Technical performance and benefits of recycling of reclaimed asphalt containing polymer modified binder into premium surface layers

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Abstract

The technical possibilities and the benefits when recycling polymer modified asphalt from surface layers into new high quality surface layers using hot mix recycling are investigated. First rheological properties are determined of blended binders, consisting of extracted binders from reclaimed asphalt containing polymer modification and virgin binders. The performance of asphalt mixtures containing reclaimed asphalt with polymer modified is tested with respect to water resistance, stiffness, rutting and fatigue. The economic and ecological effects are evaluated using LCA and LCC. It has been demonstrated that the polymer present in the reclaimed asphalt still positively affects the material behaviour of asphalt mixes produced with this material. LCA and LCC analyses clearly demonstrate the environmental and economic benefits. Based on these positive results validation in practise is the next logical step.

Keywords: recycling, polymer modified binder, surface layers, LCA, LCC

Résumé

Les possibilités techniques et les avantages lors du recyclage du bitume modifié aux polymères à partir des couches de surface dans de nouvelles couches de surface de haute qualité en utilisant le recyclage des enrobés à chaud sont étudiées. Les premières propriétés rhéologiques sont déterminés à partir de composants liants extraits d'enrobés contenant des polymères modifiés et des liants vierges. Les performances des enrobés bitumineux à polymère modifiés sont testés par rapport à la résistance à l'eau, la raideur, l'orniérage et à la fatigue. Les effets économiques et écologiques sont évalués en utilisant les analyses LCA et ACCV. Il a été démontré que le polymère présent dans l'asphalte récupéré possède un effet positif sur le comportement du mélange d'asphalte produit avec ce matériau. Les analyses LCC LCA démontrent clairement les avantages économiques et environnementaux. Sur la base de ces résultats positifs, la validation dans la pratique serait une suite logique.

Mots-clés: recyclage, bitume a polymère modifié, couche de roulement LCA, LCC

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1. Introduction

Throughout Europe polymer modified asphalt (PMA) is used extensively in the past decades for high trafficked roads and premium pavements; especially for surface layers. The addition of polymers contributes to the durability and functionality of these premium pavements, such as noise reducing pavements (the Netherlands) or rutting resisting pavements (Denmark and Slovakia). The first generation of these pavements are increasingly approaching their end of life. Therefore the road sector is facing a rapidly increasing source of reclaimed asphalt (RA) that contains polymer modified bitumen (PMB), which offers a potential premium binder contribution. Depending on the aged state of the modified binder and the deterioration of the aggregate gradation during milling and further pre-processing, it is the challenge to the road sector to ensure – as far as possible – that the RA containing PMB is recycled at its highest practical potential. The goal in recycling is not to achieve the highest possible recycling percentage, but to avoid downgrading of RA containing a potential valuable asset.

This paper describes the work done in the RECYPMA project that has been a part of the ERA-NET ROAD II program. The aim of this project was to investigate the possibilities for recycling polymer modified asphalt from surface layers into new high quality surface layers using hot mix recycling. This paper will give an overview of the results, more details can be found in the project reports (Komačka at al. 2013, Leegwater 2013, Liu 2013, Nielsen 2013a, Nielsen et al. 2013b).

The set-up of the paper is as follows. First the state-of-the-art on recycling of RA containing polymer modified binder is described in short. Next the results of the laboratory research is reported performed on three different types of RA originating from surface layers, containing SBS (Styrene-Butadiene-Styrene) modification. Starting with the characterisation of the binder properties of the reclaimed binders using different test methods like a Dynamic Shear Rheometer (DSR) and Infrared analysis. These reclaimed binders are then blended with virgin binders, the resulting binder properties are also determined with the same methods. Based on the performance of the blend binders, mix designs are made for premium pavements that contain 15 % and 40 % RA containing polymer modification. The asphalt mixes are tested under laboratory conditions, to establish their performance with respect to water resistance, stiffness, rutting and fatigue. Based on the established technical performance, the economic and ecological effects are evaluated using a Life Cycle Analyses (LCA) and a Life Cycle Cost (LCC) analyses. The paper closes with a summary of the obtained knowledge and an outline of work that is still needed before large scale application of premium polymer modified surface layers containing RA can be realized.

2. State of the Art on recycling of polymer modified asphalt

2.1. Focus and aim of literature review

As the project focuses on recycling of surface layers into new high quality surface layers, the state-of-the-art portrays documentation that especially highlights the added value of polymers in RA. For basic hot mix recycling technology readers are referred to literature, e.g. (Van den Bergh & van de Ven 2009). The literature review has also gathered information on laboratory extraction methods, which is required for characterisation of properties of an aged polymer modified bitumen. The following statements highlight the overall outline of the findings, more details can be found in (Nielsen, E. 2013a).

2.2. Extraction and recovery

The SBS type polymer modification studied in this research is the most commonly applied polymer modification in hot mix asphalt. Based on a literature review and the response of leading European laboratories and research institutions to a dedicated questionnaire the following two conclusions were drawn on extraction of polymer modified binder:

- For practical purposes the European standards EN 12697-1 and -3 can be used to recover a representative bituminous binder irrespectively of the solvent used;
- In this project dichloromethane (methylene chloride) is used as solvent for the extraction and recovery of SBS-polymer containing bituminous binder from the reclaimed asphalts.

2.3. Laboratory mixing

A laboratory mixing procedure is formulated aimed to produce a representative asphalt mix containing recycled polymer modified asphalt. The method does not mimic full scale production, since there is a huge difference in mixing efficiency and conditions in the asphalt plant compared to the laboratory mixer. The mixing procedure mentions the order of adding the different components and the considerations for determining the mixing temperature (depending on the properties of both the reclaimed binder and the virgin bitumen).

2.4. Experience with utilisation of RA containing PMB in full scale production

As the use of polymer modified bitumen in hot mix asphalt on a major scale has only started a few decades ago, only recently a level of RA is reached where selective recycling has become technically and economic feasible. As a result the amount of well documented experience found in the literature is limited. Due to this lack of knowledge the literature review has resulted in a list of challenges that are recognized when aiming for recycling of polymer modified asphalt into surface layers.

- To be able to consciously “harvest” high quality RA, information about the material is needed before milling. However often documentation existing road sections is poor, and as a result limited information is present on applied materials, like binder and aggregate type.
- The materials have also degraded over time, binders age over time and aggregated sizes are expected to be reduced trough wear and milling. Both a very aged binder and a fine aggregate gradation may limit the recycling possibilities.
- In order ensure proper mixing of the RA containing polymer modification with fresh materials, the RA has to be heated to high temperatures, resulting into the risk of burning materials.
- Recycling above 15 % is not feasible by cold mix addition of RA. As a result high recycling levels require technological advanced asphalt plants, e.g. the presence of a double drum mixer.
- RA containing polymer modified material is even more sticky compared to normal RA. This might provide problems with handling and processing of the material in the asphalt plant.

3. Materials

3.1. RA containing polymer modification

Three ‘‘old’’ SBS PMB-containing asphalt mixtures were reclaimed from typical surface layers of premium pavements in three different countries; stone mastic asphalt (SMA11) in Denmark, porous asphalt (PA4/8) in the Netherlands and dense asphalt (AC11) in Slovakia. The SMA mix was 22 years old, the binder used was Caribit Plus 85, a SBS polymer modified bituminous binder with a penetration range 70-100 dmm and a softening point above 75 ºC. The PA mix was 7 years old, the binder used was a Styrelf PMB 40/100-65 HD. The AC was 15 years old, the binder used was Apollobit MCA-S, a SBS polymer modified bituminous binder with a penetration ranging from 50 – 100 dmm and a softening point (SP) above 70 °C.

3.2. Binder extraction and virgin binders

Following European norms EN 12697-1 and EN 12697-3 extraction and recovery were performed on these three reclaimed mixtures to obtain three PMB-containing binders with abbreviations as RAD (SMA from Denmark), RAN (PA from the Netherlands) and RAS (AC from Slovakia).

In order to evaluate the benefits of the high quality RA, two types of virgin binders were used, a normal paving grader binder (PGB) and a polymer modified binder. The PGB is used to asses if the remainder of the polymer modification in the RA provides benefits for a new mix based on a PGB. The polymer modified binder is used to asses the influence of the presence of and old polymer modified binder to the new mix. Virgin binders were selected for the new asphalt mixes assuming a recycling percentage of 15 and 40 % using the “LogPen rule”. This rule indicates the expected binder penetration, of a mix of old and new binder. For the Dutch and the Slovakian mix the following binders were used:
- **PGB1:** Q8, straight run bitumen, paving grade 70/100, provided by Kuwait Petroleum (Nederland) B.V.;
- **PMB1:** 70/100-83 (KR), modified bitumen by mixing10% of D0243 SBS in B160/220 bitumen, produced by Kraton Polymers Nederland BV.

For the Danish mix, the following fresh binders are used:
- **PGB2:** 70/100, straight run bitumen produced by blending two different bitumen's (40/60) and (330/430)) in the proportion 71.2 % and 28.8 % respectively.
- **PMB2:** 90/150-75, SBS polymer modified bitumen, provided by Colas Danmark A/S as a reference sample from their production of polymer modified bitumen's.

3.3. Asphalt mixes

The three different types of asphalts for wearing courses (SMA, AC and PA) were designed and produced for laboratory testing. Five combinations of virgin material and RA were used for each type of asphalt, based on three RA contents (0 %, 15 % and 40 %). On overview of the mixtures is given in Table 1. The mixture with 0 % RA is used as a benchmark. It was chosen not to test a mixture with PGB + 15 % RA, as irrespectively of the polymer level in the RA, the total polymer level is too low to expect any effect of the polymer.

Table 1: Matrix of tested asphalt mixtures

RA content Of	SMA 11		PA 8		AC 11	
	PGB2	PMB2	PGB1	PMB1	PGB1	PMB1
0 %	x	x	x	x	x	x
15 %	–	x	–	x	–	x
40 %	x	x	x	x	x	x

Aggregate and fillers commonly used for the SMA11 production in Denmark, the PA8 production in Netherlands and the AC11 production in Slovakia were used in the mix design. More details on materials, mixture composition and mixture production can be found in the specific project report (Komačka at al. 2013). Mixing temperatures were based on viscosity measurements that were conducted on the binders (Liu et al. 2013).

The binder content in reclaimed asphalts was determined by extraction procedure according to EN 12697-1. The obtained binder contents in RA are given below:
- RAN 5,42 %
- RAS 5,05 %
- RAD 4,60 %

4. Properties of extracted and blended binders

High shear mixing was used to blend the binders, the aim was to obtain an optimal blend. Optimal blending will give an upper limit of the properties of the combined binder in mixtures, as it is expected that a lower level of blending will be achieved during mixing in practice.

Table 2 gives an overview of the binders that were studied in this research. Noteworthy is that the original RAD binder has also been characterized, as it was still available from storage. The characteristics of the binders are determined using a variety of rheological and chemical tests. The testing program on the recovered and blended binders included:
- Penetration, Softening Point
- DSR master curves
- Viscosity measurements
- FTIR (Fourier Transform Infrared Spectroscopy), showing chemical composition
- GPC (Gel Permeation Chromatography), providing particle size distribution

In (Liu en al. 2013a) detailed information is provided on test methods and the complete test results. In this paper a short summary of the results will be presented, in (Liu and al. 2013b) a more extensive summary can be found.

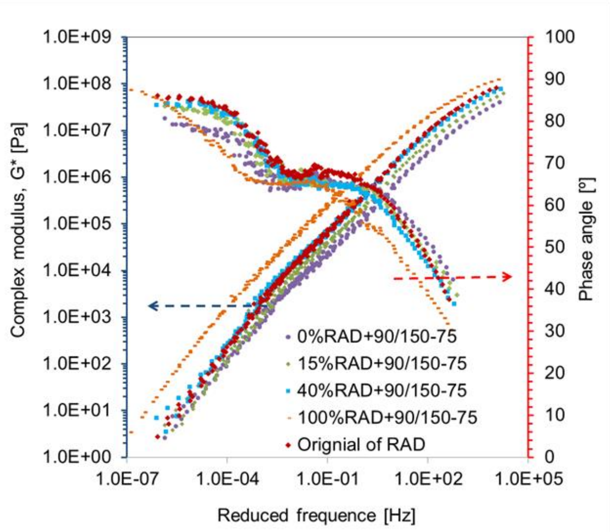
Table 2: Overview of extracted, virgin and blended binders studied

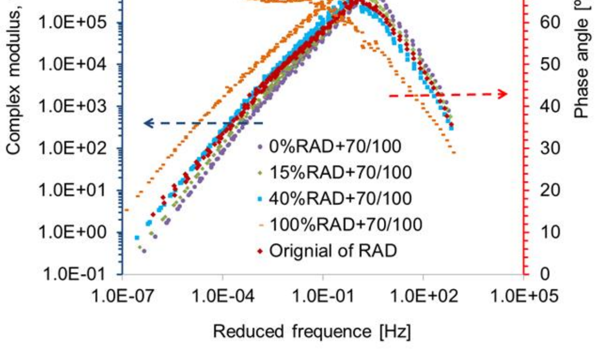
Binder		RA content [%]	Fresh bitumen content [%]
Reclaimed	RAD	100	0
	RAN	100	0
	RAS	100	0
Virgin	PGB1	0	100
	PGB2	0	100
	PMB1	0	100
	PMB2	0	100
	Original binder RAD	0	100
Blended RAD	15%RAD+85%PGB2	13.5	86.5
	40%RAD+60%PGB2	36.5	63.5
	15%RAD+85%PMB2	13.7	86.3
	40%RAD+85%PMB2	36.9	63.1
Blended RAN	15%RAN+85%PGB1	15	85
	40%RAN+60%PGB1	40	60
	15%RAN+85%PMB1	15	85
	40%RAN+60%PMB1	40	60
Blended RAS	15%RAS+85%PGB1	15	85
	40%RAS+60%PGB1	40	60
	15%RAS+85%PMB1	15	85
	40%RAS+60%PMB1	40	60

From the characteristics of the binders extracted from RA is can be observed that even though the polymer degrades over time, the binder still clearly shows the characteristic polymer behavior in the phase angle.

Figure 1 clearly demonstrates this for the extracted RAD binders. In

Figure 1 it can also be seen that the influence of the polymer remains present if the extracted binder is blended with virgin PGB bitumen or virgin PMB. Therefore it is concluded that it is possible to restore the rheological properties of the reclaimed PMB binder to its original state by mixing it with a soft virgin PMB binder.





n from Denmark (RAD), left when blending with PGB, right when blending with polymer modified bitumen.

In the mix design a combination of the logPen. model and the softening point (SP) model is used, as they approximately predict the penetration value at 25 ºC and the SP of the blended binder both for PGB and PMB. For a more detailed mix design the Grunberg-Nissan model can be used as this model gives a more detailed prediction of the rheological properties, like viscosity at different temperatures and the complex modulus at a wide frequency range.

Due to the polymer modification and aging of the binder, the required mixing temperatures for the blended binders are high, in some cases above 180 °C. As such high temperatures should be avoided to prevent degradation of the polymer, practical solutions to deal with this high mixing temperature requirement needs attentions in future research.

The SBS index obtained with FTIR can be used to asses the relative SBS content of the extracted binder, which is useful to determine the level of modification required for the virgin modified binder. However this method does needs to be calibrated to match the type of SBS used in order to be accurate. If the original binder is available as a reference, the GPC test indicates the extend of the degradation of the polymer.

5. Performance of asphalt mixtures with RA containing polymer modified binder

The aim of laboratory tests on mixtures was to investigate the impact of RA containing polymer modification on the properties of asphalt. The following tests were performed in order to assess the performance of the asphalt:

- Water sensitivity test, the Indirect Tension Strength Ratio (ITSR) values show the ratio of material strength with and without exposure to water;
- Wheel tracking test, the output of tests provides an estimate of the resistance to rutting;
- Stiffness and fatigue test, the results provide an estimate for the structural life expectancy and will also give an impression on the integrity of the material.

All mentioned tests were carried out according to the relevant European standards. An overview of the results is presented in Table 3. Komačka en al. (2013) provide detailed information on test methods and the complete test results. This paper gives a short summary of the results, a more extensive summary can be found in (Komačka, Jozef et al. 2014).

Table 3: Summary of RA addition influence

Mixture	Virgin binder	RA content	ITSdry	ITSwet	ITSR	Rutting resistance	Stiffness	Fatigue
SMA11	PGB	40 %	+	+	+	+	+	x
	PMB	15 %	+	+	-	=	+	
		40 %	+	+	-	=	+	
AC11	PGB	40 %	+	+	+	+	+	+
	PMB	15 %	+	+	-	=	+	-
		40 %	+	+	-	=	+	-
PA8	PGB	40 %	+	+	+	+	+ 1)	x
	PMB	15 %	+	+	+	=	+	
		40 %	+	+	+	=	+	

+ better than benchmark mixture (without RA)
- worse than benchmark mixture (without RA)
= comparable to benchmark mixture (without RA)
x not tested
1) only for temperatures above 0°C

The ITSR values for all mixtures are high, which means the water sensitivity of the mixtures containing RA meet the requirements for surface layers. The Indirect Tensile Strength (ITS) of the mixtures correlates well with the penetration values of the blended binder determined in the binder tests, this is shown in Figure 2. As optimal blending of the binder was targeted in the binder characterization, the good correlation indicates good blending of the binder in the asphalt mixture. Due to the extremely porous nature of the PA8 mixture The correlation is not present for, of this material.

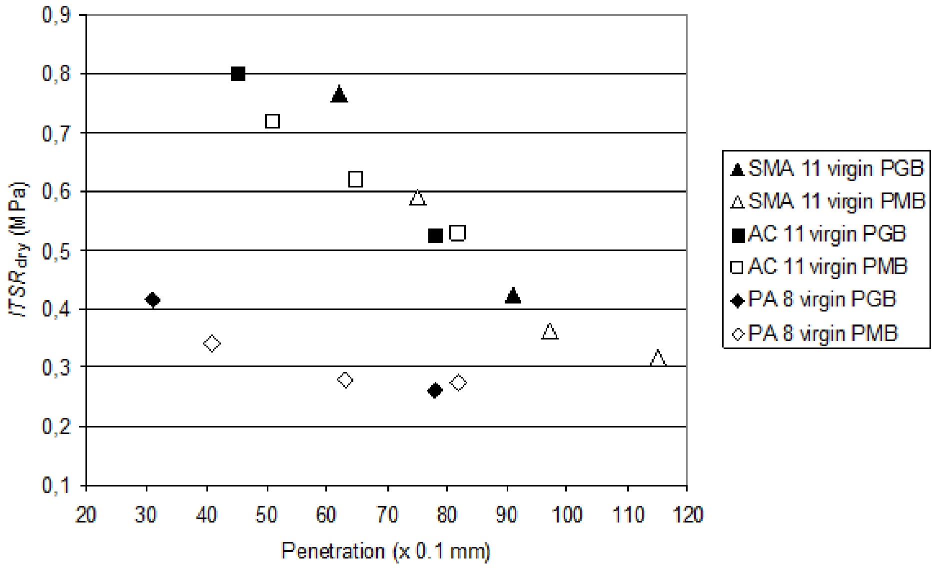


Figure 2: Relation between penetration and ITS value, AC11 and SMA 11 show a good correlation.

The wheel tracking test showed good performance with respect to rutting for all mixes containing RA. The mixture with PGB without RA showed a significant amount of rutting. The high rutting resistance might indicate an advantage of the remaining SBS in the binder, however it could also be the effect of ageing of the binder.

The mixtures with RA containing PMB have a higher stiffness compared to the mixtures without RA. This could be an advantage because a larger stiffness leads to a higher bearing capacity. However if the stiffness is very high, this could also result in brittleness at low temperatures. Therefore it is necessary to find a balance between needed stiffness and a risk of brittleness taking into account temperature conditions at the intended locality. To further investigate this, low temperature cracking and properties test according to EN 12697-46 should be performed in future.

Fatigue test were only performed on the AC 11 mixtures. The mixture with the PGB and 40 % RA showed better fatigue parameters compared to the mixture with paving grade bitumen and no RA. On the contrary the mixture with virgin PMB was the most fatigue resistant and an addition of RA decreased fatigue performance and fatigue life. It is postulated that the SBS content in blended bitumen is an important parameter for fatigue performance. The remaining SBS in RAS binder increased fatigue resistance of the mixture with PGB. As the SBS content in RAS binder is lower (± 5 %) compared to the SBS content of the virgin PMB (10 %) the RA mixtures have a lower SBS content and therefore show an inferior fatigue performance. Further research is needed to validate this hypothesis.

Based on the presented test results in this paper it is concluded that recycling of RA from surface layers into new surface layers is expected to result in comparable asphalt performance for surface layers. However this assumption still needs to be validated trough more extensive research as a limited number of asphalt mixes is tested with respect to a limited amount of performance characteristics.

6. Microscopy investigations of RA and asphalt mixes containing RA

Microscopy analysis of thin and plane sections of asphalt has been performed as part of the research to serve two goals, to analyze the three RA materials used and to provide a visual assessment of the new asphalt mixes (with and without RA, with PGB and PMB). All microcopy images and observations can be found in the relevant project report (Nielsen et al. 2013b). In this paper a short summary of the results is presented.

The plane sections give an impression of the build up of the compacted asphalt mixture. The PA8 and the AC11 mixture are homogeneous, the SMA mixtures shows some inhomogeneity's. As Marshall compaction is used in this research, which is know to result in inhomogeneity's for SMA's, this is not further investigated.

The thin sections show qualitatively the presence and extend of the dispersion of the SBS polymer from the typical yellow spots. As these spots can be observed in all RA materials it is concluded that polymer is still present in the binder. The characterization of the extracted binder demonstrates that the polymer present also affects the binder response.

Thin sections made of the asphalt mixes show some inhomogeneity's in mixing. Parts of the mortar are homogeneous, however as displayed in the micrograph in Figure 3 at some locations there is a clear distinction between old and new mortar. These inhomogeneity's do not seem to affect the material behavior, as tensile tests on the asphalt showed a good correlation with the penetration of the binder (Figure 2). As a more homogenous mixture is expected to lead to a better performance, future research using the microscope is recommended in order to investigate the homogeneity of full scale plant produced mixes to asses whether or not prolonged mixing times has the potential to improve the asphalt performance.

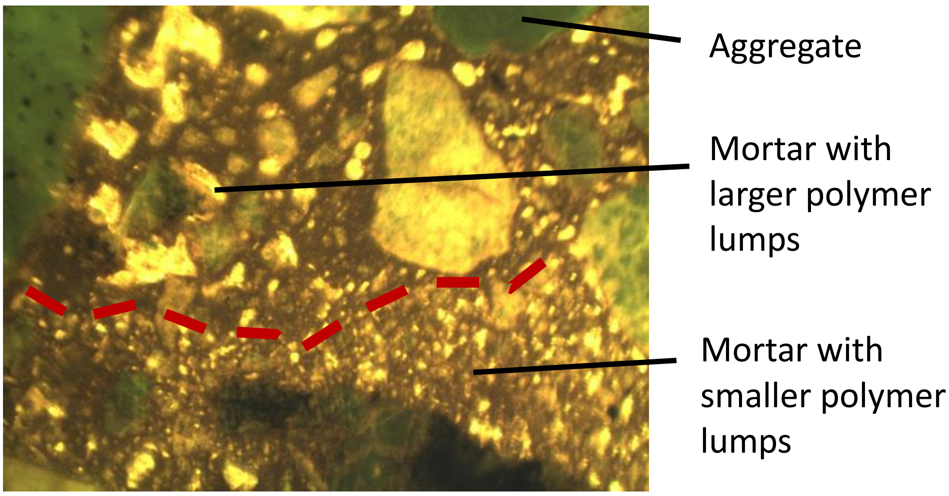


Figure 3: Details from micrograph of AC 11 with PMB and 40 % RA (Figure represents 0.80 x 1.06 mm)

7. Environmental and economic benefits

By replacing virgin material, recycling clearly reduces the amount of resources needed and waste that is produced for new roads or road maintenance, as a result recycling reduces the environmental impact. Besides this, recycling also provides a cost reduction due to the fact that reclaimed asphalt (including the needed pre-processing that is needed for recycling) is generally cheaper than virgin material. Polymer modifications are especially expensive and if the originally present polymers could also be beneficial in the recycled product this would provide an interesting economical argument for recycling of polymer modified binders.

In order to quantify these potential benefits of recycling of polymer modified asphalt an analysis of the environmental and economic impact of recycling is performed. In this analysis a road with polymer modified binder is taken as a reference and compared to a road with recycled material with polymer modification. The basis for comparison is a pavement of 3.5 m wide, representing a driving lane of a main road, over a length of 1 km during 50 years. The materials and production processes are based on the binders and mixes previously describes. Questionnaires were sent out to contractors and material suppliers to obtain cost and hauling distances. The life expectancy of the road, which is also a part of the LCA, is based on the performance of asphalt specimens in the laboratory.

In order to obtain a complete image of the environmental benefits of recycling of polymer modified asphalt an LCA analyses has been performed. The total recycling process is considered, including all materials and processes. The economic benefits are assessed using a Cycle Cost analyses, that includes all cost during the whole life span. The benefits of the different scenarios are presented in Table 4. The analyses show that the effect of using recycled material on the environmental impact and life cycle cost is significant, especially if 40% recycling is realized. With respect to costs is should be noted that the cost of the binder is responsible for up to 70 % of the materials costs. The actual price level of binders can vary substantially over the years under the influence of the oil price.

Table 4: Economic and ecologic benefits of recycling of RA containing PMB into new polymer modifies asphalt mixes

Mixture	Virgin binder	RA content	LCC Costs	LCA ReCIPe
SMA 11	PMB	15%	-7%	-8%
		40%	-19%	-22%
AC 11	PMB	15%	-5%	-6%
		40%	-12%	-21%
PA 8	PMB	15%	-5%	-8%
		40%	-13%	-23%

When the LCA method ReCIPe is used, the binder determines the environmental impact to a large extent: 40-55 %, dependent on the exact scenario. The second most important parameter is transport. There are also two other methods available in Europe used to assess the environmental impact, EDIP 2003 and Ecological scarcity. These methods attribute less impact to the binder and more to transport and the production of other raw materials, however the resulting reductions that can be realized by recycling are similar compared to the results found with ReCIPe.

The assessed environmental impact is not very sensitive to variations in key starting points. However, service life assumptions have the large influence on calculated environmental impact. Therefore quantification of the influence of RA on the service life of surface layers is very important and should be studied further.

8. Conclusions and recommendations

Binder research indicates that the extracted binder from the RA with PMB still contains an active part of polymer that influences the material behavior as can be expected from a polymer modification. Research on mixtures containing RA with PMB shows, that if proper mix design is used, a similar performance in surface layers is realized with respect to water sensitivity, stiffness and rutting resistance.

From an economic and ecological perspective, the benefits for National Road Authorities as well as the road sector are considerable because of the shorter hauling distances of aggregates and the reduction of primary resources needed. This is especially important for EU countries that are dependent on import of primary raw materials.

The research indicates that there are technical possibilities for recycling of polymer modified surface layers into new surface layers and that the benefits are expected to be significant. However still many challenges lie ahead before large scale application is possible. Risks with respect to service life when using RA need to be quantified in more detail (e.g. SBS content and fatigue performance, stiffness of asphalt versus low temperature cracking). Issues related to full scale application (e.g. to avoid degradation of the polymer at high temperatures, mixing time influence on homogeneity and performance of asphalt) also need to be explored. And finally quality assessment and assurance of the RA has to be managed including the quality of the used aggregates. All three challenges can be met trough research based on a series of pilot projects. These pilot projects are preferable realized in different European countries to incorporate different recycling techniques and different environmental conditions.

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References

Van den Bergh W & van de Ven M. (2009). Hot recycling of asphalt: experiences in Flanders and the Netherlands. *The 2nd international conference on environmentally friendly roads 2009*, Warsaw, Poland.

Komačka, Jozef, Remišová, Eva, Schlosser, František (2013). Asphalt Mixtures Using Reclaimed Asphalt containing Polymer Modified Binder, *WP4 Report of RECYPMA Project*.

Komačka, Jozef et al. (2014). Influence of reclaimed asphalt with polymer modified binder on properties of different asphalts for a wearing course, *3rd International Conference on Transportation Infrastructures*, Pisa, Italy, under review.

Leegwater, Greet, van Gijlswijk, Rene, (2013). Environmental and economic benefits of the use of polymer modified reclaimed asphalt, *WP5 Report of RECYPMA Project.*

Liu, G., van de Ven, M., Leegwater, G. (2013a). Properties of aged polymer modified binder, *WP3 Report of RECYPMA Project.*

Liu G et al. (2013b). Evaluating the rheological properties of PMB-containing RA binders from surface-layer asphalt mixtures to be recycled. *Journal of Construction and Building Materials*, article in press.

Nielsen, E. (2013a). State of the Art – Recycling Polymer Modified Asphalt, *WP2 Report of RECYPMA Project*.

Nielsen, E., Raaberg, J., Neidel, A., (2013b). Microscopy analysis of asphalt mixtures using reclaimed asphalt containing polymer modified binder, *WP4 Report of RECYPMA Project*.