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EARN

Cost and CO_2e modelling of lower temperature materials with recycled content, as used in site trials – D5

Decision model – D6

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University College Dublin

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Lagan Asphalt

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CEDR Call 2012: Recycling: Road construction in a post-fossil fuel society

EARN
Effects on Availability of Road Network

Cost and CO_2e modelling of lower-temperature asphalt materials with recycled content, as used in site trials

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Authors of this deliverable:
Matt Wayman, TRL, UK
Dominic Leal, TRL, UK
Sean Cassidy, Quality Asphalt (formerly of Lagan Asphalt), Ireland

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Executive summary

The need for society to become more resource efficient as a whole has been recognised by the European Union and features as part of the Europe 2020 Strategy. The Construction Products Regulation 574/2014 impresses resource efficiency requirements, amongst others, on construction products manufactured and used within the European Union, to promote the sustainable use of natural resources. Construction works must be designed, built and demolished in such a way that the use of natural resources is sustained and, in particular, reuse or recyclability, durability and environmental compatibility of construction works is ensured.

The asphalt industry has already made good progress with regards to recycling. At least some asphalt recycling is already achieved by the majority of countries in Europe. However, there is still great potential for improvement and higher proportions of RA to be incorporated into new mixtures. Levels of recycling can be enhanced by building confidence within the industry in relation to recycling and successful demonstration and this is one of the aims of the EARN project.

Carbon-footprinting (CF) and life-cycle costing (LCC) analyses have been conducted based on the EARN trial site. Data used to complete the analyses was collected directly, from reputable data sources or from other EARN deliverables. 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.

In general, appreciable CO_2e and cost savings were observed for the novel asphalt mixtures, to a greater or lesser degree, depending on the exact mixture recipe. CO_2e savings derived primarily from the recycled content that was incorporated, which was the primary aim of EARN, to increase recycling levels and secondly from the "added benefit" of energy savings at the plant, deriving from use of lower-temperature processes facilitated by use of a surfactant additive, to enable high recycling proportions to be incorporated into mixtures at a conventional asphalt plant. Substitution of primary aggregates and bitumen and the avoidance of their associated transport with reclaimed asphalt planings proved advantageous in cost and environmental terms. Energy savings at the plant and the associated carbon benefits were more marginal. When the plant was set up in such a way to make a direct comparison of an HMA and an LTA, the savings were more conclusive. Under these conditions, cradle-to-gate, the overall cost savings of using the lower-temperature, 30 % recycled mixture were 11.2 % and overall CO_2e savings 10.8 %.

Recycling asphalt, whilst being overwhelmingly a sustainable practice, does come with a number of conditions. Novel mixtures incorporating recycled content must perform to the same level as the conventional hot-mix alternatives because reduced durability would have the biggest negative impact in cost and environmental terms. Adequate consideration must also be given to logistics and minimising the transport within 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. Lower-temperature asphalt production should come with its own set of considerations. If additives are used, then some attention should be given to the additive, its origin and its own embodied carbon, although this consideration did not prove to be a significant factor in relation to the EARN trial section. LTA technologies which do not have to overcome the latent heat of vaporisation during heating should be considered because they can potentially realise greater CO_2e benefits compared to those mixed above 100 °C. Each of these important factors is explored as part of the analysis that has been conducted. A decision model has been prepared to provide

assistance in how to utilise recycled asphalt and which technologies are most appropriate depending on the context.

1 Introduction

1.1 EARN project

The overall aim of the EARN project has been to evaluate the effects of incorporating elevated levels of reclaimed asphalt (RA) into new asphalt mixtures and to assess the environmental and economic implications of the practice.

The need for society to become more resource efficient as a whole has been recognised by the European Union and features as part of the Europe 2020 Strategy. Furthermore, the Construction Products Regulation 574/2014 is the basis of technical performance standards and CE marking for construction products in Europe. As a passed regulation, it follows the most direct pathway of EU law and has binding requirements for each member state without the need for adoption by each individual national government. The Construction Products Regulation sets seven Basic Requirements for Construction Works (BRCW), the final one of which impresses resource efficiency requirements on construction products:

(7) Sustainable use of natural resources – The construction works must be designed, built and demolished in such a way that the use of natural resources is sustained and in particular ensure the following:

- *(a) Reuse or recyclability of the construction works, their materials and parts after demolition;*
- *(b) Durability of the construction works;*
- *(c) Use of environmentally compatible and secondary materials in the construction works.*

The asphalt industry is by no means “making a standing start” with regards to recycling. EAPA reports regularly on levels of recycling attained within most European countries (EAPA, 2012) and at least some recycling is achieved by the majority. However, there is still great potential for improvement and higher proportions of RA to be incorporated into new mixtures, achieving double-digit rather than single-digit proportions in new mixtures. The level of technology is not a limiting factor to levels of recycling because many proven recycling technologies exist and are utilised, both *in plant* and *in situ* at the road site (EAPA, 2005), albeit without the desired level of coverage as yet. Consequently, the shortfall in take-up of recycling appears to be a gap that can partially be filled by building confidence within the industry in relation to recycling and successful demonstration, which is one of the aims of the EARN project. The aim of this Deliverable is to answer some of the additional questions related to recycling, such as “is it cost effective to recycle?” and “what are the environmental benefits of recycling?”

In order to answer these two questions, a carbon-footprinting (CF) and life-cycle costing (LCC) analysis has been conducted based on the site trial that featured earlier in the project. Direct data collection at the trial and subsequent follow-up were the source of information on the key variables such as the 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. Some insight into the service lives of asphalt materials incorporating recycled content, relative to their conventional alternatives, was gained from EARN Deliverable 3 and used to provide an insight into the effect of durability on environmental and economic performance. 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.

1.2 Anticipated benefits of enhanced asphalt recycling

Improved resource efficiency, achieved through closed-loop recycling of construction products[1], is founded on the basic premise that re-use of the reclaimed resource avoids the need for some primary resources to be used instead. This sustains reserves of natural resources for future generations. Preservation of resources is particularly advantageous for critical resources, such as those with limited known remaining reserves or those which could be subject to geo-political conflict.

Aside from preserving reserves of natural resources, recycling often has associated benefits that result in recycled products having lower "embodied" impacts than their counterparts manufactured from virgin resources. Embodied impacts are comprised of those upstream from and including the manufacturing process – sometimes termed the "cradle to the gate" – such as fuel use incurred in extraction, processing and transport of the raw materials. Comparably, recycled products usually have lower embodied impacts because the requirement to initially refine the reclaimed product is usually avoided and the transport distances between source and reprocessing or remanufacturing site are often shorter than those from primary extraction site to processing and manufacture. Embodied impacts might be measured in terms of "embodied fuel" or translated into another tangible impact such as embodied carbon (evaluated as carbon dioxide equivalents; CO_2e).

In the case of asphalt, closed-loop recycling can avoid the use of both primary aggregates and bitumen because some of the valuable properties of both components can be preserved from the first use through to the second. Whilst the hardness and texture of stone do not diminish from one service life to the next, the residual activity of the bitumen coating the stone can depend on a number of factors, such as the degree of ageing in the first life and the method of recycling selected. Material "criticality" is an issue in relation to components such as aggregates with a high polished stone value (PSV) and bitumen, a crude oil fraction.

In an analysis of "embodied impacts", the conventional and recycled asphalt systems need to be determined accurately. Where hot recycling is used, the fuel demand for conventional asphalt and asphalt containing recycled content can be very similar because the processes undergone by both types of mixture are comparable. In some cases, the fuel demand for mixtures containing recycled content can be marginally in excess of those for conventional mixtures, especially if no plant modifications have been undertaken to facilitate the recycling process. In these situations, the extra fuel demand arises from the need to "superheat" the aggregate fraction to compensate for the RA that is added cold and still reach the specified temperature range. Accordingly, the benefits from recycling will derive solely from the avoided impacts of using RA in place of virgin aggregates and binder and these will need to outweigh any additional fuel demand associated with the recycling process itself.

Technologies are available that avoid the need for superheating to facilitate hot mix plant recycling, allowing the RA to be preheated before mixing and any moisture present to be driven-off. Each of these technologies involves drying the reclaimed material either with a separate dryer or a modification to the drum on the principal dryer. Implementation of any of these types of technologies requires a significant capital outlay.

[1] "Closed-loop" recycling returns products to their original use after deconstruction, reprocessing and re-manufacture. Closed-loop recycling can be directly contrasted with "open-loop" recycling, which recycles a deconstructed product to a use other than that of its previous life; usually a 'lower value' use. An example of open-loop recycling might be glass from a bottle bank being used as aggregate, rather than the higher-value closed-loop option of re-melting into new bottles.

As already stated, the aim of the EARN project was to maximise recycling. A subtext to this should have been to achieve it without any significant capital outlay and to maximise environmental benefits. Avoiding capital outlay would allow any suitable technology identified to be more widely adopted, post-project completion. The technology identified for use in EARN was the CECABASE™ RT 945 warm mix additive[2]. This additive contains the surfactant "imidazoline". By virtue of using the surfactant, it was anticipated that there would not be a need to remove all of the moisture from the aggregates and RA prior to mixing. Furthermore, higher proportions of RA than could normally be included through superheating (perhaps up to 15 %) could be incorporated using conventional plant technology. Additionally, use of this particular additive meant that lower-temperature mixing could be used in tandem with the higher recycled contents.

One of the principal benefits of the lower-temperature asphalt (LTA) technologies is the energy savings that can be realised via lower temperature mixing. This benefit can be expressed using the graph in Figure 1-1, which splits LTA into three sub-categories based on temperature. These are: warm mix asphalt (WMA); half-warm mix asphalt (HWMA); and cold mix asphalt (CMA).

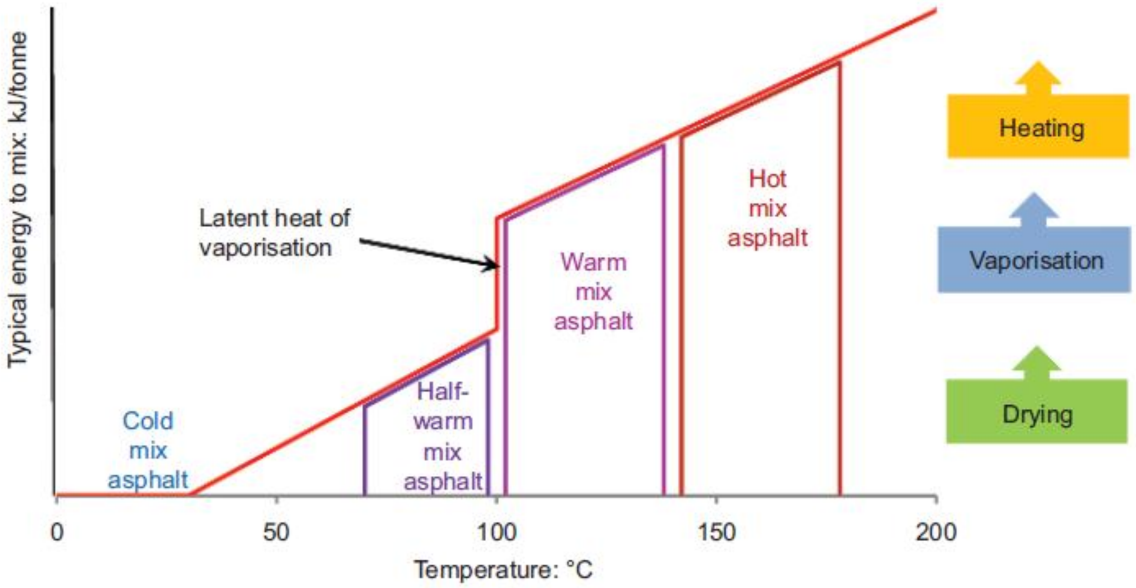


Figure 1-1: Classification of LTA technologies by temperature range
(Nicholls & James, 2011)

Conventional HMA is usually produced at temperatures of 140 °C to 180 °C, warm mix asphalt (WMA) at 100 °C to 140 °C and half-warm asphalt (HWMA) at 70 °C to 100 °C. Production at a lower temperature directly translates into energy savings for the lower-temperature technologies when compared to conventional HMAs. HWMAs and CMAs also have the significant added benefit of not requiring the complete removal of moisture from the aggregate (or RA), consequently steam is not driven off by reaching temperatures in excess of boiling point and the latent heat of vaporisation does not need to be overcome.

Selection of the additive gave scope for trial mixtures to both be designed with elevated RA contents (30 % and 40 % RA were targeted) and for mixing to be undertaken in the WMA temperature range of WMA (140 °C was selected as the target temperature).

[2] http://www.roadscience.net/products/material-science/additives/ad-here%C2%AE-cecabase%E2%84%A2-rt-945

2 Modelling the environmental and economic performance of road pavements

In both cost and CO_2e modelling, a life cycle based approach is advocated. Numerous tools are available to facilitate the calculation of carbon footprints in relation to roads. A recent overview of tools that are currently available is provided by Spriensma *et al*. (2014). Based on the findings of the review, the life cycle based approach of asPECT (the asphalt Pavement Embodied Carbon Tool [Wayman *et al*., 2014]) was selected to analyse the contribution to climate change of the mixtures used in EARN. This approach not only considers the plant energy consumption in heating, mixing and peripheral activities but also the acquisition, transport and processing of constituent materials and installation at site and thus evaluates any potential trade-offs between these steps. It also offered the following functionality that was crucial to the analysis required in EARN:

- The ability to analyse the CO_2e contributions of asphalt mixtures according to specific mixture recipes – the mixtures used in the EARN trial are "novel" in terms of recycled content and the additives that they use;
- Adequate consideration given to the properties of RA, such as active binder content and what this offers to the new mixture in terms of CO_2e benefit – the mixtures used in EARN have high recycled content and this should be fully accounted for;
- The capability to accept specific plant energy consumptions, as gathered on the day of the trials – warm mixtures in the EARN trial (and cold mixtures in the sister CoRePaSol project) have specific energy consumptions that needed to be accounted for;
- The facility to enter specific national emissions factors – key emissions factors for fuel and electricity use in Ireland were used to overwrite the default UK emissions factors in asPECT; and
- The facility to accept specific pavement lifetimes for different nations – EARN Deliverable D3 highlighted the variability in national estimates for pavements built using the same material.

The life cycle steps covered by asPECT are presented in Figure 2-1.

Life-cycle stage		Description
1	**Raw Material Acquisition**	Acquiring raw materials from the natural environment with the input of energy
2	**Raw Material Transport**	Transporting acquired raw materials to processing
3	**Raw Material Processing**	Crude oil refining, rock crushing and grading, recycled and secondary material reprocessing
4	**Processed Material Transport**	Transporting processed raw materials to site of manufacture of bitumen bound highway components
5	**Road Component Production**	Production of bitumen bound mixtures
6	**Material Transport to Site**	Delivery of materials to site
7	**Installation**	Placing materials at the construction site, mobilisation of plant and labour
8	**Scheme Specific Works**	Installation of other specified materials direct to site (e.g. aggregates and geosystems)
9	**Maintenance**	Interventions to maintain the road: overlay, surface dressing works, patching, haunching etc.
10	**End of Life**	Excavation and material management, mobilisation of plant and labour

Use

Figure 2-1: Life cycle steps covered by asPECT

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

Life cycle costs (LCC) are those directly associated with the planning, design, acquisition, disposal and support of an asset (NSW Treasury, 2004). In other words, 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 life cycle steps 1 to 10.

A bespoke model was setup to perform LCC analysis on the asphalt mixtures and trial sections applied in the EARN trial. 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 1km 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 the exact 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 as recommended by the UK Green Book (HM Treasury, 2003). 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 and, therefore, all of the results will be negative. In this case, the highest value (closest to zero) demonstrates the most financially viable option.

3 The highway maintenance schemes

3.1 EARN trial section

A section of the N3 national road was identified as a suitable road section for the site trial experiment with the assistance of the National Roads Authority. The site was located between Blanchardstown and Clonee Village, at the outskirts of Dublin. The GPS coordinates of the section are latitude 53° 24’ 19.35”, longitude -6° 24’ 30.55’’ to latitude 53° 24’ 6.43’’, longitude -6° 23’ 59.21’’. The approximate location of the site on a satellite image is indicated in Figure 3-1. The average daily traffic at the site is in excess of 15,000 vehicles.

Figure 3-1: Approximate location of the EARN trial section

On the day of the site works, the pre-existing hot rolled asphalt was milled and a nominal 20 mm depth of 6 mm stone mastic asphalt (SMA) regulating course was placed to provide a uniform substrate throughout. Above this, a nominal 40 mm depth of SMA surface course was laid along a single lane totalling 700 m in length. The single lane was effectively the inside [slower] lane of two running lanes, situated outside of a dedicated bus lane. The surfacing was split longitudinally into four sections, to enable three different material formulations plus a control section to be laid.

The arrangement of these four sections is presented in Figure 3-2.

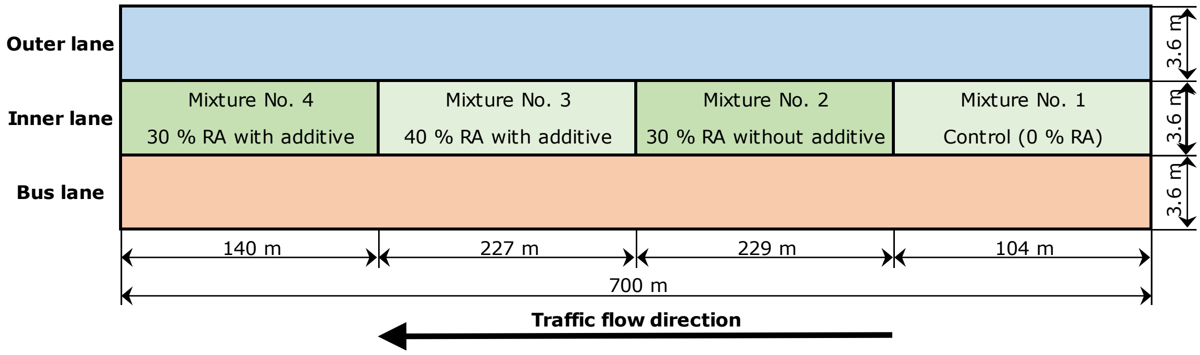


Figure 3-2: Schematic representation of trial section

Further characteristics of the four mixtures and temperatures on site are provided in Table 3-1.

Table 3-1: Laying records of the materials used

Mixture No.	RA content (%)	Containing warm mix additive?	Load No.	Chainage (m)		Temperature (°C)	
				Start	End	Discharge	Rolling
1	0	No	1	0	104	150	134
2	28.51	No	2	104	155	115	105
			3	155	220	130	115
			4	220	333	150	130
3	38.20	Yes	5	333	385	137	125
			6	385	458	135	125
			7	458	560	134	128
4	28.55	Yes	8	560	618	125	118
			9	618	672	132	124
			10	672	700	136	128

3.2 Approach taken to data collection

Data collection was tailored directly to the site trial. The following information was collated on the day of the trial or directly after the trial was carried out:

- Plant batching records;
- Mixture recipes;
- Metered energy consumption (gas oil and electricity);
- Laying records; and
- Cost data for mixture components, haulage and energy.

Real time energy monitoring was not routinely carried out at the Kinnegad batch plant; it was, therefore, necessary to directly collect data on the day of the trial. Electricity consumption, which was independent of mixture or burner temperature, was recorded directly before and directly after the 232 t of trial mixtures had been batched. Electricity consumption values were read off the meter photographed in Figure 3-3. Gas oil consumption, which was assumed to have a direct relationship with burner temperature and, therefore, the temperature of the individual batches as they were mixed, was recorded in 30 s intervals throughout batching of the trial mixtures using the meter photographed in Figure 3-4.

An excess of aggregates was heated during batching of the trial mixtures, partly due to the experimental nature of the recipes used. Under normal production runs, the cold feed settings can be controlled as all of the aggregate is fed via the cold feeds and the amount going into each hotbin can be managed; however, when adding the RA, the quantity of virgin aggregate required fluctuates due to the varying quantity of RA being added and, therefore, the hotbins can "run over" into the overflow chute which empties the material out of the plant on an ongoing basis. For the same mixtures in the future, recipes would be known and overflow would be minimised as a result. The excess of heated aggregates was weighed at the end of the trial and the total gas oil consumption was adjusted to subtract the fuel consumption that could be attributed to non-utilised, but heated aggregates. Energy expenditure per tonne of aggregates was assumed constant across the trial mixtures for the purpose of the adjustment.

Figure 3-3: Electricity consumption measured before and after batching the trial mixtures

Figure 3-4: Gas oil consumption was measured at 30 s intervals throughout batching

4 Inventory data

4.1 Parameters, data collection and assumptions

The approach taken to quantifying the contribution of the ten life cycle steps in terms of CO_2 equivalent and monetary cost is detailed in this section.

4.1.1 Steps 1-3 Acquisition, intermediate transport and processing of raw materials

The batch compositions for the mixtures produced are presented in Table 4-1. All mixtures were 10 mm stone mastic asphalt (SMA) and utilised a polymer-modified binder (PMB). Mixtures 2, 3 and 4 contained RA and Mixtures 3 and 4 the warm mix additive CECABASE™ RT 945.

Table 4-1: Component material proportions

Component	Mixture 1 (SMA 0 % RA control)	Mixture 2 (SMA 30 % RA)	Mixture 3 (40 % RA + additive)	Mixture 4 (30 % RA + additive)
Aggregates 10 mm (%)	65.06	43.68	34.40	43.89
Crushed rock fines (%)	22.31	17.08	16.99	16.95
RA planings (%)	0.00	28.51	38.20	28.55
Filler (%)	7.05	5.83	5.67	5.69
Polymer-modified bitumen (%)	5.57	4.90	4.71	4.90
CECABASE™ additive (%)	0.00	0.00	0.03	0.03
TOTAL	100.00 %	100.00 %	100.00 %	100.00 %

The CO_2e generated by Steps 1 to 3 for the asphalts investigated are covered by "cradle-to-gate" default emissions factors. The values used are presented in Table 4-2. Cost data was provided directly by Lagan Asphalt (Lagan, personal communication, 2014). For the purpose of cost modelling, all material costs are assumed to remain constant throughout the 60 year investigation period.

Table 4-2: Cradle to gate constituent CO_2e values and costs

Constituent	$kgCO_2e/t$	Cost €/t
Aggregates	4.4	16.75
Crushed rock fines	4.4	16.75
RA planings	0.31	11.00
Imported filler	4.4	20.00
Polymer-modified bitumen	370	730.87
CECABASE™ additive	2,100	5,583.20

High polished stone value (PSV) aggregates and crushed rock fines were sourced for the surface course material from Loughran Rock Industries in Armagh, Northern Ireland. Filler was sourced from the adjacent Lagan quarry at Kinnegad, County Westmeath. Figure 4-1 displays a photograph of the quarry, as observed from the asphalt plant. In the absence of an embodied carbon value specific to Ireland, which could not be identified, the equivalent value from the United Kingdom was used, sourced from the Mineral Products Association (2014). It was thought that this figure would be fairly representative of the situation in Ireland, given that some of Lagan's quarries in Northern Ireland would have contributed to this UK-wide figure.

Figure 4-1: The quarry at Kinnegad

The RA used in the trial sections originated on the M1 motorway in County Dublin. It had previously been part of a 14 mm porous asphalt surface course with a polymer modified binder, laid approximately a decade previously. During milling, care was taken to ensure that only the surface course was taken up so that the properties of the high polished stone (PSV) aggregates could be preserved into the next use. After milling, the first stockpile destination for the planings was a depot in Swords near Dublin and, shortly afterwards, the second destination was the Lagan depot at Kinnegad, County Westmeath. Here the planings were only subjected to screening (with no crushing) using a Powerscreen™ Chieftain 1400 and storage at the depot. Photographs of the RA stockpile before, during and after processing are presented in Figure 4-2. In line with the asPECT Protocol, CO_2e arising from transport and processing of RA after the first stockpile is included within the embodied carbon calculation for the material and, therefore, only the diesel used in screening and on-site movement at the depot are included. Average fuel consumption rates for the machinery used was sourced from a past European project entitled *Integration of the Measurement of Energy Usage into Road Design* (Waterford County Council, 2006). For the purpose of mixture design, the activity of the binder on the RA was estimated at 50 %.

The value for polymer modified bitumen was sourced from Appendix D of the asPECT Protocol (Wayman *et al*., 2014). This figure was derived from Eurobitume's generic inventory for bitumen (Eurobitume, 2011), with the assistance of the UK's Refined Bitumen Association.

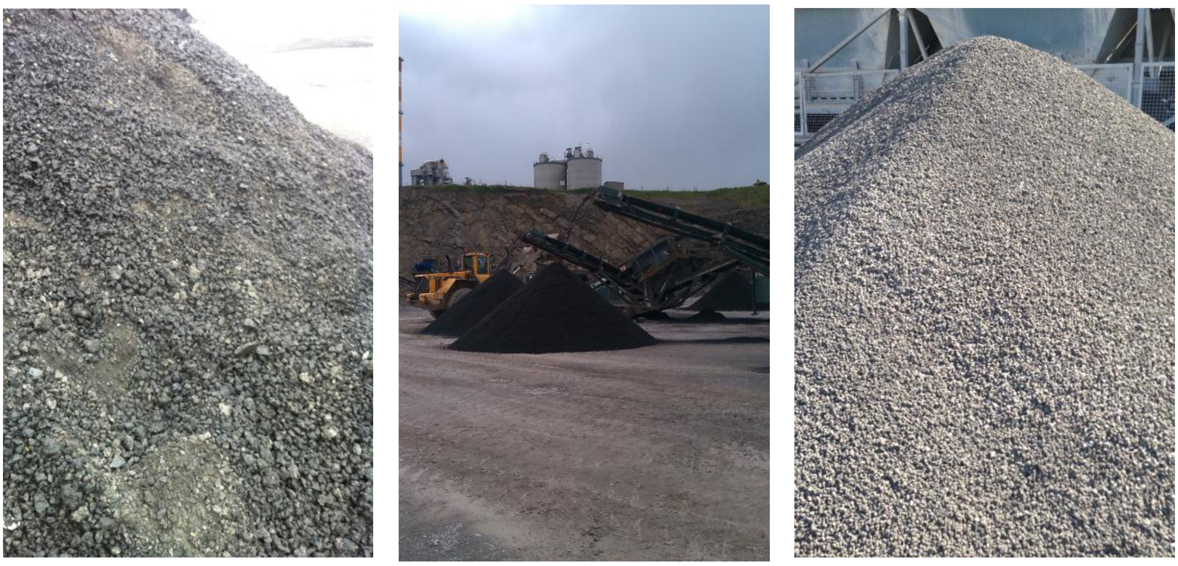


Figure 4-2: RA before, during and after screening

CECABASE™ RT945 was the warm mix additive selected for use in the trial. CECABASE is a liquid and is added directly to the asphalt feed during mixing. Photographs related to the additive are presented in Figure 4-3. As previously mentioned, CECABASE™ RT945 is a surfactant belonging to the chemical family of "imidazolines". It can be further classified as an amphoteric surfactant because it has both acidic and basic properties. Imidazoline is an oleochemical used in relatively small quantities in Europe (Patel, 2004). A life cycle inventory could not be located specifically for this chemical. Stalmans *et al*. (1995) determined life cycle inventories for a range of 22 commonly used surfactants. The global warming potential for every surfactant was in excess of 1000 $kgCO_2e/t$ of surfactant. In the absence of a specific inventory for imidazoline, it was necessary to make an estimation of the embodied carbon, which could be significant in the terms of the overall asphalt mixtures. In the absence of a more accurate method, this estimation was done by taking an average of global warming potentials for the non-animal derived olechemicals analysed by Stalmans *et al*. (1995), which ranged from 1 332 $kgCO_2e$ to 2 552 $kgCO_2e$ per tonne of surfactant.

Figure 4-3: The warm mix additive and plant access point for dosing the mixtures

4.1.2 Step 4 Transport to plant

The haulage distances for the different mixture constituents are presented in Table 4-3. Indicative freight transport costs for Europe were sourced from Maibach *et al*. (2006). All transport costs are assumed to remain constant throughout the 60 year period.

Table 4-3: Constituent transport to plant

Constituent	One–way haulage distance (km)	Mode	Cost
High PSV aggregates	118	Rigid >17 t, 20 t payload	€1,03/km
Crushed rock fines	118	Rigid >17 t, 20 t payload	€1,03/km
Filler	0	N/A	N/A
RA planings	73	Rigid >17 t, 20 t payload	€1,03/km
Polymer-modified bitumen	80	Articulated >33 t, 24 t payload	€1,03/km
	793	6200 dwt product tanker (sea)	€0,14 per 24 t payload per km
CECABASE™ additive	1 243	Articulated >33 t, 24 t payload	€1,03/km
	51	Rail freight (Channel Tunnel)	€274 each way (24 t payload)
	107	Ro-Ro ferry 4076 LM (sea)	€830 each way (24 t payload)

High polished stone value (PSV) aggregates and crushed rock fines were transported from Armagh, Northern Ireland by road. Filler is sourced from the quarry that is adjacent to the Kinnegad asphalt plant; therefore, no specific transport is assigned to these materials because diesel consumption by plant would be included in the overall embodied carbon figure for aggregates. RA was stockpiled at a depot having been removed from the M1 motorway during its previous lifetime and was then transported on to Kinnegad. The Kinnegad quarry is not a source of high PSV aggregates; these materials were imported by truck from Armagh in Northern Ireland.

Bitumen is imported into Ireland having been sourced from refineries elsewhere in Europe (e.g. Stanlow at Ellesmere Port in the UK or Bilbao in Spain) using Lagan's own ship. The source is assumed to be half from the UK and half from Spain with the average journey distance used reflecting this share. The polymer mill used to blend polymer-modified bitumen (PMB) is situated in the vicinity of Dublin Port. From the port, the PMB is transported to Kinnegad by articulated tanker. The CECABASE™ additive originates in Châteauroux, France, and it is freighted from Châteauroux through the Channel Tunnel and crosses the Irish Sea from Holyhead to Dublin before making the short road trip to Kinnegad.

Return legs were included for all transport journeys, reflecting the need for the delivery vehicles to return to their origin in order to commence the next delivery. All transport costs between material source and plant are for 2-way journeys (source – plant – source).

4.1.3 Step 5 Plant operations: heating and mixing

Section 3.2 outlined the approach taken to monitoring energy consumption on the day of production and installation of the trial mixtures.

The total electricity consumption was 1 039 kWh; and the total tonnage produced across the four mixtures was 218.2 t, giving an average of 4,8 kWh per tonne of asphalt mixed. Electricity cost is estimated at €0,136 per t for 2013 (Eurostat, 2014).

Gas oil consumption was monitored at 30 s intervals throughout production. The resulting graph of cumulative energy consumption is presented in Figure 4-4. Gas oil cost is estimated at €0,7397 per litre (Lagan, personal communication, 2014).

For the purpose of modelling, it is assumed that fuel and electricity unit costs remain constant throughout the 60 year modelling period. It is also assumed that the amount of energy required to heat, mix and install a given mixture does not vary across the 60 year analysis period.

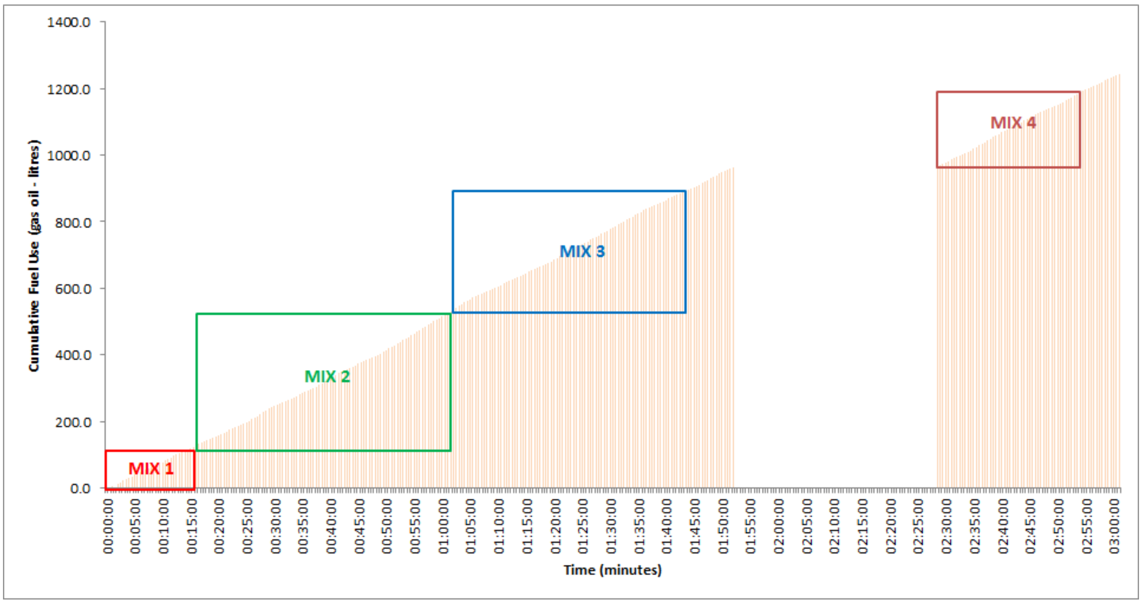


Figure 4-4: Cumulative energy consumption through trial mixture production

The start and finish times of batching of each of the four mixtures was informed by the plant control room. In reality, there would have been a short time lag between heating the aggregates and mixing, probably resulting in slightly more energy consumption being attributed to each mixture type before the "cut-off"; however, this condition remained constant for each mixture.

Figure 4-4 also shows were heating continued after batching had concluded for Mixtures 3 and 4, this energy was not attributed to the mixtures because it was associated with the heating of aggregates that were surplus to requirements; a process that necessitated by the requirement to produce trial mixtures including varying levels of RA. Total fuel consumption during asphalt production is summarised in Table 4-4. Gas oil consumption figures are presented after an adjustment has been made for the heating of excess aggregates (as discussed in Section 3.2).

Table 4-4: Fuel consumption during asphalt production

Component	Quantity mixed (t)	Total gas oil consumption (L)	Gas oil consumption per tonne mixed (L/t)	Electricity consumption per tonne mixed (kWh/t)
Mixture 1 (0 % RA control)	32,02	49,9	1,6	4,8
Mixture 2 (30 % RA)	62,05	165,6	2,7	4,8
Mixture 3 (40 % RA + additive)	61,95	141,5	2,3	4,8
Mixture 4 – 30 % RA + additive)	62,19	88,9	1,4	4,8

Considering the graph in Figure 4-4, the most equitable comparison between the energy consumption of conventional and warm mix asphalt should be done on the basis of comparing Mixtures 1 and 4. Before production of each of these mixtures, the plant was close to ambient temperature whereas the plant temperature had already been raised before production of Mixtures 2 and 3. Raising the plant to operational temperature from ambient would have an associated, defined energy consumption that is proportional to the specific heat requirement of the materials from which the plant is constructed and the difference between ambient and operational temperature. This energy requirement would only be reflected in fuel consumption associated with Mixtures 1 and 4. Material costs (in Table 4-2) and fuel costs together contribute an average of 82 % to overall asphalt costs per tonne (Boston Consulting Group, 2009). An uplift of 7 % to the total cost of materials and fuel is applied to cover labour (*ibid*.).

Steps 6 to 10 are included to calculate the total carbon footprint of the site works carried out on the night of the trial. These factors are not material specific, apart from the sensitivity analysis conducted around the indicative lifetime (Step 9).

4.1.4 Step 6 Transport to site

The haulage distance from asphalt plant to site was 59 km one-way. The journey was undertaken by rigid 8-wheeled trucks (>17 t) with 20 t payloads that returned the same distance to plant empty. Haulage costs were assumed to be €1,03 per vehicle-km travelled (Maibach, 2006). The return journey is assumed to cost the same amount as the original journey, despite carrying no payload.

4.1.5 Step 7 Installation

In line with the asPECT protocol, laying and compacting impacts were included at a rate of 4,7 kgCO_2e per tonne of asphalt.

Plant and labour during installation together cost €3,86 per m^2 (Institute of Civil Engineers, 2012). Using the depth of 40 mm and a density for asphalt of 2,3 t per m^2, this equates to €41,96 per t of asphalt. For the purpose of costs modelling, it is assumed that he site is assumed to have already been excavated for the first intervention (Year 0) and that the price of plant and labour is constant for all interventions over the 60 year investigation period.

There are also indirect costs associated with user delay during installation, these were calculated as "indirect" costs and are presented separately to the "direct" costs. Indirect costs are associated with user delays during the intervention's installation. The QUADRO (Queues and Delays at Roadworks; Highways Agency, 2009) tool was used to determine to collective cost to users for the delay in their journeys. A purely exploratory scenario was established to investigate the likely effects of shorter working windows for LTAs. The installation time for Mixtures 2 to 4 was selected as 7 h for a kilometre as compared to 8 h for

Mixture 1. Other assumptions reflect a typical motorway scenario with the following conditions:

- One primary lane closure alongside three secondary lanes.
- User delay costs based on 10 000 annual average daily traffic (AADT).
- A night time closure.
- User delay costs are assumed to be proportional to the lane closure time.
- User delay cost constant per km of lane closure.
- An estimated cost of €1,342.50 per hour of road closure.

4.1.6 Step 8 Site specific materials

Tack coat bitumen emulsion was applied at a rate of 0,4 L/m^2 of laid asphalt. The total site area was 2520 m^2 (see Section 3.1), so 1,008 L of emulsion were applied in total. This rate equates to 0,68 t of residual bitumen, assuming a density of 1,04 kg/L for bitumen and an emulsion with 65 % bitumen. The origin of the bitumen emulsion is assumed to be Dublin Port, which is the import location for bitumen transported from Europe to Ireland. The site was located 15 km from the port by road. Haulage costs were assumed to be €1,03 per vehicle-km travelled (Maibach, 2006), with a 24 t payload.

The plant and labour costs per square metre of tack coat is €0,39 (Institute of Civil Engineers, 2012). The quantity of tack coat bitumen emulsion applied is equal for all mixtures.

The 20 mm SMA regulating course was also common to all sections. This application equated to 115,92 t of the conventional hot mix SMA (Mixture 1) with conventional bitumen (not PMB) plus a tack coat underneath. Plant and labour costs associated with placing the regulating course are €83,91 per tonne. The composition and quantity of SMA regulating course is constant for all mixtures. All other relevant assumptions from Stages 1 to 7 apply to the tack coat and SMA regulating course.

4.1.7 Step 9 Lifetimes and maintenance intervals

Indicative lifetimes for the SMA material have been provided by EARN Deliverable 3. An extract from this report is provided in Table 4-5. The design lifetimes for SMA in Germany (16 years), the Netherlands (11 years) and the UK (8 years) are considered over the 60 year analysis period to explore the resultant effect on overall carbon footprint. This type of analysis gives an insight into the influence of durability on carbon footprint. For the purpose of modelling, it is assumed the asphalt will only last for its full estimated lifetime with no under/over performance.

Table 4-5: Indicative lifetimes for surface course SMA material

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 course	SMA	16	22	11	17	8	–

4.1.8 Step 10 Excavation

To complete the life cycle, cradle-to-grave, it is anticipated that the top 60 mm of asphalt (40 mm surface course and 20 mm regulating course) will be milled using a 2.2 m planer and the material stockpiled 59 km away. The labour and plant costs per square metre of pavement removed were assumed to be €8,98. Haulage costs were assumed to be €1,03 per vehicle-km travelled (Maibach, 2006), with a 20 t payload. Excavations are only associated with interventions subsequent to initial installation at which point both surface and regulating courses are replaced The costs of labour/plant prices remain constant throughout the 60 year investigation period.

4.2 General assumptions for the economic model

A few assumptions have been used that apply to the economic model only, these are:

- Each section (Mixtures 1 to 4) is assumed to be equally speculative.
- A linear deterioration rate is assumed to derive the residual value.
- The remaining value for the last intervention is subtracted from the total cost of that intervention.
- NPV assumes reinvestment at the discount rate.
- From start to 30 year 30, the discount rate is assumed to be 3,5 % (HM Treasury, 2003).
- From year 31 to year 60, the discount rate is assumed to be 3,0 % (HM Treasury, 2003).
- The inflow and outflow of cash, other than the initial investment, occur at the end of each year. The cash generated is immediately reinvested to generate a return at a rate that is equal to the discount rate used in present value analysis.
- NPV assumes a perfect capital market.
- All cash flows occur within even time frames.
- The indirect NPV assumes the standard discount rates used above with no social time preference rate.

5 Results

Using the parameters specified in Section 4.1, the cradle-to-gate, cradle-to-site and total CO_2e footprints could be calculated for the works carried out at the trial site, these 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			

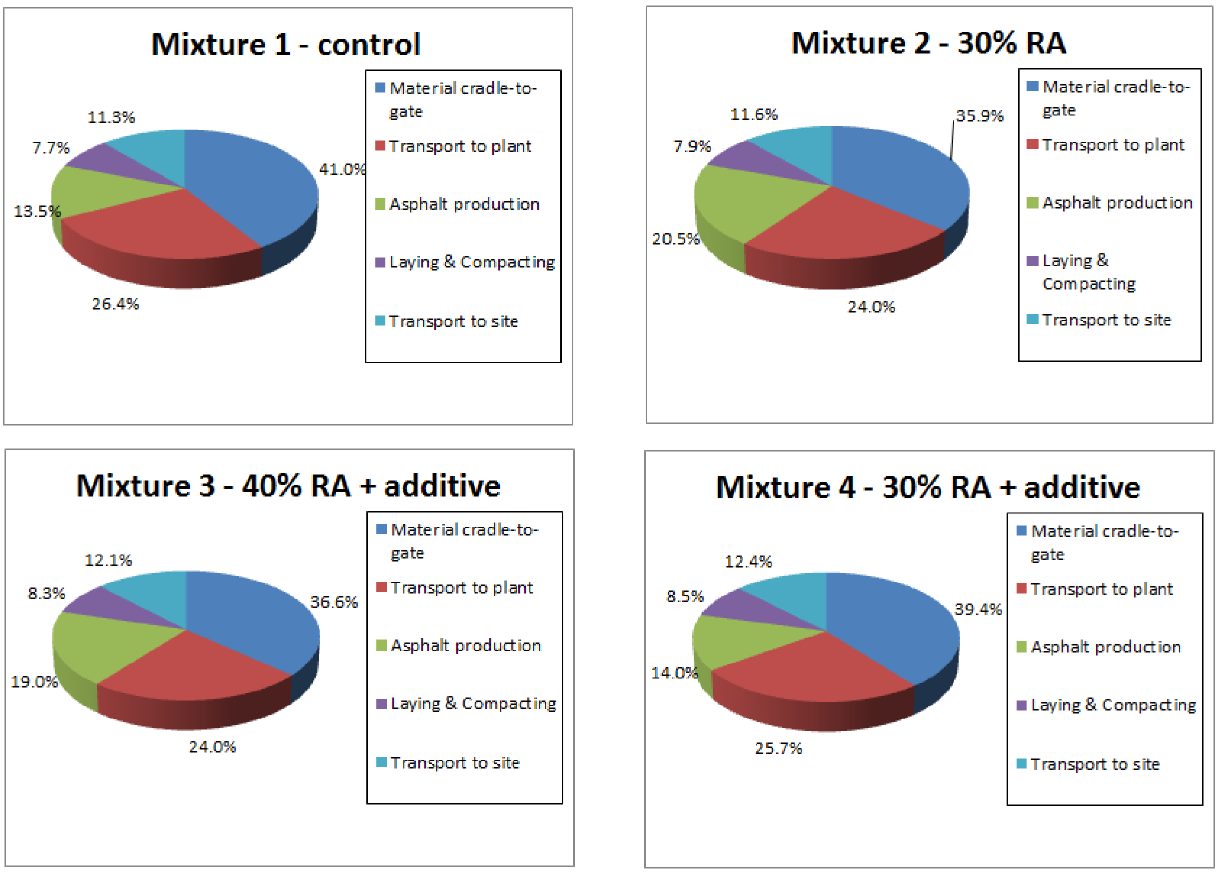


Figure 5-1: Contribution of the life cycle steps to the overall footprints cradle-to-site

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

Cost parameters were also specified in Section 4.1. These 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 ($kgCO_2e$) including regulating course and tack coat	72,482			

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

6 Discussion

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.

CO_2e savings range from between 3,3 % to 10,7 % cradle-to-gate and 2,7 % to 8,7 % cradle-to-site on a per tonne basis. As discussed in Section 4.1.3, Mixtures 1 and 4 provide the most equitable basis for comparison between a hot and lower-temperature mixture containing RA. Comparing Mixtures 1 and 4, the savings associated with using the hot mix 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 18,8 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 (used in both surface and regulating course) were Mixture 4, the total footprint would have been 17,8 t CO_2e compared to 19,5 t for all HMA, a saving of 1,7 t CO_2e. This saving is equivalent to undertaking a 1478 km one-way journey in an average-laden heavy goods vehicle (Defra, 2014) or the energy required to run three typical 250 W motorway lights for their entire average 4,000 h lifetime (*ibid*.).

In terms of cost, the mix designs that incorporated high recycled content showed appreciable savings on a tonne-for-tonne basis, relative to the hot mix control. Cost savings are in the region of 11,2 % to 14,9 % cradle-to-gate and 6,5 to 8,7 % cradle-to-site on a per tonne basis. Comparing Mixtures 1 and 4, the cost savings associated with the lower-temperature, high recycled content mixture would be 11,2 % cradle-to-gate and 6,5 % cradle-to-gate.

In terms of the streamlined footprints, cradle-to-gate or site, the highest CO_2e benefits are associated with Mixture 4; a mixture that had the highest fuel savings per tonne batched (Table 4-4) but not the highest recycled content. Mixture 3, the mixture with the highest recycled content at 40 %, had the lowest cost. Both the lowest CO_2e and lowest cost mixtures utilised the warm mix additive, so this component did not appear to have an adverse effect despite its high CO_2e content and long journey from manufacturing site to batching plant. It might, therefore, be concluded that the additive more than compensated for its own CO_2e and cost impacts in the benefits that it yielded. It would be interesting to analyse other lower-temperature asphalt additives on a similar basis, so see if they also exceed their initial outlay in terms of the benefits they deliver.

CO_2e and cost were also analysed on full life cycle basis, considering a hypothetical 1 km single lane highway section that would be maintained to serviceable condition over 60 years. Here slight differences cradle-to-site are accentuated and appreciable savings for a relatively short section of highway (12,6 tCO_2e or €17,8k for the best performing asphalt relative to the worst in a UK situation) can be observed. This analysis also highlighted the importance of durability in a somewhat indirect way. Huge differences were observed for anticipated design lives for the same type of asphalt in different countries. For example, SMA surface course in the Netherlands is anticipated to last 37,5 % longer than in the UK and 100 % longer in Germany. Within the parameters established for this analysis, a 37,5 % more durable pavement equates to a saving of 40 tonnes of CO_2e and €131k for the best performing asphalt material over a 1 km section – far exceeding the savings by switching from HMA to LTA with high recycled content. For this reason, performance (durability) should be the foremost concern when designing asphalt pavements. A speculative analysis was used to investigate the effect of a shorter road closure that might be achieved through utilising lower-temperature materials. It was determined for the UK that, if a closure of 7 h instead of 8 h was realised, €5k of user delay costs could be saved over the lifetime of the road.

The CoRePaSol project investigating the application of cold mix asphalt was carried out at the same time as EARN. Whilst not strictly within the remit of EARN, the existence of CoRePaSol gave scope to conduct a carbon footprinting analysis on road trial section that was installed as part of the project, using the same parameters as EARN. Whilst the conditions and boundaries for the analysis were established as similarly as possible, the results for the EARN and CoRePaSol trials are not strictly comparable because the asphalts the two projects perform different functions. Surface course asphalts containing high specification aggregates and PMB were produced in EARN whereas structural courses were produced in CoRePaSol, using techniques that are permitted by the NRA (2011) for use in structural but not surface courses in Ireland. Nevertheless, the results obtained are interesting and indicate the potential for the use of cold mix to reduce carbon footprints and are presented in Annex C. The cradle-to-site footprints for the cold mix materials range from between 19,08 kgCO_2e/t to 22,85 kgCO_2e/t for mixtures utilising emulsions and 17,67 kgCO_2e/t to 21,78 kgCO_2e/t for mixtures utilising a foamed asphalt. One emulsion-based mixture was trialled that utilised no cement and had a minimal footprint of 8,84 kgCO_2e/t.

The analysis of asphalt mixtures produced *in situ* as part of the CoRePaSol project further highlights the significance of the contribution of transport in the asphalt life cycle. In situ mixing eliminates the need for transport of the asphalt material from plant to site and the recycling process vastly reduces the need to transport aggregate. The situation of the CoRePaSol trial section enabled the finer fraction aggregates that needed to be imported to be sourced from a quarry just 8 km away, although this will not always be the case. Quarry to plant distances in the UK are around 44 km one way on average (Mineral Products Association, 2014). In the plant mixing based regime used in the EARN trial, opportunities also exist to minimise the impact of transport. The first opportunity would be to utilise RA planings directly from the site being remediated, which presents an opportunity to utilise reverse logistics in the trucks used for asphalt deliveries. The return journeys of delivery trucks could be used to backhaul planings that can replenish stocks of RA at the asphalt plant and avoid the need for dedicated journeys from RA stockpiles to plant in future. The results of this analysis are presented in Table 6-1. The cradle-to-site footprints are reduced by 4,7 % to 10,8 % with the least benefit being realised for Mixture 1 because this mixture does not benefit from the avoided RA transport with 100 % utilised delivery trucks (see the asPECT Protocol Section 2.9 for further explanation of how the benefits are calculated; Wayman *et al*., 2014).

Table 6-1: Reducing transport in the HMA life cycle

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-site CO_2e footprint - original (kgCO_2e/t)	60.83	59.22	56.78	55.54
Cradle-to-site CO_2e footprint – backhauling (kgCO_2e/t)	58.00	53.97	50.70	50.29
Cradle-to-site CO_2e footprint – backhauling + quarry and plant co-located (kgCO_2e/t)	45.38	45.19	43.28	41.50

Also presented in Table 6-1 are the results of a scenario where a further opportunity to reduce transport has been exploited. Here quarry and asphalt plant are co-located (similar to the setup at Kinnegad, but the quarry is assumed to produce high PSV aggregates). Savings for this scenario are in the region of 25 % for all mixtures.

One further factor could prove significant in the future is energy price increases. Energy is rising in cost all the time as oil reserves deplete and electricity becomes more expensive to generate as the proportion of renewables in the energy mix increases. Energy price increases have the potential to affect costs across the complete life cycle of asphalt because energy is consumed in all stages, whether as diesel for transport or plant or directly in heating and mixing as gas oil or electricity. When energy prices rise, the cost energy becomes more significant as a proportion of the overall cost of asphalt. In situations such as these, the demand for energy efficiency measures such as lower-temperature mixing and backhauling is likely to increase.

7 Conclusions and proposed decision model

A site on the N3 near Dublin utilised three novel asphalt mixtures and a control material as part of a wider programme of resurfacing works. The novel asphalt mixtures utilised high recycled asphalt content facilitated by lower-temperature asphalt batching. The EARN project set out to oversee the installation of the materials and to understand their performance, both in terms of meeting their function as a highway surfacing material and contributing to the wider goal of sustainable development. This report presents the findings of analyses into life cycle cost and life cycle carbon generated for each of the mixtures utilised.

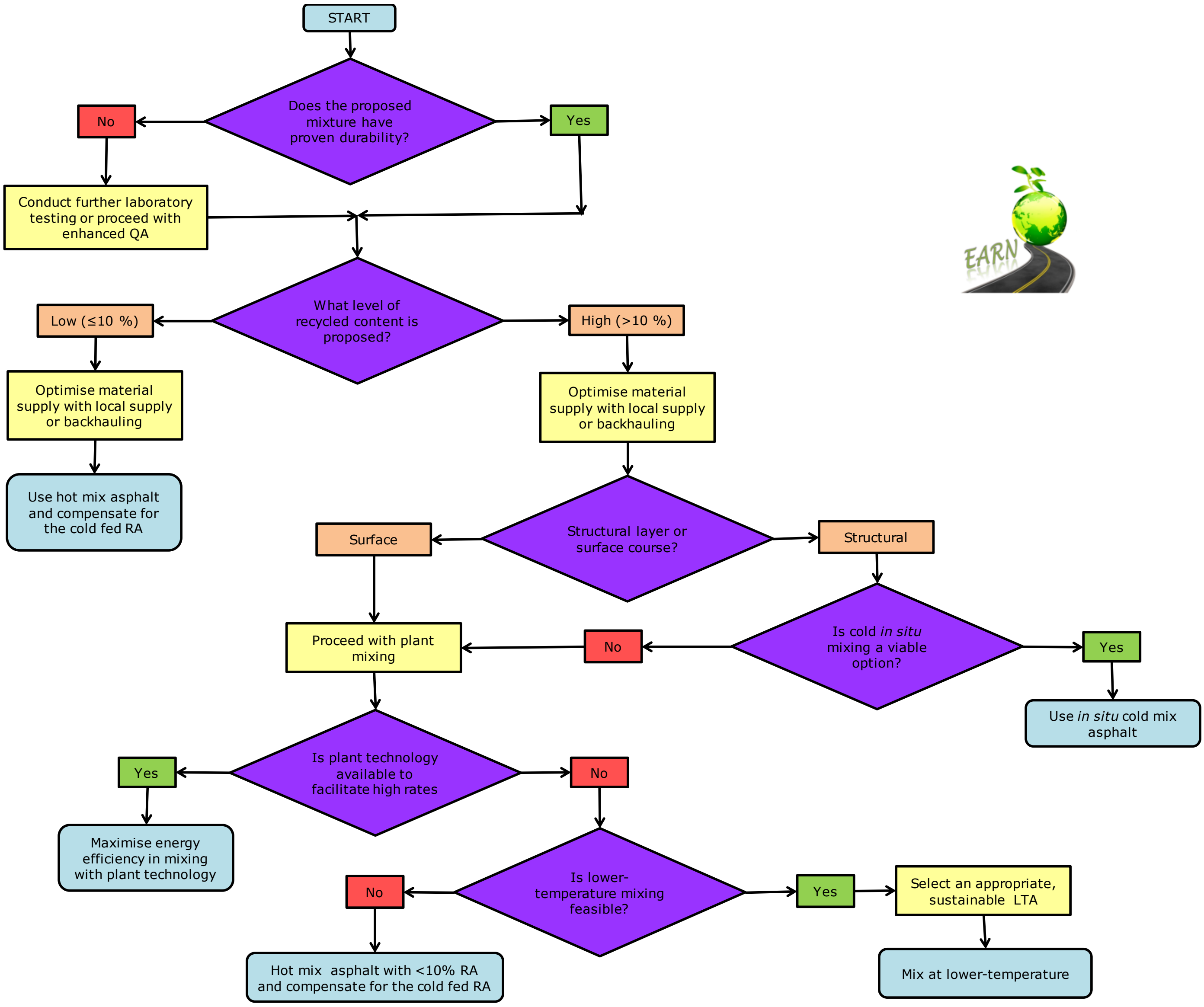
In general, appreciable CO_2e and cost savings can be observed for the novel asphalt mixtures relative to the control, to a greater or lesser degree, depending on the exact mixture recipe. CO_2e savings derived primarily from the recycled content that was incorporated (which was the primary aim of EARN) and secondly from energy savings at the plant (through the lower heating and drying energy of the LTA mixtures). The substitution of primary aggregates and bitumen and the avoidance of their associated transport through use of reclaimed asphalt planings proved advantageous in cost and environmental terms. Energy savings at the plant and the associated carbon benefits were more marginal, however. When the plant was set up in such a way to make a direct comparison of an HMA and an LTA, the savings were more conclusive. Under these conditions, cradle-to-gate, the overall cost savings associated with using the lower-temperature, 30 % recycled mixture were 11,2 % and overall CO_2e savings 10,8 %. In conclusion, it would appear that incorporating recycled content should be a primary consideration and lower-temperature mixing secondary. This was essentially the approach adopted in EARN because lower-temperature mixing was pursued mainly to facilitate higher recycling rates and avoid the need to superheat aggregates at a plant with no specific recycling technology. Recycling also has positive implications in terms of preserving stocks of finite resources.

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 hot-mix 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 consider in relation to recycling asphalt are summarised in the decision model presented in Figure 7-1 (EARN Deliverable D6).

Figure 7-1: Hierarchy of considerations for asphalt recycling (decision model)



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Annex A Parameters and emissions factors identified for modelling

The following data sources will be used in the modelling; they were initially reported in EARN Milestone 7.

	Common factors	
Life cycle element	**Source**	**Notes**
Materials – costs	Indicative costs requested from Lagan Asphalt	Costs are hard to determine from other sources
Materials – carbon	asPECT v4.0, Mineral Products Association (UK)	An estimation will be made for the embodied CO_2e of CECAbase additive
Transport – distances	Collected site data, Re-Road project (FP7) and Mineral Products Association (UK)	Distances will be subjected to sensitivity analysis
Transport – emissions factors	http://www.ukconversionfactorscarbonsmart.co.uk/	
Transport – costs	Indicative costs requested from Lagan Asphalt	Costs are hard to determine from other sources
Planing-off energy consumption	asPECT v4.0	Review CEREAL outputs for relevance
Laying & compacting energy consumption	asPECT v4.0	Review CEREAL outputs for relevance
Energy consumption – emissions factors	http://www.ukconversionfactorscarbonsmart.co.uk/	
Energy consumption – costs	http://epp.eurostat.ec.europa.eu/statistics	Energy prices will be subjected to sensitivity analysis
Energy consumption – plant	Hot and warm recycled mix collected from Kinnegad plant 11th July 2013; cold to be collected via CoRePaSol Summer 2014	Obtaining cold plant energy consumption is dependent on CoRePaSol project
Material – mix recipes	Collected post trial 11th July 2013	Mix recipes also requested from CoRePaSol trial
Site working (closure) times	Hot & warm mix laying observed on 11th July 2013 and determined to be no notable differences in times taken to lay (both paver laid with warm ambient temperature); cold to be observed via CoRePaSol trial	Investigate significance of the length of closure in terms of carbon and cost
Durability	Deliverable 3 (EARN)	Durability will be subject to sensitivity analysis
Rolling resistance of materials in place	Reviewed published sources, no significant difference observed between asphalt with similar grading profiles	Assumed to be identical between hot, warm and recycled SMA mixtures

Annex B CoRePaSol

B.1 *CoRePaSol project*

A carbon footprinting analysis was undertaken of the trial sections laid as part of another CEDR project commissioned under the "recycling" theme entitled CoRePaSol: *Characterisation of Advanced Cold-Recycled Bitumen Stabilised Pavement Solutions*. Undertaking this analysis facilitated calculation of the carbon footprints of cold, warm and hot mix asphalt technologies on the same platform. The steps common to the different temperature materials were limited to "cradle-to-site".

It should be noted that the CoRePaSol project focussed on providing binder course and base materials, whereas the EARN project focussed on surface course materials. This effectively means that the two projects are investigating materials that fulfil different functions, meeting different specifications. For example, cold materials are not permitted as surface course materials in the specifications for Ireland and, therefore, are not required to include PMB or high PSV aggregates from disparate sources. The upshot of this means that the footprints of base or binder course materials cannot be directly compared to that for a surface course material. Despite this difference, calculating footprints on the same platform does allow a picture of a fully "energy efficient" road structure to be built up.

B.2 *CoRePaSol trial section*

The N77 road, 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 B-1 indicates the approximate location.

Figure B-1: Approximate location of the CoRePaSol trial section

The trial site was split into three sections where different types of cold mixes 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 B-2.

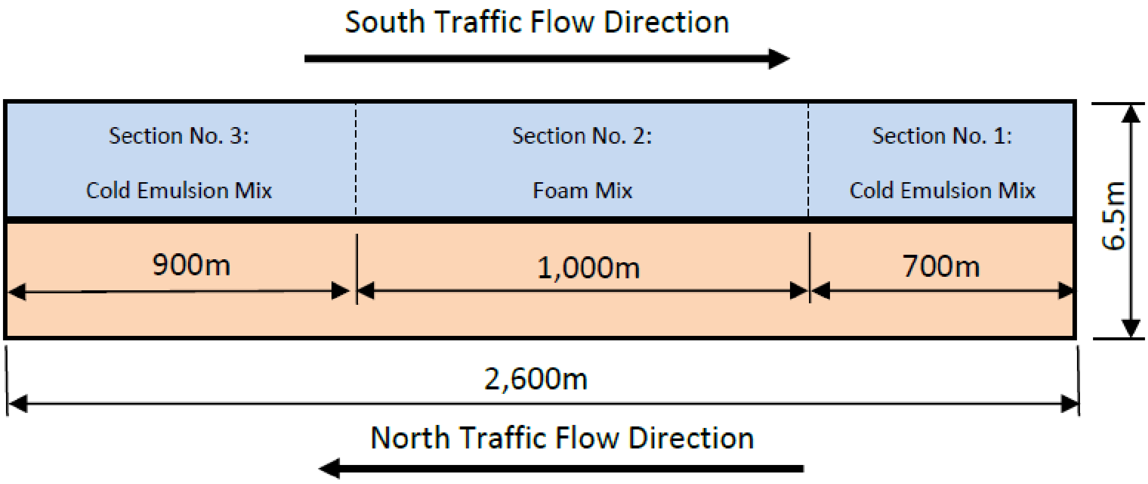

Figure B-2: Schematic representation of trial section

To enable carbon footprints of the materials used to be estimated after construction, fuel consumptions and material quantities used were recorded daily throughout site operations across all nine days of the works. Fuel consumption specific to the road recycling plant was recorded, along with that which corresponded individually to the grader, three rollers, emulsion and bitumen tankers, two water tankers, tractor, dumper and excavator. Together, these fuel consumptions created a picture of how much energy was consumed in relation to specific mixtures laid on specific chainages of the site. Ultimately the energy consumption could be equated to the specific tonnages of mixtures laid. In practice, a total of ten different mixture types were produced and installed, rather than the three indicated in Figure B-2.

B.3 *Parameters, data collection and assumptions*

The approach taken to quantifying the contribution of the eight life cycle steps in terms of CO_2 equivalent is detailed in this section.

B.3.1 Steps 1-3 Acquisition, intermediate transport and processing of raw materials

The batch compositions for the mixtures produced are presented in Table B.1, calculated from site records gathered by Tabakovic (2014). The mixtures were quick viscoelastic cold material mixtures. Section 1 had a target composition of 2,2 % residual binder (3,5 % bitumen emulsion) with 1,5 % cement. Section 2 utilised a foam mix with 1 % cement. Section 3 had a target composition of 2,2 % residual binder (3,5 % bitumen emulsion) with no cement.

The CO_2e generated by Steps 1 to 3 for the asphalts investigated are covered by “cradle-to-gate” default emissions factors. The values used are presented in Table B.2.

Table B-1: Component material proportions (from site records)

Mixture	Mixture 1 (Emulsion mix with cement)	Mixture 2 (Emulsion mix with cement)	Mixture 3 (Emulsion mix with cement)	Mixture 4 (Emulsion mix without cement)	Mixture 5 (Emulsion mix with cement)
Site chainage (m)	0 – 200	200 – 500	500 – 700	1690 – 1800	1800 – 2020
Planings (%)	96,54	86,70	86,90	97,70	86,17
Crushed rock fines (%)	0,00	9,69	9,40	0,00	9,66
Cement (%)	1,44	0,99	0,98	0,00	0,98
Bitumen (%)	0,00	0,00	0,00	0,00	0,00
Bitumen emulsion (residual bitumen) (%)	2,02	2,63	2,72	2,30	3,18
TOTAL	100,00 %	100,00 %	100,00 %	100,00 %	100,00 %

Mixture	Mixture 6 (Emulsion mix with cement)	Mixture 7 (Foam mix with cement)	Mixture 8 (Foam mix with cement)	Mixture 9 (Foam mix with cement)	Mixture 10 (Foam mix with cement)
Site chainage (m)	2020-2450	700-970	970-1180	1180-1400	1400-1620
Planings (%)	88,75	88,51	89,76	88,53	90,44
Crushed rock fines (%)	7,43	8,28	6,27	7,53	5,94
Cement (%)	0,99	0,96	0,97	1,05	1,00
Bitumen (%)	0,00	2,25	3,00	2,89	2,62
Bitumen emulsion (residual bitumen) (%)	2,83	0,00	0,00	0,00	0,00
TOTAL	100,00 %	100,00 %	100,00 %	100,00 %	100,00 %

Table B-2: Cradle to gate constituent CO_2e values

Constituent	kgCO_2e/t
Planings	0
Crushed rock fines	4.4
Cement	930
Bitumen	190
Bitumen emulsion (residual bitumen)	220

Planings were taken from the road by the road recycler in-situ. Crushed rock fines were imported from Kilkenny Block Company Limited. In the absence of an embodied carbon value specific to Ireland, which could not be identified, the equivalent value from the United Kingdom was used, sourced from the Mineral Products Association (2014). This figure to the one used to evaluate the EARN trial, to maximise comparability.

The values for bitumen and bitumen emulsion were sourced from Appendix D of the asPECT Protocol (Wayman *et al*., 2014). These figures were derived from Eurobitume's generic inventory for bitumen (Eurobitume, 2011), with the assistance of the UK's Refined Bitumen Association. The value for cement was also sourced from the asPECT Protocol.

B.3.2 Step 4 Transport to plant

The haulage distances for the different mixture constituents are presented in Table B-3.

Table B-3: Constituent transport to plant

Constituent	One–way haulage distance (km)	Mode
Planings	0	N/A (in situ)
Crushed rock fines	8	Rigid >17 t, 20 t payload
Cement	115	Articulated >33 t, 24 t payload
Bitumen	133	Articulated >33 t, 24 t payload
	793	6200 dwt product tanker (sea)
Bitumen emulsion	133	Articulated >33 t, 24 t payload
	793	6200 dwt product tanker (sea)

Crushed rock fines are sourced from Kilkenny Block Company, where the quarry is adjacent to the depot. There are four cement kilns in Ireland with the nearest to the site being Lagan Cement in Kinnegad which is, therefore, the source of cement that the modelling is based on. RA is generated in situ by the road recycling machines. The sources of bitumen and bitumen emulsion are modelled as being identical to those used in the EARN trial. Bitumen is imported into Ireland having been sourced from refineries elsewhere in Europe (e.g. Stanlow at Ellesmere Port in the UK or Bilbao in Spain) using Lagan's own ship. The source is assumed to be half from the UK and half from Spain with the average journey distance used reflecting this share. The emulsion mill used to blend bitumen emulsion is situated in the vicinity of Dublin Port. From the port, bitumen and bitumen emulsion are transported to site by articulated tanker. Return legs were included for all journeys, reflecting the need for the delivery vehicles to return to their origin in order to commence the next delivery.

B.3.3 Step 5 In-situ plant operations: milling, grading and mixing

Section 3.2 outlined the approach taken to monitoring fuel consumption throughout removal of expired materials, mixing fresh asphalt and installation at the site. Fuel consumption is recorded against the tonnage of each material laid.

Steps 6 to 10 are included to calculate the total carbon footprint of the site works carried out on the night of the trial. These factors are not material specific, apart from the sensitivity analysis conducted around the indicative lifetime (Step 9).

B.3.4 Step 6 Transport to site

A journey plant to site was not required because asphalt production was undertaken by road recycling equipment in situ.

B.3.5 Step 7 Installation

Fuel consumption associated with installation of the specific mixtures is indicated in Table B-4.

Table B-4: Cumulative energy consumption through trial mixture production

Site chainage (m)	Mixture		Quantity produced (t)	Diesel consumption (L)		
				Mixing	Installation	Total
0-200	Mixture 1	(Emulsion mix with cement)	864,34	340	410	750
200-500	Mixture 2	(Emulsion mix with cement)	1296,51	450	289	739
500-700	Mixture 3	(Emulsion mix with cement)	864,34	520	346	866
1690-1800	Mixture 4	(Emulsion mix without cement)	396,15			
1800-2020	Mixture 5	(Emulsion mix with cement)	792,31	660	350	1010
2020-2450	Mixture 6	(Emulsion mix with cement)	1548,60	1050	372	1422
700-970	Mixture 7	(Foam mix with cement)	1166,86	620	308	928
970-1180	Mixture 8	(Foam mix with cement)	907,55	1025	288	1313
1180-1400	Mixture 9	(Foam mix with cement)	950,77	971	281	1252
1400-1620	Mixture 10	(Foam mix with cement)	950,77	990	298	1288

B.4 Results

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

Table B-5: 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.