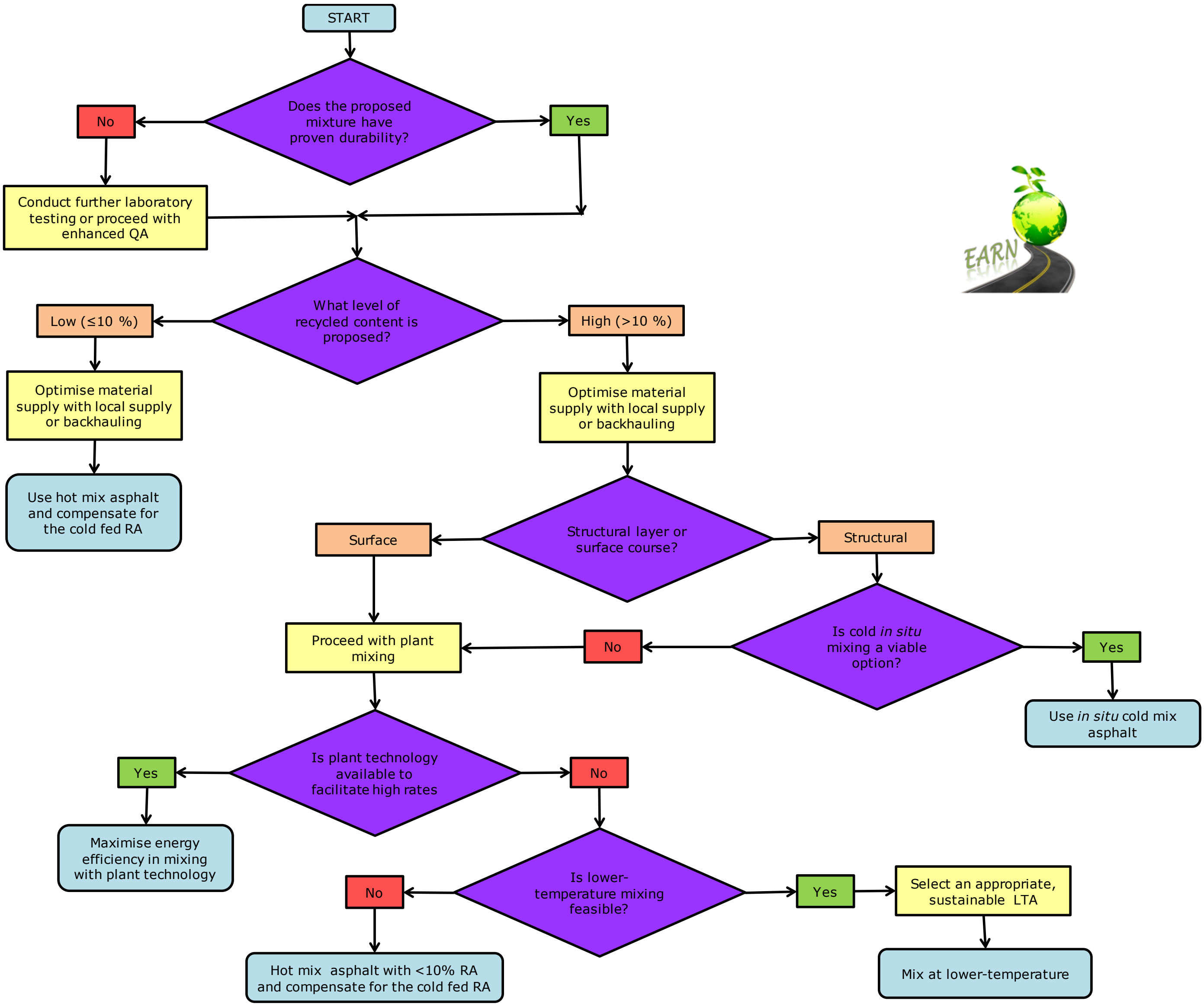
5.5 Decision model

Recycling asphalt, whilst overwhelmingly a sustainable practice, does of course come with a number of conditions. The first would be durability. Novel mixtures incorporating recycled content must perform to the same or an enhanced level when compared to the conventional HMA alternatives because reduced durability has the potential to make a huge negative impact in cost and environmental terms. Adequate consideration must also be given to logistics and minimising transport in the life cycle. Transport of recycled materials should not exceed that of primary materials and opportunities to improve logistics (such as backhauling) should be considered. Furthermore, LTA production should come with its own set of considerations. Analysis of the CoRePaSol trial section showed that considerable CO_2e reductions can be achieved if in situ recycling can be utilised in appropriate situations, i.e. to produce structural asphalt courses. If LTAs are plant mixed, then some attention should be given to the additive, its origin and its embodied carbon, though this did not prove to overly significant in relation to the EARN trial mixtures.

In future, LTA technologies which do not have to overcome the latent heat of vaporisation during heating, might be considered because they can potentially realise greater CO_2e benefits compared to those mixed above 100 °C. LTA technologies should, however, not be pursued at the expense of recycling. To maximise energy efficiency during production of asphalt, operations should be carefully planned to avoid repeatedly switching between hot and lower-temperature mixtures in order to realise the greatest benefits. The cost savings associated with energy use in relation to LTAs might become more apparent in the future when energy prices rise.

The important factors to be considered in relation to recycling asphalt are summarised in the decision model presented in Figure 5-4 (EARN Deliverable D6).

Figure 5-4: Hierarchy of considerations for asphalt recycling (decision model)



6 Implementation and dissemination of findings

6.1 Service life of asphalt with reclaimed asphalt

There are limited data on the actual service life of pavements with asphalt mixtures incorporating a significant proportion, or even a low proportion, of RA because such mixtures were not widely used at a time so that they would now have reached the end of their service life and could be assessed. However, the indications are that the use of RA can have an adverse effect on the properties of the mixture, and therefore on its potential durability, although there was a significant scatter in the available data.

To minimise any adverse effect, the mixture needs to be appropriately designed. The main aspect of the design process that could affect the relative durability is how the binder derived from the RA in terms of grade and effective quantity when selecting the quantity and grade of virgin binder needed to be added in order to provide the appropriate quantity and grade of the combined binder. Furthermore, there are increasing indications that the pre-aged RA binder, and hence the combined binder to a lesser extent, will age differently from fresh binder. Hence, the change in the asphalt properties that occurs with all bituminous mixtures may be at a different rate so that the properties of mixtures with and without RA that initial are similar may diverge with time.

Overall, the expected service life of pavements with asphalt mixtures incorporating RA can be taken as being marginally less than that of pavements with asphalt mixtures without RA. However, definitive data is needed to confirm this assumption and, if there is any difference in service life, the extent to which the proportion and consistency of the RA incorporated effects that change will also need to be assessed. Such assurance will be built up with time but will only be fully validated once a significant number of documented sites with RA have reached the end of their service lives.

6.2 Service life of low temperature asphalts

As with RA, there are limited data on the actual service life of pavements with LTA mixtures because such mixtures were not widely used at a time so that they would now have reached the end of their service life and could be assessed. The indications are that the use of LTA should not have adverse effects on the properties of the mixture, and therefore its potential durability, provided it is adequately designed, although there are also counter indications. However, in the case of LTAs, there are several markedly different techniques to produce LTA which could have distinctly different service lives.

The main concerns about the durability of some LTA systems is the need to incorporate significant quantities of water, whether to foam or emulsify the binder, and the time need to develop its initial properties relative to the just the drop in temperature from mixing temperatures for HMA.

The expected service life of pavements with LTA can be taken as being comparable to that of pavements with HMA, at least for WMA and HWMA. However, definitive data is needed to confirm this assumption for each LTA technology. Such assurance will be built up with time but will only be fully validated once a significant number of documented sites with each technology have reached the end of their service lives.

6.3 MIST test

The MIST procedure has been shown to be appropriate for accelerated conditioning of asphalt mixtures in order to evaluate their resistance to stripping by simulating the high pressure fields which develop within an asphalt layer due to traffic loading. Therefore, the procedure should be offered to the relevant Comité Européen de Normalisation group, TC227/WG1/TG2, for incorporation into the EN 12697 series of asphalt test methods and preparation procedures.

6.4 Implementation of the EARN decision model

Engineers need to consider the effects on the future availability of the road network when choosing the type of asphalt and component materials of the mixture. The understanding of the financial implications, as well as the congestion itself, of the unavailability of sections of the network for maintenance or replacement is increasing become understood. The use of the decision offered by this project forms a good starting point for such considerations. However, some of the inputs to make the necessary assessments are not fully known and data on the effect on the durability of the pavement of using LTA systems and/or RA need to be collected in order to increase the precision of the model.

6.5 Dissemination

It is hoped that the findings of this project will be of use to managers of road networks in assessing the impact of using different materials and techniques on those networks. However, before they can make use of the findings, they need to know about them. In order to spread the word about the findings, several papers have been and are being presented by members of the consortium at different conferences around Europe. Whilst the earlier papers covered the aims of the project and the mechanism being undertaken to achieve the goal, the future presentation will stress the outcomes and the potential advantages of implementing the findings, in particular the decision model, and of collecting data to develop more robust understandings of the effect on durability of using LTA systems and/or RA.

7 Conclusions

7.1 Review of existing data

The main conclusions reached from the review of existing data are:

[1] No databases exist to identify the influence of the use of recycled construction materials or secondary by-products on the durability of the road pavements.

[2] The application of RA in HMA can reduce the expected service life but the evaluation showed a large scatter. Furthermore, international literature shows that the use of RA in new HMA mixtures results in adequate material durability performance most of the time.

[3] Feasible laboratory conditioning procedures are needed that can represent the long-term effects of incorporating additives and/or recycled materials into the mixture order to allow the estimation of durability during the mix design process.

[4] Paving during adverse weather conditions will slightly increase the risk from insufficient compaction and poor interlaying bonding.

[5] The splitting of larger construction sites into smaller patches, which may be required in order to undertake maintenance during times of low traffic volume, will increase the disadvantage of an increased number of joints.

7.2 Site trial

The main conclusions reached from the site trial, where four different mixtures containing varying proportions of RA and warm mix additive were used, are:

[1] Site quality testing of international roughness index (IRI), mean profile depth (MPD) and corrected SCRIM Coefficient (SC) showed good asphalt material performance, although the MPD values were slightly lower than usual national value for Ireland of 1.4 mm.

[2] Laboratory tests showed good material performance throughout a 12 month test period although the stiffness of the mixtures containing RA did decrease over the monitoring period, which may represent a cause for concern in the long term.

[3] The tests showed good material resistance to water damage, with ITSR values above the required 80 % threshold. The mixture containing 30 % RA and warm mix additive at 12 months saw an improvement in its wet ITS value that resulted in an ITSR value above 100 % while the ITSR value for the mixture containing 40 % RA and warm mix additive decreased by 4.6 % between months 6 and 12.

7.3 Laboratory evaluation of moisture damage and ageing

The main conclusions reached from the laboratory sensitivity testing are:

[1] The inclusion of RA has an effect on mixture tensile strength with:
  - the ITS values increasing with increasing RA content;
  - the rate of strength degradation due to moisture damage reduced for mixtures containing RA compared to control mixtures; and
  - the use of warm mix additive increasing the resistance to moisture damage induced both by bath conditioning alone and by combined bath-MIST conditioning.

[2] A change in the amount of RA content, from 30 % to 40 % did not change the dry and wet ITS and ITSR values significantly.

[3] The TSR values of the RA mixtures, with and without WMA additive, improved for the field-aged mixtures, indicating that the asphalt underwent a curing process that increased the strength with time and enhanced the response to moisture damage.

[4] The use of warm mix additive was found to increase the resistance to moisture damage induced both by bath and bath-MIST conditioning.

[5] It is recommended that ageing is considered when validating a mix design with respect to moisture damage susceptibility.

7.4 Impact assessment modelling

The main conclusions reached from the impact assessment modelling are:

[1] Generally, appreciable CO_2e and cost savings can be observed for the novel asphalt mixtures to a greater or lesser degree with the CO_2e savings being derived from both energy savings at the plant (the lower heating and drying energy of the LTA asphalt mixtures) and the recycled content that was incorporated.

[2] Direct comparisons were possible for the surface course materials which both had a recycled content of 28.6 %; in relation to these mixtures a saving of 13 % could be attributed to lower plant energy consumption and a further 5 % saving due to the recycled content.

[3] To maximise energy efficiency during production of asphalt, operations should be carefully planned to avoid repeatedly switching between HMA and LTA mixtures.

[4] The carbon footprint calculation indicates a cradle-to-gate CO_2e saving in the region of 13 % to 16 % associated with the use of LTA materials over their conventional HMA alternatives.

7.5 Overall conclusions

Combining the conclusions from the various Work packages, the main overall conclusions from this research are:

[1] The use of LTA systems, RA, secondary by-products and/or binder additives can have an effect on the durability of flexible pavements, but that affect is not always adverse and may not be great.

[2] The effect of using LTA systems, RA, secondary by-products and/or binder additives can be modelled in the expected service life of mixtures.

[3] Data on the effect of each specific components and the extent to which they are incorporated into the mixture need to be collected in order to make the model more accurate.

[4] The MIST procedure is suitable for standardisation as an asphalt conditioning procedure in the EN 12697 series.

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Appendix A – Summary of lower temperature asphalt systems

Product	Company	Description	Dosage of additive	Country used	Production Temperature or reduction ranges	Website
Zeolite additives						
Advera	PQ Corporation	Water containing using Zeolite	0.25 % of mixture by mass	USA	(10-30) °C	www.pqcorp.com/products/AdveraWMA.asp
Aspha-Min	Eurovia and MHI	Water containing Zeolite	0.3 % of mixture by mass	Worldwide including France, Germany and USA	(20-30) °C	www.eurovia.fr/en/produit/135.aspx?print=y
Organic (Wax) additives						
Asphaltan A Romonta N	Romonta GmbH	Montan wax for mastic asphalt	(1.5-2.0) % of bitumen by mass	Germany	20 °C	www.romonta.de/ie4/english/romonta/i_wachse.htm
Asphaltan B		Rafined Montan wax with fatty acid amide for rolled asphalt	(2-4) % by mixture by mass	Germany	(20-30) °C	
Sasobit	Sasol	Fischer-Tropsch wax	(2.5-3.0) % of bitumen by mass in Germany; (1.0-1.5) % of bitumen by mass in USA	Worldwide including EU, RSA and USA	(20-30) °C	www.sasolwax.us.com/sasobit.html
Sasolwax Flex		Fischer-Tropsch wax plus polymer (choice of type)	Unspecified		At least 28 °C	www.sasolwax.com/More_about_Sasolwax_Flex.html

Product	Company	Description	Dosage of additive	Country used	Production Temperature or reduction ranges	Website
Fatty acid derivative additives						
Hypertherm	Coco Asphalt Engineering	Fatty acid derivative	Unspecified	Canada	Unspecified	www.cocoasphaltengineering.com/warm_mix.aspx
Licomont BS 100	Clariant	Fatty acid amide wax	3 % of bitumen by mass	Germany	(20-30) °C	http://clariant.com/C12576850036A6E9/A0F44E23B922E21CC12576BF00484894/$FILE/20100203_Clariant_LowEmissionModifierBoosts.pdf
Chemical additives						
Cecabase RT	CECA Arkema group	Chemical package	(0.2-0.4) % of mixture by mass	France and USA	120 °C	www.cecachemicals.com/sites/ceca/en/business/bitumen_additives/warm_coated_material/warm_coated_material.page
Ecoflex or 3ELT	Colas	Unspecified additive	Unspecified	France	(30-40) °C	www.colas.com/en/innovations/products/products-list/fiche-produit-1101193.html%26product=73
Evotherm DAT	Mead-Westvaco	Chemical package plus water	30 % of binder by mass	Worldwide including France and USA	(85-115) °C	www.meadwestvaco.com/Products/MWV002106
Evotherm 3G or REVIX		Water-free chemical package	Unspecified	USA	(15-27) °C	
Qualitherm	QPR ShopWorx	Unspecified additive	Unspecified	Canada and USA	Unspecified	www.qprshopworx.com/products/asphalt-engineering/qpr%C2%AE-qualitherm/
Rediset WMX	Akzo Nobel	Cationic surfactants and organic additive	(1.5-2) % of bitumen by mass	Norway and USA	≥30 °C 126 °C	www.surfactants.akzonobel.com/asphalt/pdf/Rediset%20Brochure_0907.PDF
Sübit VR	GKG Mineraloel Handel	Unspecified additive	Unspecified	Germany	Unspecified	www.gkg-oel.de/fileadmin/gkg-oel/Dokumente/Produktbeschreibung.pdf

Product	Company	Description	Dosage of additive	Country used	Production Temperature or reduction ranges	Website
Other specified additives						
Thipoave	Shell	Sulphur plus compaction aid	(30-50) % of bitumen by mass	Worldwide	20 °C	www.shell.com/home/content/sulphur/your_needs/products/in_roads/
TLA-X	Lake Asphalt of Trinidad and Tobago	Trinidad Lake Asphalt plus modifiers	Unspecified	Worldwide	Unspecified	www.trinidadlakeasphalt.com/home/products/tla-x-warm-mix-technology.html
Emulsions						
ECOMAC	SCREG	Cold mix warmed before laying	Unknown type or quantity	France	c.45 °C	www.colas.com/en/innovations/products/products-list/fiche-produit-1101193.html%26product=75
Evotherm ET	Mead-Westvaco	Chemical bitumen emulsion	Delivered in form of bitumen emulsion	Worldwide including France and USA	(85-115) °C	www.meadwestvaco.com/Products/MWV002106
Foaming technology						
Accu-Shear Dual Warm Mix Additive System	Stansteel	Water-based foaming process	Unnecessary	USA	Unspecified	www.stansteel.com/sip.html
Adesco/Madsen Static Inline Vortex Mixer	Adesco/ Madsen	Water-based foaming process	Unnecessary	USA	Unspecified	www.asphaltequipment.com/documents/Static%20Inline%20Vortex%20Mixer%20Brochure.pdf
Aquablack WMA	MAXAM equipment	Water-based foaming process	Unnecessary	USA	Unspecified	http://maxamequipment.com/AQUABlackWMA.htm
AquaFoam	Reliable Asphalt Products	Water-based foaming process	Unnecessary	USA	Unspecified	www.reliableasphalt.com/Default.asp

Product	Company	Description	Dosage of additive	Country used	Production Temperature or reduction ranges	Website
Double Barrel Green	Astec	Water-based foaming process	Optional anti-stripping agent	USA	(116-135) °C	www.astecinc.com/index.php?option=com_content&view=article&id=117&Itemid=188
ECO-Foam II	Aesco / Madsen	Water-based foaming process	Unnecessary	USA	Unspecified	www.asphaltequipment.com/documents/EcoFoamII.pdf
NA Foamtec	Foamtec International	Water-based foaming process	(1.5 - 3.0) % by mass of binder	RSA and USA	Unspecified	www.aapaq.org/q/2011st/docs/110909_Lewis_Discussion_with_Aussie_delegation_WMA.pdf
HGrant Warm Mix System	Herman Grant Company	Water-based foaming process	Unnecessary	USA	Unspecified	www.hermangrant.com/warm-mix.htm
LEA (Low Energy Asphalt)	LEACO and McConnaughay	Water-based hot coarse aggregate mixed with wet sand	±0.5 % of bitumen by mass of coating and adhesion additive	France, Italy, Spain and USA	≤100 °C	–
LEAB	BAM Wegen bv	Water-based mixing of aggregates below water boiling point	0.1 % of bitumen by mass of coating and adhesion additive	Netherlands	90 °C	www.bamwegen.nl/sites/www.bamwegen.nl/files/site_images/LEAB%20-%20Asphalt%20English.pdf
LT Asphalt	Nynas	Water-based binder foaming with hygrophilic filler	Hygroscopic filler at (0.5-1.0) % of mixture by mass	Worldwide including Italy and Netherlands	90 °C	http://nyport.nynas.com/Apps/1112.nsf/wpis/GB_EN_LT-Asphalt/$File/LT-Asphalt_GB_EN_PIS.pdf
Meeker Warm Mix Asphalt System	Meeker Equipment	Water-based foaming process	Unnecessary	Spain	Unspecified	www.meekerequipment.com/new_warmmixad1.html
Ultrafoam GX	Gencor Industries	Water-based foaming process	Unnecessary	USA	Unspecified	http://gencorgreenmachine.com
Warm Mix Asphalt System	Terex Roadbuilding	Water-based foaming process	Unnecessary	USA	<32 °C	www.terexrb.com/default.aspx?pgID=308

Product	Company	Description	Dosage of additive	Country used	Production Temperature or reduction ranges	Website
Other processes						
Low Emission Asphalt	McConnaughay Technologies	Combination of chemical and water based foaming technology	0.4 % of bitumen by mass	USA	90 °C	www.mcconnaughay.com/lowemissionasphalt_intro.php
WAM-Foam	Shell, Kolo Veidekke	Foaming process using two binder grades	Anti-stripping agents can be added to soften binder	Norway, France, Canada, Italy, Luxemburg, Netherlands, Sweden, Switzerland, UK and USA	(110-120) °C	www.shell.com/home/content/bitumen/products/shell_wam_foam/