Effect of using of reclaimed asphalt and/or lower temperature asphalt on the Availability of the Road Network

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Abstract

There is a need for a method for assessing the results from changes in the potential durability of road materials due to the inclusion of reclaimed and secondary component materials in the manufacture of new road materials. Such changes will have an effect on the cost of the construction maintenance, both financially to the client and environmentally to society in general, and any savings may be transitory. A site trial has been laid of mixtures with and without reclaimed asphalt and work started to assess their durability from early-life properties. The trials are being monitored for their initial performance whilst laboratory trials are concentrating on the combined effect of ageing and moisture damage on the performance of asphalt mixtures on the trial. All three strands are being used to develop 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, both initial and whole-life. The costs will be identified as being direct (of the construction and maintenance) and indirect (on society in general, such as congestion).

Keywords: Recycling, Secondary aggregates, Durability, Whole-life costs.

Résumé

Il existe un besoin de trouver une méthode pour évaluer les résultats de la variation de la durée de vie potentielle de matériaux routiers en raison de l'inclusion des matériaux de construction recyclés et secondaires dans la fabrication de nouveaux matériaux routiers. Ces changements auront un effet sur le coût de l'entretien de la construction, à la fois financièrement concernant la clientèle et de l'environnement pour la société et les économies réalisées peuvent être éphémères. Un essai du site a été fait avec des mélanges avec et sans enrobés et des travaux ont été entrepris afin d'évaluer leur durabilité et les propriétés en début de la vie. Les essais sont surveillés pour leur performance alors que les essais en laboratoire se concentrent sur l'effet combiné des dommages causés par le vieillissement et de l'humidité sur la performance des enrobés bitumineux sur le procès. Les trois brins sont utilisés pour développer des modèles d'analyse du cycle de vie pour les adapter à ll'utilisation des matériaux des composants alternatifs sur la disponibilité du réseau et leur coût global financier et environnemental, que se soit pour l'état initial que pour la vie entière. Les coûts seront identifiés comme étant directe (de la construction et de l'entretien) et indirects (sur la société en général, tels que la congestion).

Mots-clé: Recyclage, Agrégats secondaires, Durabilité des coûts, Vie entière.

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1. Introduction

The durability of road materials is an important factor influencing the service lifetime of the road structure or parts of it. Because of its effects on the frequency and extend 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. The EARN project, on which this report is based, was designed to assess the effect that changes in durability of road materials due to the inclusion of reclaimed and secondary component materials in the manufacture of new road materials will have on the cost of the construction, both financially and with regard to the environment.

The project is building 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. Existing knowledge has been reviewed to determine the service lifetime of the different pavement layers whilst a site trial sections mixtures with and without reclaimed asphalt has been laid to assess their durability from early-life properties. Laboratory trials are starting, concentrating on the combined effect of ageing and moisture damage on the performance of the asphalt mixtures in the site trial. All three strands are being 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. Review of existing knowledge

2.1. Relevant parameters for pavement service life

Asphalt pavement durability is a key factor in determining the performance of a pavement material and, as such, the pavement service lifetime together with the pavement maintenance requirements during its 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 summary has been produced (Mollenhauer *et al*., 2013). However, many data sets are required to evaluate the effect of one parameter on the service lifetime of the pavement. Furthermore, the modelling of a pavement's service lifetime is only possible if most of the parameters are known; otherwise, it is subjected to a wide range of uncertainty.

In pavement management systems (PMS), service lifetimes and qualitative functions for relevant pavement distresses are already incorporated. One approach considers a general design lifetime of the pavement structure of a defined time (e.g. 20 or 30 years) for a design traffic loading. For pavement management, the actual known traffic loading from the beginning of the service life is used for service lifetime prognosis. This approach considers the pavement structure as a whole without utilisation in layers and/or materials. Another approach is that some national guidelines already contain service lifetimes for selected pavement materials which are applied in PMS. In Table 1, these assumed service lifetimes derived from various sources are summarised for different pavement materials.

2.2. Service life of low-temperature asphalt mixtures

Low-temperature asphalt mixtures were developed in order to reduce the paving temperature, the energy used and greenhouse gases emitted. The development of low-temperature asphalt mixtures has been driven by the aim to reduce the temperature effect on asphalt pavement production, laying and compaction, in order to improve effect of asphalt production on the environment. Furthermore, low-temperature mix asphalts have been utilised to allow the recycling of existing pavements at the end of their service life with reduced demand for material transport, heating energy and raw-material consumption.

However, the low-temperature asphalt pavements may also result in shorter service life in comparison to equivalent standard hot mix asphalt pavements. It is believed that this reduction occurs because the different mixing and paving technologies used in the production of low-temperature asphalt result in weaker mechanical material properties as well as its resistance against cracking.

Table 1. General service life assumptions given in guidelines and specifications for pavement management systems

Road layer	Pavement material	Germany (FGSV, 2001)		Netherlands (IVON, 2012)		UK (SWEEP, 2014)	
		≥ 300 ESAL/day	< 300 ESAL/day	Right hand lane	Full width	Skid res. lifetime	Structural lifetime
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	*	*	–	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 hot-mix asphalt layer on sealing	8	10	–	–		

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

The WMA technologies can be classified in several ways. One way is to classify the technologies by the degree of temperature reduction. Figure 1 shows the classification of asphalt mixtures according to the production temperature. Warm asphalt mixes are separated from half-warm asphalt mixtures by the resulting mixture temperature. Specifically, for the warm and half-warm asphalt mixtures the mixing, laying and compaction are usually undertaken at 100 ºC to 140 ºC and at 70 ºC to 100 ºC, respectively, whereas for the hot asphalt mixtures the temperatures can reach 138 °C to 160 °C depending on the bitumen grade used.

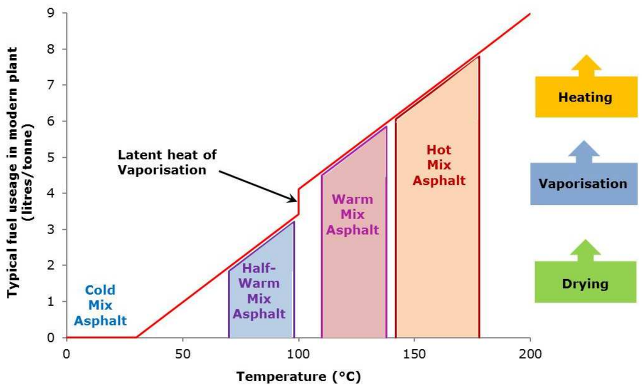

Figure 1. Definition of low-temperature asphalt mixtures (EAPA, 2010)

A large number of different products that can be used in lower temperature asphalt technologies are currently available in the market. The additives and/or processes used to produce them tend to be proprietary products that may not necessarily have data available that is comparable with that of other products. A list of 35 products that are, or have been, on the market in Europe and/or America has been produced (Mollenhauer, 2013).

Despite economic and environmental benefits of the WMA technologies, there are still doubts about its long term performance (Prowell *et al*., 2007). Prowell *et al*. recommended that further research is needed in order to validate the expected field performance of WMA mixtures, particularity in relation to mix compactibility, rate of gain of structural strength after construction (i.e. curing), rutting, fatigue, moisture sensitivity and the effect of different binder modifiers on the pavement design life.

The potential environmental and social benefits promised by WMA technology will undoubtedly stimulate interest for the wider use of WMA. It may be appropriate to give some advantage to green technologies in the procurement process in order to encourage their use, as were used in the Greenroad project rating system (Soderlund, 2007). However, if the long-term performance of WMA is inferior to HMA, this difference could negate any long-term financial or environmental benefits. Therefore, European Asphalt Pavement Association (EAPA) in its position paper on use of WMA (2010) stated that WMA procurement should be subjected to Life-Cycle Cost assessment in order to ensure that WMA technologies provide equivalent performance to HMA technologies and that the appropriate maintenance scenarios are fully assessed. Holt (2008) demonstrated that, with a good pavement life-cycle model, significant economic and energy saving can be achieved. He demonstrated that, for highway and national road maintenance cost, reductions can be made with costs reduced by 12 % and CO2 emissions by 56 % on a large road maintenance project.

For selected asphalt pavements, the effect of durability in a life-cycle analysis was evaluated during Re-Road project (Wayman *et al*., 2012a). The beneficial effect by applying warm-mix technologies can be outnumbered by the effects from extended road maintenance needs if the durability of the pavement is influenced significantly.

3. Trial site

3.1. Need for full size trial

There are particular advantages that are uniquely associated with full-scale testing over simulated laboratory test programmes (Hartman *et al*., 2001). The effects of size, manufacturing, environment, substructure and loading represent can be better assessed from on-site conditions than from what can be simulated directly with scaled models. However, full-scale tests, which are generally in outdoor ambient conditions, do not permit temperature and moisture to be controlled and, consequently, they are always inherent disparities relating laboratory and on-site test data.

Various pavement monitoring procedures exist (Hartman *et al*., 2001), the most basic being the evaluation of structural integrity though monitoring of crack initiation and propagation and permanent deformation on the pavement surface and more complicated, in-depth, evaluation being monitoring surface and subgrade layers transverse and longitudinal strains, wheel loads, contact pressures. On-site material properties can be evaluated by obtaining material cores from the road trial and testing it the laboratory for stiffness, water sensitivity ageing and fatigue. The falling weight deflectometer (FWD) can be used to measure on-site surface deflection, and applying appropriate back calculating method stiffness of the pavement layers can be determined.

3.2. Mixture 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 2, 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 2.

Table 2. Mixture designs

Mixture No.	Proportional content (%)					
	RA	10 mm	CRF *	Filler	Fresh Binder	Warm Mix 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.

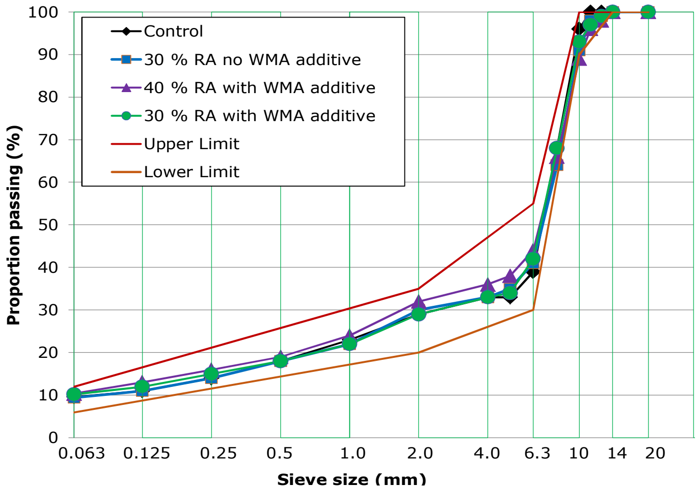

Figure 2. Particle size distribution

3.3. Selection and construction of the test section

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 (http://nraextra.nra.ie/CurrentTrafficCounterData/index.html). Figure 3 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 4 shows a schematic layout of the trial section. The site was split into four sections of varying lengths for the different mixtures.

Figure 3. Satellite image of the trial road section

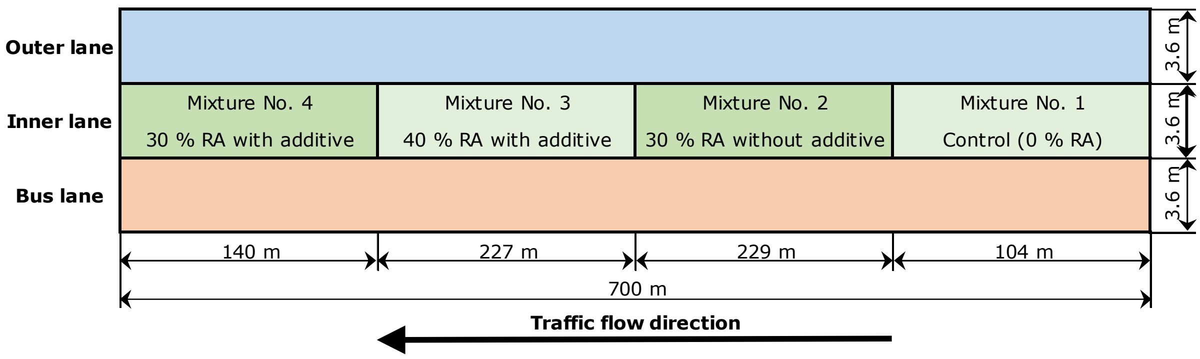

Figure 4. Schematic representation of the trail section

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 4) 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 5 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, giving section lengths, temperature and weight of each mixture.

Figure 5. Paving process of the trial section

Table 3 On-site work record of asphalt material

Mix No.	RA content (%)	Containing warm mix additive	Load No.	Start Chainage (m)	End Chainage (m)	Discharge temp. (^oC)	Rolling temp. (^oC)	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

3.4. Reclaimed asphalt feedback

The reclaimed asphalt feedstock was supplied from a site on the M1 motorway in North County Dublin and is derived from a single-source 14 mm porous asphalt. The material was milled and stored in a depot until required on this project. The total amount of reclaimed asphalt material supplied was 170 tonnes. The quantity of the processed reclaimed asphalt material by size is given in Table 4. The visual inspection revealed that the >16 mm material contained binder course material aggregate. Therefore, the >16 mm and <6 mm reclaimed asphalt aggregate was screened out and not used for the trial asphalt mixtures.

Table 4. 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 of total (%)	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 reclaimed asphalt material aggregate size distribution/grading is shown in Figure 5 and the binder contents were 5.2 %, 5.4 %, 4.8 %, 5.7 % and 5.4 % with an average of 5.3 %.

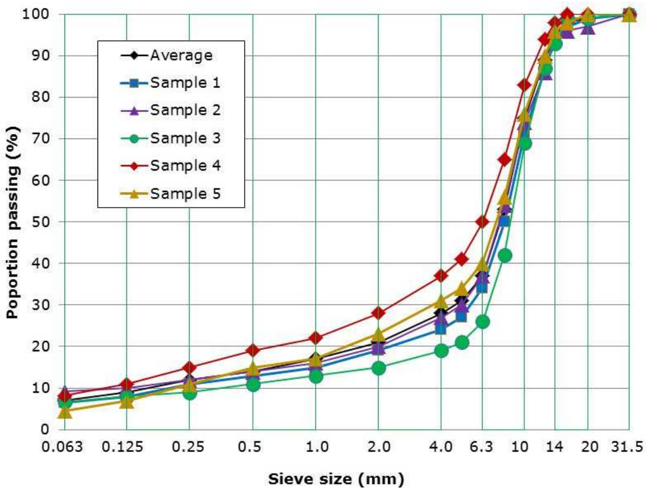

Figure 5. RA material grading after the binder removal

3.5. Testing

The asphalt mixture material was sampled from the paver as shown in Figure 6a; this material is used for stiffness and water sensitivity testing at a later stage. In addition, a total of 108 cores (27 from each trial section) were taken 24 hours after the construction was completed. These cores will be used for subsequent laboratory moisture conditioning by the MIST device. The coring procedure is shown in Figure 6b & 6c. The laboratory testing procedures are further described in the Section 4 of this paper.

As part of the study the ride quality of the test site will be investigated. A number of tests will be conducted to allow evaluation of the international roughness index (IRI), pavement conditioning index (PCI) and skid resistance. At the time of writing, only the IRI testing had been completed. Continuous measurements of IRI were acquired using the Road Surface Profiler (RSP). The data was collected at speeds of 70-80 km/h in order to ensure that there was no delay or disruption for other road users. The entire data collection process was non-contact, using high-frequency lasers and accelerometers in conjunction with a very accurate distance measurement system. The IRI measurements were continuously measured in both inner and outer wheel paths and the values were recorded at 10 m intervals. Table 6 shows average IRI values for the test sections. The average IRI value for each section is < 2 which shows good ride quality of the pavement surface.

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

Figure 6. Collection of samples from site

Table 6. Average IRI values of the test site.

Section	IRI (m/km)		
	Left	Right	Average
1	1.25	1.23	1.24
2	0.96	0.99	0.98
3	1.04	1.10	1.07
4	1.33	1.43	1.38

4. Laboratory testing

During their service life, the performance of asphalt pavements is greatly affected by different environmental factors such as moisture, oxygen, heat, pressure and UV light. Primarily in this work, moisture damage and ageing due to oxygen diffusion were assumed to be the most important parameters that can shorten the pavement life and accelerate pavement distresses. The use of reclaimed asphalt, secondary aggregates and lower temperatures will affect the various factors in different ways, further complicating an already complex situation. Presently laboratory trials are starting, concentrating on the combined effect of ageing and moisture damage on the performance of the asphalt mixtures in the site trial.

Another important parameter that is considered to be a serious cause for diminishing the long-term performance of asphalt concrete pavements is moisture damage. Regardless of the mix composition, asphalt mixtures with moisture will suffer from moisture damage at some time during their service life. At micromechanical level, moisture-induced damage is described as the loss of strength and durability of the asphalt mixture through loss of adhesion between the asphalt binder and the aggregates, as well as through loss of cohesive resistance of the asphalt binder itself (Kiggundu and Roberts, 1988). Moisture diffusion, desorption of the asphalt binder due to fast water flows and cyclic pore pressure development from entrapped water in the air voids (i.e. pumping action) were identified as the physical and/or mechanical processes that ultimately can lead to pavement distresses (Kringos and Scarpas, 2005, Kringos *et al*., 2008).

In this project, moisture diffusion and pumping action were identified as the dominant moisture damage inducing mechanisms. However, the time frame over which each mechanism occurs in the field differs significantly. Moisture infiltration occurs over a longer timeframe, while excess pore pressure development takes place in very short times. In order to address the individual damage mechanisms associated with these two moisture damage inducing processes, the test protocol utilized consists of a combination of two different conditioning methods: (a) bath conditioning and (b) cyclic water pore pressure application. Bath conditioning is performed at elevated temperatures so as to facilitate the infiltration of water into the asphaltic mixture and, consequently, to accelerate the long-term degradation of the material properties. 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 (InstroTek, 2009).

In order to evaluate the material used on-site, a series of laboratory tests are planned, including the indirect tensile stiffness modulus (ITSM) test to EN 12697-26, a water sensitivity test to EN 12697-12 and the moisture induced sensitivity test (MIST). The ITSM and water sensitivity test will be carried out at four stages starting from the initial trial construction, with further testing scheduled for 3, 6, and 12 months. The initial testing stage is underway at the time of writing using material collected from the paver during the construction process. These are later compacted in the laboratory using the gyratory compaction procedure given by the EN 12697-31.

For MIST testing, cylindrical samples of 100 mm in diameter and 50 mm in thickness cored out from the site trials are obtained. The specimens first will be subjected to moisture infiltration by placing them in a bath filled with distilled water, at a temperature of 60 °C. At fixed time intervals of 0, 3 and 6 weeks, three specimens per mixture are removed from the bath, placed in a bath at 20 °C for 2 hours and then stored at a climatic chamber at 20 °C until tested for their strength using the indirect tension test (ITT). The rest of the samples are further conditioned in the MIST device by applying 3500 cycles of water pumping action at a temperature of 60 °C and a pressure of 0.48 MPa. After MIST conditioning, the samples are placed into a water bath at 20 °C and kept there for 2 hours before ITT testing.

5. Assessment of life-cycle cost and carbon footprint

5.1. Assessment on a life-cycle basis

Life cycle cost and contribution to climate change of the mixtures will both be assessed on a life cycle basis. The applicable standards will be followed for each assessment; ISO 14067:2013 for the carbon footprint and ISO 15686-5 for the life cycle costing. In addition, calculation of the carbon footprint will be facilitated using an updated version of the asphalt Pavement Embodied Carbon Tool (asPECT; Wayman *et al*. 2012b); a tool that meets to the appropriate standards and is specific to asphalt life cycle, providing the necessary level of granularity to assess the impacts of the inclusion of recycled content, lower-temperature production and variable durability. Cost and carbon impacts will be assessed over a 60 year analysis period, allowing for the effects of multiple asphalt renewal cycles to be observed. The rates of renewal will be directly informed by the laboratory assessment outlined in Section 4, and early observations of the trial site. Furthermore, both assessments will consider multiple repetitions of raw material acquisition, through to product production, installation, maintenance and end-of-life.

5.2. Formulation of the carbon footprint

Whereas the life cycle cost assessment can be informed by data that is readily available to plant and infrastructure managers, some of the data to inform the carbon footprinting assessment needs to be collected first hand, while the asphalt production takes place. To this end, minute-by-minute readings of energy consumption at the Lagan Kinnegad production plant were taken during production of the four mixtures detailed in Table 3, in order to truly observe the consequences of lower-temperature mixing with recycled content during a typical batch plant production cycle. Having observed and collected data from a typical batch production cycle, where the plant is heated only once from ambient temperature to produce all four mixtures consecutively, there is a need to apportion the overall energy consumption (both gas oil and electricity) equitably between the mixtures according to their particular characteristics, including the recycled asphalt content and heating temperature, having first accounted for factors common to all mixtures, such as the efficiency of the plant and the associated heat loss. The outcome of this analysis will be a methodology that can be applied to future trial mixtures produced in a similar manner, a quick an easy method to investigate the carbon footprints of trial low temperature asphalts.

Plant energy consumptions will be one component of the cradle-to-site carbon footprints of the materials and these will be combined with the contributions of raw materials, transport and installation works. Later in the project, the durability of the materials will be factored in order to extend the analyses from cradle to end-of-life.

6. Conclusions

This report describes the initial work of a project to develop a model that can to assess the effect that changes in durability of road materials due to the inclusion of reclaimed and secondary component materials in the manufacture of new road materials will have on the cost of the construction, both financially and with regard to the environment. The work has not been completed at the time of writing, but the data necessary to build the model is being collected.

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References

European Asphalt Pavement Association (2010). The use of warm mix asphalt. EAPA position paper. Brussels: EAPA. http://eapa.org/usr_img/position_paper/ the_use_of_warm_mix_asphalt_january_2010.pdf.

Objectbeheerregime Verhardingen, IVON (2012). Fiola van der, P. Version 1.1. Delft: Rijkswaterstaat

Forschungsgesellschaft für Straßen- und Verkehrswesen (2001). Richtlinie für die planung von erhaltungsmaßnahmen (Guideline for the planning of conservation measures). Köln: FGSV.

Hartman, A.M.; Gilchrist, M.D.; Owende, PMO; Ward, S.M. and Clancy, F. (2001). In-situ accelerated testing of bituminous mixtures. Road Materials and Pavement Design, Vol. 2 (4), pp. 337 – 357.

Holt, C. (2008). New and better tools for life-cycle assessment. Proceedings of Sustainable Transport Forum Workshop, Toronto, Canada, May 28 – 29.

InstroTek. (2009). Moisture induced sensitivity test operators guide, Version 1. Raleigh, NC.

Kiggundu, B. M. and Roberts, F. L. (1998). Stripping in HMA mixtures: state-of-the-art and critical review of test methods. NCAT Report 88-02, National Center for Asphalt Technology Alabama: Auburn University.

Kringos, N., and Scarpas, A. (2005). Raveling of asphaltic mixes due to water damage: Computational identification of controlling parameters. In Transportation Research Record: Journal of the Transportation Research Board, No. 1929, Transportation Research Board of the National Academies, Washington, D.C., pp.79–87.

Kringos, N., Scarpas, A., Kasbergen, C., & Selvadurai, P. (2008). Modelling of combined physical mechanical moisture-induced damage in asphaltic mixes, Part 1: Governing processes and formulations. International Journal of Pavement Engineering, Vol. 9, No. 2, pp. 115-118.

Mollenhauer, K., Nicholls, J. C., Varveri, A., McNally, C., Gibney, A & Tabaković, A. (2013). Service lifetime, suitable test methods for characterising and main parameters controlling durability of warm-mix asphalt containing RA. Wokingham: TRL. http://www.trl.co.uk/EARN/.

Prowell, B. D., Hurley, G. C., & Crews, E. (2007). Field performance of warm mix asphalt at the NCAT track test. Transportation Record Board, 86th Annual Meeting, Washington DC, USA.

Soderlund, M., Muench, S. T., Willoughby, K., Uhlmeyer, J., & Weston, J. (2008). Green Roads: A sustainability rating system for roadways. Transportation Record Board, 87th Annual Meeting, Washington DC, USA.

Wayman, M., Parry, T., Andersson-Sköld, Y., Raaberg, J., Bergman, R., Enell, A., & Huang, Y. (2012a). Life cycle assessment of reclaimed asphalt. Re-Road deliverable D3.4, 01 October 2012. http://re-road.fehrl.org.

Wayman, M., Schiavi Mellor, I., Cordell, B., James, D., Gossling, R., Loveday, C., Simms, M., Southwell, C. (2012b). The asphalt pavement embodied carbon tool (asPECT): Developing a carbon footprinting methodology for asphalt products. 5th Eurasphalt & Eurobitume Congress, Istanbul, Turkey.