Review and environmental impact assessment of green technologies for base courses in bituminous pavements

<u>Review and environmental impact assessment of green technologies for base courses in bituminous pavements</u>

Joke Anthonissen [a,*], Wim Van den bergh [a,1], Johan Braet [b]

[a] Faculty of Applied Engineering, University of Antwerp, Rodestraat 4, 2000 Antwerp, Belgium
[b] Department Engineering Management, Faculty of Applied Economics, University of Antwerp, Prinsstraat 13, 2000 Antwerp, Belgium, E-mail address: johan.braet@uantwerpen.be

*Corresponding author:
Tel.: +32 3 213 79 34
E-mail address: joke.anthonissen@uantwerpen.be
[1] E-mail address: wim.vandenbergh@uantwerpen.be

Abstract
This paper provides a critical review of different approaches applied in the Belgian asphalt sector in order to reduce the environmental impact of bituminous road construction works. The focus is on (1) reusing reclaimed asphalt pavement; (2) reducing the asphalt production temperature; and (3) prolonging the service life of the pavement. Environmental impact assessment of these methods is necessary to be able to compare these approaches and understand better the ability to reduce the environmental impact during the life cycle of the road pavement. Attention should be drawn to the possible shift in environmental impact between various life cycle stages e.g., raw material production, asphalt production or waste treatment. Life cycle assessment is necessary to adequately assess the environmental impact of these approaches over the entire service life of the bituminous pavement. The three approaches and their implementation in the road sector in Flanders (region in Belgium) are described and the main findings from life cycle assessment studies on these subjects are discussed. It was found from the review that using reclaimed asphalt pavement in new bituminous mixtures might yield significant environmental gains. The environmental impact of the application of warm mix asphalt technologies, on the other hand, depends on the technique used.

Keywords
Bituminous pavement, life cycle assessment (LCA), reclaimed asphalt pavement (RAP), warm mix asphalt (WMA), half-warm asphalt (HWMA), Flanders

Abbreviations

AADT	Average annual daily traffic	HWMA	Half-warm mix asphalt
AADTT	Average annual daily truck traffic	IBA	Incinerator bottom ash
ADT	Average daily traffic	LCA	Life cycle assessment
AP	Acidification potential	LCCA	Life cycle cost analysis
CED	Cumulative energy demand	LCIA	Life cycle impact assessment
CMA	Cold mix asphalt	NRD	Natural resource depletion
CSOL	Crack, seat, and overlay	PAH	Polycyclic aromatic hydrocarbon
EE	Energy equivalent	PCC	Portland cement concrete
EI	Eutrophication index	PCR	Product category rules
EP	Ecotoxic potential	POPC	Photochemical ozone creation potential
EPD	Environmental product declaration	RAP	Reclaimed asphalt pavement
EU ETS	European Union emission trading system	SMA	Stone mastic asphalt
GWP	Global warming potential	TP	Toxic potential (human)
HMA	Hot mix asphalt	VOC	Volatile organic compounds
HMB	High modulus bituminous	WMA	Warm mix asphalt

1 Introduction

Framework and problem

On the occasion of the Kyoto Protocol, adopted and signed in 1997 and setting binding obligations on industrialized countries in order to reduce emissions of greenhouse gases, the European Union emissions trading system (EU ETS) was initiated in 2005 for energy-intensive industrial installations and the electricity sector. The EU ETS works based on the 'cap and trade' principle (Departement Leefmilieu Natuur en Energie, 2014; European Union, 2013). The overall volume of greenhouse gases that can be emitted each year by the companies covered by the system is subject to a cap set at EU level. Within this Europe-wide cap, companies receive or buy emission allowances they can trade if wanted. All companies subjected to the EU ETS have to monitor and report on their CO_2 emissions. Each year, the companies have to hand in emission allowances in accordance with the emitted quantity.

In Flanders, about 220 companies were subjected to the EU ETS in 2014 altogether responsible for 40% of the CO_2 emissions in Flanders. These 220 companies emitted together 31.6 million tons of CO_2 equivalents in 2014. Since 2013, all installations with a net heat excess of 20 MW or more are subjected to the Kyoto Protocol, including 13 of the 18 Flemish asphalt plants. These 13 asphalt plants are responsible for 0.13% of all Flemish CO_2 emissions registered according to EU ETS (Departement Leefmilieu Natuur en Energie, 2014). The EU ETS regulations induced some innovative technologies in order to reduce the greenhouse gas emissions.

Besides, triggered by economic benefits, some new technologies were introduced in the bituminous road pavement sector earlier, which are nowadays considered to have also a beneficial impact on the environment. These techniques, which are considered to be "green" needs to be analysed in detail in order to be able to make an informed decision on the environmental impact. The environmental impact of a certain product is dependent on various preconditions e.g. local aspects, valid regulations, and application and performance in practice.

Objective and scope

The objective of the current study is to evaluate the possibilities for the industry to reduce the life cycle environmental impact of bituminous pavements in Flanders.

Kluts & Miliutenko (2012) and Stripple & Erlandsson (2004) presented three decision stages in the road infrastructure planning: (1) network level: choice of transport modality at the national level; (2) corridor level: choice of localization and construction type of a specific project; (3) project level: choice of specific design. Kluts & Miliutenko (2012) mention that it is likely to use one single environmental impact assessment process to evaluate both the second and third decision level. Based on this idea, Butt et al. (2015) suggested a framework which includes two complexity levels (network and project level) and two decision situations (early planning and late planning/design).

The current study focuses on the possible reductions of environmental impact which might be realized by efforts of the industry. Hence, according to the framework suggested by Butt et al. (2015), the current study concerns decisions at the project level in the late planning and design stage. This includes questions as “Which road or material alternative to select?” and “What specific design alternative to choose?”.

It is important to note that Belgium is divided in three different regions (Flanders, the Walloon Region, and Brussels) where road infrastructure is subjected to the regional regulations. The Flemish road standard SB250 v3.1 prescribes all rules and conditions for asphalt mixtures to be used for public road construction. The current version of this standard does not allow the use of reclaimed asphalt pavement (RAP) in surface courses of road pavements. In order to allow comparison between the use of RAP and other green techniques, the current contribution focuses on base layers. This justifies the exclusion of some important components in road infrastructure as described by Araújo et al. (2014), AzariJafari et al. (2016), Muench (2010), and Santero et al. (2011b). As base courses do not affect the noise from pavement tire interaction, lighting requirements, albedo effect, carbonation, etc., these components are excluded from the scope of the current literature review. Although the deformation of base courses affects the international roughness index of the pavement and consequently the vehicle fuel consumption, the use phase in general is beyond the scope of this study. Nevertheless, the authors recognize the importance of these aspects and the use phase impacts in environmental impact assessment studies within another research scope.

Research approach

Three groups of techniques are investigated: (1) reducing the demand for virgin materials e.g., by recycling recuperated materials into new asphalt mixtures i.e., reclaimed asphalt pavement (RAP); (2) reducing the energy consumption e.g., by decreasing the production temperature of asphalt mixtures; and (3) lengthening the service life of the pavements by optimizing the mechanical properties of asphalt mixtures. Other aspects affecting the environmental impact are considered as well e.g., transport distances, moisture content in aggregates, energy consumption in the asphalt plant, etc.

Life cycle assessment (LCA) is seen as the appropriate method to assess the environmental impact of bituminous road pavements. It allows including different life cycle stages and multiple environmental issues. The framework of Butt et al. (2015) for the implementation of LCA in road infrastructure indicates that stand-alone LCA studies and attributional LCA studies are suitable methodologies to answer the defined research questions in the current study.

A literature review focusing on the current practices in Flanders is conducted. Various literature reviews of pavement LCA are published (AzariJafari et al., 2016; Muench, 2010; Santero et al., 2011c), but the current one is different because of the different, specific scope and area of applications. Both regional (Flanders and Belgium) and international (Europe and worldwide) literature have been consulted for this review. First, the techniques that are supposed to reduce the environmental impact are described e.g., the influence on the mechanical properties, the required adaptation of the asphalt plant or the implementation of the techniques in the Flemish road sector. Subsequently, a review of selected life cycle assessment (LCA) studies on road pavement is given in order to discuss the environmental impact of these techniques. Note that the aim of the study is not to compare framework gaps and inconsistencies in LCA studies. The findings of this study can be used by bench makers in order to decide for investments or funding and by the asphalt sector to optimize the environmental performance.

2 Approaches in order to address sustainability and their use in Flanders

In general, it can be stated that efforts are made in order to make the bituminous road sector in Flanders more environmentally friendly. The Flemish road agency recently implemented a pilot project, assigning a public tender for repaving a road section based on both criteria: economic cost and CO_2 emissions of the project (Anthonissen et al., 2015b).

2.1 Use of reclaimed asphalt pavement

Among the various materials (steel slag, fly ashes, cast iron sand, dredging spoil, glass, crumb rubber, roofing waste and bio base bitumen) mentioned in the Best Available Techniques study (Leyssens et al., 2013), reclaimed asphalt pavement (RAP) is the most used material to replace virgin raw materials in asphalt mixtures in Flanders. Reclaimed asphalt pavement is released during maintenance interventions. It is a high quality material that contains valuable constituents (inert material and bituminous binder). The reuse and the recycling of RAP are encouraged by some economic benefits and started more than 30 years ago, and nowadays, it has become common practice in many European countries (EAPA, 2008).

The Flemish Road Standard (for public road works) SB250 defines criteria for mixture compositions (empirical method) or the required minimum performances (fundamental method). The current version SB250 v.3.1 (Vlaamse Overheid, 2014) prohibits the use of RAP in asphalt mixtures for surface courses. On the other hand, some mixtures for base courses are defined based on the fundamental method without a limit on the percentage of RAP.

Before the RAP is reused, it is screened for contaminations (tar, organic material, etc.) and pre-treated (breaking, sieving) in order to control its homogeneity. Thereafter, it can be used in new asphalt mixtures reducing the need (and costs) for virgin inert materials and virgin bitumen. This type of recycling is called closed loop recycling. This means that the output of the product system (the end of service life of a road pavement) is used as its input again (material produced in order to repave the road).

In practice, different ways are applied in order to use RAP in asphalt mixtures. The RAP can be added cold in the mixer together with the overheated virgin materials or the RAP can be preheated (e.g., by parallel drum) before it is added to the asphalt mixture. Cold recycling is quite easy and only few additions to the asphalt plant are required to enable, but the main disadvantages are the required higher temperature of the virgin materials and a longer mixing time at high recycling rates. Following the Flemish Road Standard SB250 v.3.1, maximum 20% of the bitumen in the asphalt mixture may come from RAP when applying cold recycling. The implementation of a parallel drum demands extensive adaptations of the asphalt plant with higher investments, but is a more efficient approach for recycling. Most Flemish asphalt plants are equipped with a parallel drum. The use of a parallel drum allows a better control of the moisture content in RAP. It was found in literature (Vidal et al., 2013; Wayman et al., 2012) that the moisture content in RAP is higher compared to virgin aggregates since water is used for milling the old pavement. In Flanders, virgin aggregates are washed and might therefore be very wet as well. Remaining moisture in asphalt mixtures will influence the performances and hence the service life in a negative way, and more moisture requires more energy for drying the aggregates during the asphalt production process. Depending on the circumstances, the moisture in RAP may offset the environmental benefits from using RAP instead of virgin materials.
In general, no additives for the production of asphalt mixtures with RAP are used in the Flemish asphalt sector.

In 2014, 38 asphalt plants are located in Belgium, of which 18 in Flanders, 19 in the Walloon Region and 1 in Brussels (Belgian Road Research Centre, 2014). COPRO [1] publishes the results of measurements on certified asphalt mixtures and certified asphalt plants. 17 Flemish and 4 Walloon asphalt production plants are COPRO certified (meaning 1 Flemish, 15 Walloon and 1 Brussels asphalt plants are not and thus excluded from this COPRO data collection) (COPRO, 2015). All COPRO-certified asphalt plants are able to produce asphalt mixtures with RAP.
The data from the publications COPRO (2015, 2014, 2013) and European Asphalt Pavement Association (2015, 2014, 2013) – discussing some figures on asphalt production and the use of RAP – are compared in Table 1. The data from EAPA are an estimation of the national industry sector, made by the Belgian association of asphalt producers. Hence the scope of the data sources is different (see number of production sites). This is reflected in the annual asphalt production, which is reported to be higher in EAPA figures compared to COPRO. The available amount of RAP, on the other hand, is higher in the COPRO report. These figures account all COPRO-certified RAP which can be used in new asphalt mixtures or in unbound base material. Also, the percentages on the use of RAP differ for both data sources. In general, it is assumed that the COPRO data are more accurate in its specific scope.

[1] COPRO is the abbreviation for "COntrol of PROducts". COPRO is an independent Belgian organization and implements controls of quality on construction products as on their integration on sites.

Table 1: figures of asphalt production in Belgium in 2012, 2013 and 2014

	2012		**2013**		**2014**	
	EAPA	**COPRO**	**EAPA**	**COPRO**	**EAPA**	**COPRO**
Number of production sites	38	21	38	21	38	22
HMA and WMA production (million tons)	5.6	3.7	5.3	3.3	5.2	3.3
Available amount of RAP (million tons)	1.5	1.9	1.5	2.0	1.5	1.6
Available RAP used in asphalt (%)	61	50	61	43		61
Mixtures containing RAP (%)	49	58	51	58		61
RAP content in mixtures with RAP (%)		39		45		43

The proportion of residual binder from RAP and virgin binder in asphalt mixtures is expected to affect mixture volumetric and mechanical properties. Contradiction is found in literature concerning the percentage of actual blending occurring between RAP and virgin binders. Some studies assume that aged and virgin binder approaches complete mixing (Al-Qadi et al., 2009; Lopes et al., 2015; Shen et al., 2007), while others assume partial blending (Apeagyei et al., 2011; Huang and Bird, 2007) and Huang et al. (2005) found that mechanical blending affects only a small portion of aged asphalt binder in RAP.

Li et al. (2008), Lopes et al. (2015) and Swamy et al. (2011) found that asphalt mixtures containing RAP have higher dynamic modulus values and hence become stiffer than the same mixtures containing no RAP. Colbert & You (2012), on the other hand, notice a decrease of the dynamic modulus and the resilient modulus as RAP percentage increased. Several investigations (Al-Qadi et al., 2009; Li et al., 2008; Mogawer et al., 2012; Tapsoba et al., 2012; Zhao et al., 2013) have shown that mixtures with RAP have a lower thermal cracking resistance. Colbert & You (2012), Lopes et al. (2015) and Zhao et al. (2013) found that the addition of RAP increases the rutting resistance; while Apeagyei et al. (2011) found similar rutting performances for a mixture without RAP and a similar mixture with 25% RAP. Finally, Zhao et al. (2013) found that adding RAP decreases the fatigue resistance, while Lopes et al. (2015) found that the presence of RAP improves the fatigue life of hot mix asphalt.

Mogawer et al. (2012) found that some production parameters at the plant i.e., discharge temperature and silo storage may have an impact on the relative degree of blending between the RAP and virgin binders and hence affect the mixture stiffness and cracking properties.

2.2 Warm mix asphalt

The annual emitted CO_2 equivalents in the scope of the EU ETS (as described in §1) are calculated based on the fuel consumption of an installation. In this scope, techniques are implemented in order to reduce asphalt production temperature.

Leyssens et al. (2013) define four main categories of asphalt processing techniques in relation to the temperature: (1) cold mix asphalt (CMA) manufactured at temperature lower than 40 °C; (2) half-warm asphalt mix (HWMA) manufactured at temperatures of 60 to 95 °C; (3) warm mix asphalt (WMA) manufactured at temperatures of 100 to 150 °C; and (4) hot mix asphalt (HMA) manufactured at temperatures higher than 150°C. Currently, WMA is the best of those alternatives to replace HMA due to similar performances. In general, three main groups of techniques for the production of WMA can be distinguished (Rubio et al., 2012): (1) organic additives, (2) chemical additives, and (3) water-based foaming processes. The effect of the different techniques is equal: reducing the viscosity of bitumen in order to improve the workability of the asphalt mixture at lower temperature.

WMA production using organic or chemical additives is rarely applied in Flanders. The WMA production based on foaming techniques does not require the addition of additives at the asphalt plant. The implementation of a foam-unit in an asphalt plant requires only small adjustments. A number of asphalt plants in Belgium are provided with a foam-unit. Nevertheless, this technique is not yet used in order to produce WMA on a large scale. In Flanders, WMA mixtures are currently only produced in the scope of research and pilot projects. SB250 v.3.1 includes specifications for WMA e.g., the production temperature is defined to be 105 to 160 °C compared to 140 to 210 °C for HMA. After acceptance of a validation dossier for a specific asphalt mixture produced at decreased temperatures, this mixture can be used for public road works. In this way, the Flemish Road Agency encourages the industry to use the WMA technology. The use of the WMA mixtures in practice on a large scale is necessary to build up experience and confidence.

Regarding the mechanical performances, Hill (2011) and Zhao et al. (2013) found that WMA is less resistant to rutting than a corresponding HMA, while Zhang (2010) concludes that WMA generally presents better rut resistance than their HMA counterparts. Hill (2011), Zhang (2010) and Zhao et al. (2013) indicate that WMA mixtures are more susceptible to moisture compared with their HMA equivalents.
Furthermore, the studies by Hill (2011), Hurley et al. (2009) and Zhang (2010) investigate the impact of different WMA additives on the mechanical performances of the WMA mixture. The Fischer Tropsch wax positively affects the rut resistance (Hill, 2011; Zhang, 2010) while an emulsion additive increases the rut depths (Hill, 2011; Hurley et al., 2009).
It is recommended to not decrease the heating temperature of the virgin and recycled materials beneath 100 °C for WMA because the drying process would not be complete and the remaining moisture could affect negatively the pavement durability (van Bochove et al., 2012).
The feasibility of applying high percentages of RAP (75% to 100%) in WMA is proved by studies of D'Angelo et al. (2008) and Mallick et al. (2008). In a laboratory research environment, different researchers found an improvement of WMA performances by adding RAP: higher rut resistance (Hill, 2011; Zhao et al., 2012), better moisture damage resistance (Hill, 2011; Shu et al., 2012; Zhao et al., 2012), and better fatigue performance (Zhao et al., 2012). Performance evaluation, however, needs to be conducted in situ on the road in order to investigate its capability to resist pavement distresses during service life (Zhao et al., 2013).

2.3 Longer lasting roads

The longer the service life of material on the road, the fewer maintenance interventions are necessary, implying less material and energy consumption, less transport, less emissions etc. Therefore, research was conducted in order to develop more sustainable materials.

A well-known binder type is polymer-modified bitumen. Studies indicate that the properties of polymer-modified bitumen are significantly improved compared to penetration bitumen e.g., higher elastic recovery, a higher softening point, higher viscosity, larger cohesive strength or greater ductility (Yildirim, 2007), resulting in an improved resistance to rutting, to fatigue and to thermal cracking and an extended service live of the road pavement (Buncher and Rosenberger, 2005; Glanzman, 2005).

The addition of fibres is another technique to improve the mechanical properties of an asphalt mixture and thereby the service life of a pavement. A field and laboratory study by Kaloush et al. (2010) of bituminous mixtures with polypropylene and aramid fibres indicated that an improvement was found in permanent deformation, fatigue cracking and thermal cracking compared with a control mix with no fibres. A Flemish laboratory study by Anthonissen and Boonen (2012) investigated the impact of aramid, polyester and glass fibres on the performances of asphalt and bitumen and compared the results to a reference without fibres. Both asphalt mixtures with aramid and polyester fibres have an increased rutting resistance. The results of the Bending Beam Rheometer (BBR) reveals a higher minimal user temperature for the aramid fibre, which might yield thermal cracks at higher temperatures. The force ductility test showed a very high force but a small prolongation for the aramid fibres. A first test section on a Belgian road was constructed in 2013 using fibres in the mixture for the surface course in order to absorb the high tensile strains in the pavement.
Using fibres is an interesting possibility to improve the mechanical properties of the asphalt mixture and lengthen the service life of the pavement, but needs more research. An important research topic is the recyclability of road pavements with fibres at the end of the service life.

Another innovative concept is the use of old bituminous roofing felt waste in hot mix asphalt. A mixture was developed, composed of 3% reduced bituminous roofing waste, 45 to 55% reclaimed asphalt pavement, 40 to 50% new granulates and only 1% new bituminous binder, called i-aB³ (improved aged-Bitumen Bound Base) (Van den bergh and Stoop, 2009; Van den bergh et al., 2008). This mixture, preliminary designed for asphalt base courses, is currently described as bitumen grave in SB250 v3.1 and can be used as a bound base material. When using this mixture in the construction of a flexible road pavement, the thickness of the structure can be reduced, while at the same time the service life and the durability of the pavement are increased. Three different test sections were constructed in Flanders in 2001, 2006 and 2010 and the evaluation (i.e. falling weight deflection measurements) of these test sections shows – still – promising results (Van den bergh et al., 2013).

The standard value for the design life of road structures with an asphalt concrete pavement is set at 20 years in Flanders. The default service life is 14 years for the wearing course and 24 years for the base course [reference: interview with senior adviser at Agency for Roads and Traffic]. In the Netherlands, the default service life of the bituminous road structure is defined to be 20 years and the surface course has a service life of 10 to 12 years (Van Gelder, 2012).
Generally, it is difficult to predict the prolongation of the roads service life when improved asphalt mixtures are used. Many contextual parameters influence the service life of a road pavement: conscientious execution of the works (asphalt production and road construction), (extreme) weather conditions, traffic load, performances of other courses in the road construction, etc. Besides, the necessary maintenance interventions are often not executed based on mechanical failure of the road pavement, but in practice these are scheduled based on the financial policy of the responsible authorities.

				Layers					Life cycle stages									Environmental indicators / LCIA method													
No.	Reference & country	Objective of environmental LCA study	Functional Unit	surface	binder	base	sub-base	Lifespan/ analysis period (years)	Materials extraction	Production	Earth works	Pavement construction	Maintenance	Traffic congestion during works	Use	End of life	Sensitivity analyses	EE / CED	Bitumen feedstock energy	GWP	Ecological scarcity / NRD	Fossil (fuel) depletion	POPC / smog	EP	TP	ODP	EI	AP	AD	relevant to LCA of roads:
1	Ventura et al. 2008 France	compare binding courses of pavement sections made of RAP using various recycling rates (0, 10, 20 and 30%) in a hot mix process	road section (±350 m x 3,8 m wide x 7 cm thick) corresponding to one hour of mixing plant output (±100 tons)		x			/	x	x		x						x		x	x		x	x	x		x	x		RAP
2	Ventura et al. 2009 France	assess a half-warm mix process by means of measurements at the plant as well as during actual road works	surface area of 3750 m², 6 cm thick (=560 ton)	x				/	x	x		x						x		x			x				x	x		WMA
3	Leng & Al-Qadi 2011 Illinois, USA	compare the life cycle environmental and economic performances of WMA SMA and HMA SMA binder courses as part of an overlay project	one lane-mile (3,6 m width; 4,45 cm thick) with AADT=60120 vehicles north bound and 35920 vehicles south bound		x			/	x	x		x						 + criteria air pollutants		x		x	x							WMA
4	Nicuţă, 2011 Romania	evaluate and compare two asphalt mixtures (0% or 75% RAP) and conclude on the advantages or disadvantages of one road structure type	1 km road pavement, 7 m width	x	x	x		15	x	x		x						 aSPECT software		x										RAP
5	Santero et al. 2011 California, USA	evaluate the environmental effectiveness of long-life pavements	3 different roads (different AADTT) with 3 different structures (layer thickness) in order to reach the design life	x		x	x	20, 40, 100	x	x		x	x			x	x	x EIO-LCA		x										general
6	Tatari et al. 2012 USA	develop a hybrid Eco-LCA model to evaluate pavements: WMA with different additives and HMA	1 km two-lane (7,2 m width) highway, AADTT=2000 vehicles/day, 50% trucks	x		x		30	x	x		x					x	x + atmospheric emissions			x									WMA
7	Wayman et al. 2012 Europe	identify product level parameters that have a significant impact on the environmental performance of RAP	1 m² single lane highway with ADT = 450 vehicles (across all classes) in 1 direction with 1% growth	x	x	x	x	60	x	x		x	x			x	x	 CML2000 Midpoint impact categories (10)		x			x	x	x	x	x	x	x	general RAP
8	Yu & Lu 2012 Florida, USA	develop a LCA model with six modules and use it to explore three overlay options: PCC, HMA and CSOL	1 km, 2 x 2 lanes, AADT=70000 with 8% trucks, 4% growth a year	x	x			40	x	x		x	x	x	x	x		x	x	x										general
9	Gschösser & Wallbaum 2013 Switzerland	analyze typical Swiss asphalt, concrete, and composite road pavements for national roads (highways) by performing LCA combined with LCCA	10 km four-lane (20,5 m width) highway, traffic load class T6	x	x	x	x	75	x	x		x	x		x	x	x	x	x	x	x									general
10	Rubio et al. 2013 Spain	compare HWMA and HMA in order to obtain field data (emission measurements)	*(does not apply)*	x				/		x		x						 Channeled and diffuse emissions												WMA
11	Vidal et al. 2013 Spain	calculate the impacts of different road pavements: HMA and zeolite-based WMA, both with and without RAP	1 km long, 13 m with, 8 cm thick with ADT=1000 vehicles/day with 8% of heavy vehicles	x				40	x	x		x	x		x	x		x ReCiPe Midpoint (18) & Endpoint (3) categories, Hierarhist perspective + CED		x		x	x	x	x	x	x	x	x	RAP WMA
12	Anthonissen et al. 2014 Flanders, Belgium	compare the production of a HMA, a WMA with foamed bitumen technology and a HMA with 50% RAP	1 ton asphalt mixture			x		/	x	x							x	 ReCiPe Midpoint (17), Endpoint (3) and single score impact, Hierarhist perspective + other LCIA methods		x		x	x	x	x	x	x	x	x	WMA
13	Blankendaal et al. 2014 North-Western Europe	gain insight in and improve upon the environmental impact of concrete and asphalt	1 m³ asphalt				?	?	x	x		x			x	x		 ReCiPe single score impact, Individualist, Hierarchist and Egalitarian perspectives		x		x	x	x	x	x	x	x	x	WMA
14	Gschösser et al. 2014 Switzerland	determine the impacts for the new construction and maintenance of typical asphalt, concrete and composite road constructions	4 lanes (20,5 m width), 10 km length (traffic load class T6); and 2 lanes (7,5 m width), 0,5 km long (traffic load class T5 or T4)	x		x	x	?	x	x		x	x				x	x (CED non-renewable)		x	x									general
15	Anthonissen et al. 2015 Flanders, Belgium	compare different bituminous binders or manufacturing methods for road pavement construction	section of 300 m length and 6 m width	x				48	x	x		x	x				x	 ReCiPe Midpoint (18) and single score impact, Hierarhist perspective + other LCIA methods		x		x	x	x	x	x	x	x	x	WMA
16	Giani et al. 2015 Italy	quantify the environmental savings producing asphalt pavements with a major percentage of RAP and using WMA	1 km suburban road 2x2 lanes, 15 m width and 25 cm thick	x	x	x		15	x	x		x	x			x		x ReCiPe Midpoint (17), Endpoint (3), Hierarchist perspective + selected LCI results, Water Consumption	x	x		x	x	x	x	x	x	x	x	RAP

3 Life Cycle Assessment of pavements

An extensive analysis about the environmental impact of the techniques discussed (§2) is necessary in order to evaluate the impact over the lifetime of the road pavement. Life cycle assessment is an appropriate technique for this environmental analysis. Buyle et al. (2013) clearly describe the theoretical frame and the four steps of a life cycle assessment according to ISO 14040 series (ISO 14040, 2006; ISO 14044, 2006).

Table 2 presents more information on the LCA studies which are discussed in this chapter. The only LCA studies included in the table are those who contribute relevant information to the study objective. In this way, the results of the study can be described in text and other background information of the study might be looked up in this table to see the conclusions in a broader context.

3.1 LCA of roads: general

Wayman et al. (2012) conducted a cradle-to-grave study and divided the life cycle in different stages. Asphalt production (incorporating raw material acquisition and processing, raw material transport, raw material storage and asphalt production at plant), transport of asphalt to the work site, laying and compaction of the road, in situ (including leaching from the in situ road pavement and dust from wear of the surface layer), and end-of-life (including milling of surface, binder and base layer after 60 year service life and transport of these materials to a stockpile). Asphalt production, transport to site and laying and compaction includes the initial construction and all maintenance interventions (three times inlay of surface layer and one time inlay of binding layer). The contribution of the different life cycle stages to the environmental impact over the life cycle depends on the impact category. Asphalt production represents 45 to 95% of the environmental impact, transport to site 1 to 8%, laying and compaction 1 to 12%, in situ 0 to 1% and end-of-life 0 to 40%. Within the asphalt production, the bitumen production (56 to 67%), the transport for supplying raw materials to the plant (13 to 16%) and the energy to dry and heat raw materials (11 to 25%) are found to be the main impacting processes.
Similarly, Giani et al. (2015), Gschösser and Wallbauw (2013), and Gschösser et al. (2014) found that extraction and material production have the biggest environmental impact during the lifecycle, while the pavement construction and deconstruction processes have a marginal impact on the analysed environmental indicators.

When analysing the environmental impact of the asphalt production process, it is important not to confuse energy resources used for processing (process energy) and energy resources used as raw material (feedstock energy e.g., in bitumen). The first is mostly included in LCA studies. The feedstock energy, however, is not a direct energy consumption because the bitumen is not burned when it is used for road materials and hence the energy is not released. Moreover, at the end of the service life of the pavement, the bitumen can be used again as raw material binder without losing the feedstock energy. The feedstock energy of bitumen is rarely mentioned in LCA studies because it is rather complex to model.
Nevertheless, the inclusion or exclusion of it may be a decisive parameter when comparing the environmental impact of different materials e.g., asphalt and concrete (Yu and Lu, 2012). Including

feedstock energy is less important when comparing different types of asphalt. The best practice is to include the feedstock energy (as stated in ISO 14040 (2006)) but present (the impact of) it separately in LCA results. Butt et al. (2014) describe a method to calculate the feedstock energy in bitumen.

Another factor with a major influence on the environmental impact during the life cycle of the road pavement is the intermediate maintenance period. Wayman et al. (2012) found a reduction of the environmental impact of minimum 10% in each impact category when the intermediate maintenance period of a surface course is prolonged from 10 to 14 years. Gschösser and Wallbauw (2013) found a reduction of the global warming potential of 25% when the intermediate maintenance periods are prolonged from 7.5 to 12.5 years for the surface course and from 15 to 25 years for the base course. Hence, the definition of the service life of a road pavement is an important subject of the definition of the functional unit of an LCA, but difficult to predict as described in §2.3. For LCA calculations, the service life of the pavement is chosen based on experiences of local transportation administration or based on rehabilitation program and life design of the road (AzariJafari et al., 2016).
Santero et al. (2011a) investigated the environmental impact of a road structure with a 20, 40 and 100 year design life. The structural design is a doweled Portland cement concrete pavement with an asphalt concrete base and a granular sub-base. The layer thicknesses vary in function of the design life. In spite of the fact that concrete pavements are behind the scope of the current literature review, some interesting conclusions were formulated, which are applicable to asphalt layers as well. When comparing the 20- and 40-year design, Santero et al. (2011a) found a crossover point of 29 to 45 years. This means that after a maximum of 45 years, the life cycle global warming potential (GWP) and energy consumption of the 20-year design exceeds the GWP and energy consumption of the 40-year design. Comparing the 40- and 100-year design, the authors found a minimum crossover point of 93 years and a maximum of more than 100 years. If the analysis period in an LCA study is shorter than the period before crossover, then the environmental benefits will not be realized in time. Furthermore, Santero et al. (2011a) stated that the rigidity of longer-life pavements makes them more susceptible to unforeseen shifts in their functionality and serviceability expectations.

The extra environmental impact caused by traffic disturbance during maintenance interventions is another important issue. Huang et al. (2009) found that reducing the duration of the roadwork by three days for a full reconstruction (base, binder and surface course) results in an important amount of avoided emissions and avoided energy consumption by the disturbed traffic. The amount of avoided carbon oxide (CO) and particulate matter (PM) emissions are almost equal to those caused by the roadwork itself. This indicates the importance of limiting the disturbance of the traffic during road works.
Similarly, it was found in literature (Carlson, 2011) that the energy consumption and emissions of the traffic using a road over its service life exceeds the energy consumptions and emissions from the other stages in the life cycle by 2 to 500 times, depending e.g. on the analysis period, the traffic intensity and the road construction alternative. The impact from vehicles using the road might be reduced by increased car energy efficiency and by optimizing the surface structure of the pavement.

Furthermore, it is found in literature that the results of LCA studies are not directly comparable since the specific contextual characteristics, environmental data sources and system boundaries differ considerably

(Carlson, 2011; Santero et al., 2010; Ventura and Jullien, 2009). This finding emphasizes the importance of a specific framework for LCA studies on bituminous pavements. Butt et al. (2015) introduced a framework for pavement LCA studies with a distinction in the components which should be included in the study depending on the decision level (network or project) and decision stage (early planning or late planning/design). The International EPD® System, on the other hand, intends the development of Product Category Rules (PCR). A PCR is defined in ISO 14025 (ISO 14025, 2006) as a set of specific rules, requirements and guidelines for developing Type III environmental declarations for one or more product categories. It defines the type of data that should be collected, measured and reported in a life cycle analysis. At this moment, the most appropriate PCR related to the current research topic is “Highways (except elevated highways), streets and roads” (EPD International, n.d.).

3.2 LCA of asphalt mixtures containing RAP

The environmental impact of using RAP in new hot or warm asphalt mixtures is affected by factors, such as moisture content (National Technology Development, 2009; Wayman et al., 2012), hot mix asphalt discharge temperature (National Technology Development, 2009), RAP content (National Technology Development, 2009), transport process (Ventura et al., 2008) and the quality of RAP (homogeneity, bitumen content, tar, etc.).

A study by Wayman et al. (2012) found that recycling of asphalt to bound courses is favoured compared with recycling asphalt to unbound applications (sub-base or fill) and waste management alternatives (landfill or incineration). These benefits mainly stem from the avoided extraction and refining of virgin bitumen that comes with a significant environmental impact (see §3.1). Furthermore, Wayman et al. (2012) indicate that recycling RAP from surface courses and use it again in surface courses (recycling surface-to-surface) might realise some additional benefit if high specification aggregates are (re)used in order to optimize the surface characteristics. Recycling surface-to-surface is particularly pertinent if the high specification aggregate sources are widely dispersed or if road transport is the only available transport mode between quarry and plant.

Giani et al. (2015) found that the environmental impact reduces when adding 10% and 20% RAP in the HMA mixtures for surface and binder course respectively. The percentage of reduction is 6.8% for greenhouse gasses (ton CO_2eq) and 6.4% for the single score endpoint impact over a lifetime of 15 years.

Vidal et al. (2013) found that all endpoint impacts (human health, ecosystem diversity, resource availability), as well as midpoint impacts (climate change and fossil depletion) and the total cumulative energy demand were decreased by 13 to 14% when adding 15% RAP to HMA or WMA. Only a very small increase of the two midpoint impact categories were reported when considering only the asphalt production, which includes the asphalt plant (land use, infrastructure and machinery) and the electricity and fuel consumption for the asphalt production process (screening, drying, mixing and storing).

In the specific context of the study, Ventura et al. (2008) found a trend of decreasing potential environmental impacts with an increasing recycling rate except for the (eco)toxicity. The (eco)toxicity impact is mainly due to emission of PAH during roadwork (paving and rolling) and shows an increase with recycling rate.

Nicuţă (2011) found a reduction of the CO_2e emissions by 40% if 75% RAP is used in a cradle-to-laid environmental analysis of a road structure.

A disadvantage of using RAP is the increased energy costs during asphalt production due to the use of an additional burner in the parallel drum (van den Berk, 2004). A parallel drum is used in order to preheat the RAP before it is added to the mixer. The energy consumption is assumed to rise up to 14% when using 15 to 30% RAP and up to 17% if more than 45% RAP is used in new asphalt mixtures.

Another important environmental issue related to the use of RAP is the possible contamination of the subsoil and groundwater through leaching. It was stated in a study by EAPA (2008) that the leaching behaviour of asphalt containing RAP is not different from asphalt produced with virgin materials. Asphalt with or without RAP does meet the most onerous requirements in Europe with regard to leaching. Legret et al. (2005) show that pollutant leaching from stockpiles is rather weak and generally remained below EC limit values for drinking water. Nevertheless, the comparison between new conventional asphalt and RAP seemed to indicate that concentrations of total hydrocarbons and some PAHs were higher in leachate from RAP. The grain size of the material and the percolation water flow rate were found to be factors influencing the results. A study by Enell et al. (2012) remarks that the use of RAP within bound pavement mixtures results in no increase in environmental risk related to leaching of contaminants. On the other hand, appreciable levels of leaching associated with water infiltrating stockpiles of RAP are observed. The risk associated with storing RAP (with high levels of contaminants) outdoors appears high. Furthermore, tar-contaminated RAP is associated with the highest leaching levels and with highest emissions. Hence, no alarming amounts of leaching values for asphalt and (not-contaminated) RAP were found in literature. The findings are supporting the practice of restricting the use of tar containing RAP in road construction and encourages the storage of RAP under a shelf, particularly when it is contaminated.

Besides, Enell et al. (2012) conclude that the total emission of asphalt fumes during plant hot recycling does not change substantially due to addition of uncontaminated RAP. Jullien et al. (2006), on the other hand, investigate the release of airborne emissions related to asphalt laying among various recycling rates. This study found that some gaseous emissions (VOC, PAH) increase with the recycling rate while odours decrease.

3.3 LCA of WMA and HWMA

A reduced production temperature is generally associated with a reduced energy consumption and consequently less emissions. Nevertheless, it is important to investigate in detail the used technology in order to enable a lower production temperature.

Ventura et al. (2009) found that for the asphalt mix processes, there is an energy (natural gas, gasoil and electricity) saving for HWMA when compared to HMA. The study also reports that the amount of most airborne emissions (measured in the stack) reduces, except for CO and CH_4, which are correlated with the burner adjustments and natural gas combustion reactions. Rubio et al. (2013) conducted similar measurements in the stack of the plant and did found a reduction of CO (and other) emissions for HWMA compared to HMA. The main difference with the study of Ventura et al. (2009) is the fact that the HWMA

was produced at a plant, with a burner specially designed to heat aggregate at temperatures of 65 to 130 °C.
For the airborne emissions during road works, it was found by Ventura et al. (2009) that the amount of non-methanic gaseous organic compounds decreases while the amount of CO_2, N_2O, SO_2 and particles increases, which is explained by the longer compaction process of the HWMA pavement compared to HMA. Within the scope of the experiment, the HWMA has been found to reduce all environmental indicators. Note that the study by Ventura et al. (2009) does not include information on both the production processes and transport of the chemical additive.

The environmental burden from the production of additives might counteract the environmental gain at the asphalt plant by lowering the production temperature. Three WMA mixtures with different additives (a synthetic zeolite, a Fischer Tropsch wax and an emulsion) are compared with a conventional HMA in a cradle-to-laid study (Tatari et al., 2012). Overall, the WMA do not appear to perform better than HMA. The environmental impact of the WMA with zeolite and wax is highly dependent on the additive production, while that of the mixture with emulsion is dependent on the energy consumption during mixing. Anthonissen et al. (2015a) and Vidal et al. (2013) conclude similarly that the reduction of the impacts of WMA due to lowering the manufacturing temperature is offset by the greater impacts of the synthetic zeolites production.
These results indicate that including the supply chain (material production and transportation) is very important in order to get a comprehensive environmental assessment of asphalt production or a road pavement.

Furthermore, some research was carried out on WMA mixtures containing RAP. It is important to note that the savings of airborne emissions expressed in terms of CO_2 equivalent achieved by recycling RAP far outweigh those that may be achieved by reducing the production temperature (Anthonissen et al., 2014, 2013; van Bochove et al., 2012; Wayman et al., 2012). Likewise, the results of studies by Vidal et al. (2013) and Wayman et al. (2012) indicate that the environmental benefits in most impact categories of WMA are inferior to those achieved by a low recycling rate of 15%. Blankendaal et al. (2014) on the other hand found that WMA compared to HMA can reduce the single score environmental impact with 26 to 39% while adding (extra) 20% RAP to a HMA mixture reduces this environmental impact by only 10 to 13%. Note that it is not clearly described which WMA technique is used, which processes are included, and what analysis period is applied in the LCA analysis of Blankendaal et al. (2014).
Some studies by van Bochove et al. (2012), D'Angelo et al. (2008), Leng & Al-Qadi (2011) and Vidal et al. (2013) indicate the potentially larger use of RAP as a key advantage of WMA.

An important advantage of WMA compared to HMA is the lower diffusion emissions during road construction, which is clearly visible to the naked eye (Finset, 2012; Ventura et al., 2009). This is associated with higher safety for the road workers who work day after day in the fumes of the hot or warm materials. Nevertheless, the advantages of WMA for the human health of the road workers do not show up in the results of the LCA calculations. This is due to the fact that the environmental impact of the production of bitumen or the energy for drying and heating the aggregates is very large and therefore the relative reduction of the diffusion emissions due to the warm mix technology is invisible. Furthermore, some aspects are not included (i.e. increased safety), because at this moment, it is not possible to model it in LCA. Hence it is important to always critically evaluate the results from LCA and even look further than these numerical values.

4 Conclusions

Even though the aim of the study is not to compare the methodology of LCA studies, it is obvious that the results of the studies discussed are difficult to compare since the specific contextual characteristics differ considerably, as seen in Table2. For instance, they include different stages in the life cycle (e.g., including or excluding use phase, end-of-life, etc.) and different aspects of the environmental impacts (e.g., analysis of greenhouse gases or energy consumption opposed to a broad environmental assessment with multiple impact categories). Besides, each road section is unique due to various geotechnical conditions, traffic intensity, etc. Therefore, only the rough trends found in different studies can be compared. As discussed, a specific framework for LCA studies on pavements might reduce such varieties and is therefore important.

The use of RAP in new asphalt mixtures yields significant environmental advantages due to virgin material savings and reduced transport distances. Therefore, it would be beneficial to allow the use of RAP in surface courses of public works, by lifting this ban in the next version of the Flemish Road Standard SB250. Nevertheless, the contamination with tar leads to a significant environmental burden and therefore tar containing RAP should be avoided by removing it from the cycle.
The use of additives in WMA technologies is a determining factor considering the environmental impact. The shift of the environmental impact from the asphalt plant to the producer of additives should be avoided because it might lead to increased life cycle environmental impact. WMA techniques without (impacting) additives are favoured i.e., foam techniques. It is also concludes that the production of asphalt at reduced temperatures (HWMA and WMA) is only environmentally beneficial (reduced energy and emissions) when these mixtures are produced in asphalt plants with adjusted burners.

In general, independent of the asphalt mixture used, the durability of the asphalt pavement is a parameter with a significant effect on the total environmental impact. The service life and hence the intermediate maintenance interval have to be increased if possible. It is therefore recommended to further investigate the service life in practice of asphalt pavements with RAP or produced with various WMA techniques and it is necessary to incorporate this in LCA studies.

Furthermore, it is important to note that the EU ETS only accounts for the emissions due to fuel consumption in particular companies, while it is seen from the current literature review that other interventions might yield more significant reductions of the environmental impact i.e., recycling. A certain asphalt plant may gain beneficial grades in the EU ETS when producing WMA with scarce aggregates and impacting additives. On a life cycle point of view, the environmental impact of such asphalt mixture would be pernicious. Therefore, it might be wondered if there is a need for other regulations in order to encourage environmentally friendly road infrastructure.

It is seen that some Flemish asphalt plants invest in the construction of a shelter in order to protect raw material from rain during storage. In this way, the moisture content of virgin and recycled aggregates might decrease during storage and hence the energy consumption to dry the raw materials might decrease as well. Remaining moisture content in asphalt mixtures negatively affect the mechanical properties of asphalt mixtures and hence the service life of a road pavement. The moisture content of RAP and virgin aggregates should be investigated in practice since it is mandatory in Flanders to use washed virgin aggregates. Consequently, both virgin and recycled aggregates could be very wet when delivered at the asphalt plant. For HWMA and WMA, on the other hand, the risk for remaining moisture in the mixture is due to the lower temperatures and an incomplete evaporation of the water. Other advantage of the sheltered materials are the lower energy consumption for drying and heating aggregates with a lower moisture content and reduced leaching from RAP stockpiles.

5 References

Al-Qadi, I.L., Carpenter, S.H., Roberts, G., Hasan, O., Augangzeb, Q., Elseifi, M., Trepanier, J., 2009. Determination of usable residual asphalt binder in RAP.

Anthonissen, J., Boonen, T., 2012. Fiber reinforced asphalt (Vezelversterkt Asfalt). Artesis Hogeschool Antwerpen.

Anthonissen, J., Braet, J., Van den bergh, W., 2015a. Life cycle assessment of bituminous pavements produced at various temperatures in the Belgium context. Transp. Res. Part D Transp. Environ. 41, 306–317. doi:10.1016/j.trd.2015.10.011

Anthonissen, J., Van den bergh, W., Braet, J., 2014. Cradle-to-Gate Life Cycle Assessment of Recycling and Impact of Reduced Production Temperature for the Asphalt sector in Belgium, in: International Symposion on Pavement LCA 2014. Davis, California, pp. 61–74.

Anthonissen, J., Van Troyen, D., Braet, J., Van den bergh, W., 2015b. Using carbon dioxide emissions as a criterion to award road construction projects: a pilot case in Flanders. J. Clean. Prod. 102, 96–102. doi:10.1016/j.jclepro.2015.04.020

Anthonissen, J., Ven, D., Van Dessel, A., Van den bergh, W., 2013. Preliminary research on the possibilities to reduce CO2 emissions in Flemish asphalt plants (Vooronderzoek naar de mogelijkheden om CO_2-uitstoot en energie te verminderen in Vlaamse asfaltcentrales), in: XXIIste Belgisch Wegencongres van de Belgische Wegenvereniging. Liège, Belgium.

Apeagyei, A.K., Diefenderfer, B.K., Diefenderfer, S.D., 2011. Rutting Resistance of Asphalt Concrete Mixtures that contain Recycled Asphalt Pavement. Transp. Res. Rec. J. Transp. Res. Board 2208, 9–16. doi:10.3141/2208-02

Araújo, J.P.C., Oliveira, J.R.M., Silva, H.M.R.D., 2014. The importance of the use phase on the LCA of environmentally friendly solutions for asphalt road pavements. Transp. Res. Part D Transp. Environ. 32, 97–110. doi:10.1016/j.trd.2014.07.006

AzariJafari, H., Yahia, A., Ben Amor, M., 2016. Life cycle assessment of pavements: Reviewing research challenges and opportunities. J. Clean. Prod. 112, 2187–2197. doi:10.1016/j.jclepro.2015.09.080

Belgian Road Research Centre, 2014. Asphalt plants (Asfaltmenginstallaties).

Blankendaal, T., Schuur, P., Voordijk, H., 2014. Reducing the environmental impact of concrete and asphalt: a scenario approach. J. Clean. Prod. 66, 27–36. doi:10.1016/j.jclepro.2013.10.012

Buncher, B.Y.M., Rosenberger, C., 2005. Understanding the True Economics of Using Polymer Modified Asphalt through Life Cycle Cost Analysis. Asph. Mag. 28–30.

Butt, A.A., Mirzadeh, I., Toller, S., Birgisson, B., 2014. Life cycle assessment framework for asphalt pavements: methods to calculate and allocate energy of binder and additives. Int. J. Pavement Eng.

15, 290–302. doi:10.1080/10298436.2012.718348
Butt, A.A., Toller, S., Birgisson, B., 2015. Life cycle assessment for the green procurement of roads: a way forward. J. Clean. Prod. 90, 163–170. doi:10.1016/j.jclepro.2014.11.068
Buyle, M., Braet, J., Audenaert, A., 2013. Life cycle assessment in the construction sector: A review. Renew. Sustain. Energy Rev. 26, 379–388. doi:10.1016/j.rser.2013.05.001
Carlson, A., 2011. Life cycle assessment of roads and pavements - Studies made in Europe. Linköping, Sweden.
Colbert, B., You, Z., 2012. The determination of mechanical performance of laboratory produced hot mix asphalt mixtures using controlled RAP and virgin aggregate size fractions. Constr. Build. Mater. 26, 655–662. doi:10.1016/j.conbuildmat.2011.06.068
COPRO, 2015. Activity Report 2014 (Activiteitenverslag 2014).
COPRO, 2014. Activity Report 2013 (Activiteitenverslag 2013).
COPRO, 2013. Activity Report 2012 (Activiteitenverslag 2012).
D'Angelo, J., Harm, E., Bartoszek, J., Baumgardner, G., Corrigan, M., Cowsert, J., Harman, T., Jamshidi, M., Jones, W., Newcomb, D., Prowell, B., Sines, R., Yeaton, B., 2008. Warm-Mix Asphalt : European Practice. Alexandria, Virginia.
Departement Leefmilieu Natuur en Energie, 2014. Carbon Credit (Emissiehandel) [WWW Document]. URL http://www.lne.be/themas/klimaatverandering/co$_2$-emissiehandel/vaste-installaties-1 (accessed 5.19.14).
EAPA, 2008. Arguments to stimulate the government to promote asphalt reuse and recycling.
Enell, A., Wayman, M., McNally, C., Wik, O., Andersson-Sköld, Y., Bergman, R., Parry, T., Huang, Y., Raaberg, J., Quinn, A., Ličbinský, R., Huzlík, J., Jandová, V., 2012. Environmental Performance of Reclaimed Asphalt – Final Report.
EPD International, n.d. Product Category Rules (PCR) [WWW Document]. URL http://environdec.com/en/PCR/?id=236&epslanguage=en (accessed 2.18.16).
European Asphalt Pavement Association, 2015. Asphalt in Figures 2014. Brussels.
European Asphalt Pavement Association, 2014. Asphalt in Figures 2013. Brussels.
European Asphalt Pavement Association, 2013. Asphalt in Figures 2012. Brussels, Belgium.
European Union, 2015. EU transport in figures - statistical pocketbook [WWW Document]. doi:10.2832/90922
European Union, 2013. The EU Emissions Trading System (EU ETS). doi:10.2834/55480
Finset, J.B., 2012. Low Temperature Asphalt - Norwegian project. Nynäshamn.
FOD Mobiliteit en Vervoer, 2011. Lengte van het Belgische wegennet [WWW Document]. URL http://mobilit.belgium.be/nl/mobiliteit/mobiliteit_cijfers/evolutie_wegennet (accessed 9.19.15).
Giani, M.I., Dotelli, G., Brandini, N., Zampori, L., 2015. Comparative life cycle assessment of asphalt pavements using reclaimed asphalt, warm mix technology and cold in-place recycling. Resour. Conserv. Recycl. 104, 224–238. doi:10.1016/j.resconrec.2015.08.006
Glanzman, T., 2005. Quantifying the Benefits of Polymer Modified Asphalt. Asph. Mag. 18–20.
Gschösser, F., Wallbaum, H., Adey, B.T., 2014. Environmental analysis of new construction and maintenance processes of road pavements in Switzerland. Struct. Infrastruct. Eng. 10, 1–24. doi:10.1080/15732479.2012.688977
Gschösser, F., Wallbaum, H., 2013. Life Cycle Assessment of Representative Swiss Road Pavements for National Roads with an Accompanying Life Cycle Cost Analysis. Environ. Sci. Technol. 47, 8453–8461. doi:10.1021/es400309e
Hill, B., 2011. Performance evaluation of warm mix asphalt mixtures incorporating reclaimed asphalt pavement. University of Illinois.
Huang, B., Li, G., Vukosavljevic, D., Shu, X., Egan, B.K., 2005. Laboratory Investigation of Mixing Hot-Mix Asphalt with Reclaimed Asphalt Pavement. Transp. Res. Rec. J. Transp. Res. Board 1929, 37–45.

doi:10.3141/1929-05

Huang, Y., Bird, R.N., 2007. Life Cycle Assessment of Use of Recycled Materials in Asphalt Pavements. Newcastle University.

Huang, Y., Bird, R.N., Bell, M., 2009. A comparative study of the emissions by road maintenance works and the disrupted traffic using life cycle assessment and micro-simulation. *Transportation Research Part D: Transport and Environment*, *14*(3), 197–204. http://doi.org/10.1016/j.trd.2008.12.003

Hurley, G.C., Prowell, B.D., Kvasnak, A.N., 2009. Ohio field trial of warm mix asphalt technologies: Construction Summary. Auburn, Alabama.

ISO 14025, 2006. Environmental labels and declarations - Type III environmental declarations - Principles and procedures. Geneva.

ISO 14040, 2006. Environmental management - Life cycle assessment - Principles and framework. Geneva.

ISO 14044, 2006. Environmental management - Life cycle assessment - Requirements and guidelines. Geneva, Switserland.

Jullien, A., Monéron, P., Quaranta, G., Gaillard, D., 2006. Air emissions from pavement layers composed of varying rates of reclaimed asphalt. Resour. Conserv. Recycl. 47, 356–374. doi:10.1016/j.resconrec.2005.09.004

Kaloush, K.E., Zeiada, W.A., Biligiri, K.P., Reed, J., 2010. Evaluation of Fiber-Reinforced Asphalt Mixtures Using Advanced Material Characterization Tests. J. Test. Eval. 38. doi:10.1520/JTE102442

Kluts, I., Miliutenko, S., 2012. Overview of road infrastructure planning process and the use of Environmental Assessments in the Netherlands and Sweden. Stockholm.

Legret, M., Odie, L., Demare, D., Jullien, a, 2005. Leaching of heavy metals and polycyclic aromatic hydrocarbons from reclaimed asphalt pavement. Water Res. 39, 3675–3685. doi:10.1016/j.watres.2005.06.017

Leng, Z., Al-Qadi, I., 2011. Comparative Life Cycle Assessment between Warm SMA and Conventional SMA. Champaign, Illinois.

Leyssens, D., Verstappen, B., Huybrechts, D., 2013. Best available techniques for asphalt plants (Beste Beschikbare Technieken voor asfaltcentrales). BBT-kenniscentrum VITO, Mol.

Li, X., Marasteanu, M.O., Williams, R.C., Clyne, T.R., 2008. Effect of Reclaimed asphalt Pavement (Proportion and Type) and Binder Grade on Asphalt Mixtures. Transp. Res. Rec. J. Transp. Res. Board 2051, 90–97. doi:10.3141/2051-11

Lopes, M., Gabet, T., Bernucci, L., Mouillet, V., 2015. Durability of hot and warm asphalt mixtures containing high rates of reclaimed asphalt at laboratory scale. Mater. Struct. 48, 3937–3948. doi:10.1617/s11527-014-0454-9

Mallick, R.B., Kandhal, P.S., Bradbury, R.L., 2008. Using Warm-Mix Asphalt Technology to Incorporate High Percentage of Reclaimed Asphalt Pavement Material in Asphalt Mixtures. Transp. Res. Rec. J. Transp. Res. Board 2051, 71–79. doi:10.3141/2051-09

Mogawer, W., Bennert, T., Daniel, J.S., Bonaquist, R., Austerman, A., Booshehrian, A., 2012. Performance characteristics of plant produced high RAP mixtures. Road Mater. Pavement Des. 13, 183–208. doi:10.1080/14680629.2012.657070

Muench, S.T., 2010. Roadway Construction Sustainability Impacts. Transp. Res. Rec. J. Transp. Res. Board 2151, 36–45. doi:10.3141/2151-05

National Technology Development, 2009. Quantify the Energy and Environmental Effects of Using Recycled Asphalt and Recycled Concrete for Pavement Construction. New York, USA.

Nicuţă, A.-M., 2011. Life Cycle Assessment study for new and recycled asphalt pavements.

Rubio, M. del C., Moreno, F., Martínez-Echevarría, M.J., Martínez, G., Vázquez, J.M., 2013. Comparative analysis of emissions from the manufacture and use of hot and half-warm mix asphalt. J. Clean. Prod. 41, 1–6. doi:10.1016/j.jclepro.2012.09.036

Rubio, M.C., Martínez, G., Baena, L., Moreno, F., 2012. Warm mix asphalt: an overview. J. Clean. Prod. 24,

76–84. doi:10.1016/j.jclepro.2011.11.053
Santero, N., Masanet, E., Horvath, A., 2010. Life Cycle Assessment of Pavements: A Critical Review of Existing Literature and Research. Skokie, Illinois, USA.
Santero, N.J., Harvey, J., Horvath, A., 2011a. Environmental policy for long-life pavements. Transp. Res. Part D Transp. Environ. 16, 129–136. doi:10.1016/j.trd.2010.09.005
Santero, N.J., Masanet, E., Horvath, A., 2011b. Life-cycle assessment of pavements Part II: Filling the research gaps. Resour. Conserv. Recycl. 55, 810–818. doi:10.1016/j.resconrec.2011.03.009
Santero, N.J., Masanet, E., Horvath, A., 2011c. Life-cycle assessment of pavements. Part I: Critical review. Resour. Conserv. Recycl. 55, 801–809. doi:10.1016/j.resconrec.2011.03.010
Shen, J., Amirkhanian, S., Aune Miller, J., 2007. Effects of Rejuvenating Agents on Superpave Mixtures Containing Reclaimed Asphalt Pavement. J. Mater. Civ. Eng. 19, 376–384. doi:10.1061/(ASCE)0899-1561(2007)19:5(376)
Shu, X., Huang, B., Shrum, E.D., Jia, X., 2012. Laboratory evaluation of moisture susceptibility of foamed warm mix asphalt containing high percentages of RAP. Constr. Build. Mater. 35, 125–130. doi:10.1016/j.conbuildmat.2012.02.095
Stripple, H., Erlandsson, M., 2004. Methods and Possibilities for Application of Life Cycle Assessment in Strategic Environmental Assessment of Transport Infrastructures. Stockholm.
Swamy, A.K., Mitchell, L.F., Hall, S.J., Daniel, J.S., 2011. Impact of RAP on the Volumetric, Stiffness, Strength, and Low-Temperature Properties of HMA. J. Mater. Civ. Eng. 23, 1490–1497. doi:10.1061/(ASCE)MT.1943-5533 .0000245.
Tapsoba, N., Sauzéat, C., Benedetto, H. Di, Baaj, H., Ech, M., 2012. Low-Temperature Cracking of Recycled Asphalt Mixtures, in: 7the RILEM International Conference on Cracking in Pavements. pp. 1261–1270.
Tatari, O., Nazzal, M., Kucukvar, M., 2012. Comparative sustainability assessment of warm-mix asphalts: A thermodynamic based hybrid life cycle analysis. Resour. Conserv. Recycl. 58, 18–24. doi:10.1016/j.resconrec.2011.07.005
van Bochove, G. Van, Bolk, H., Poncelet, K., Lecomte, M., 2012. Lowering the production temperature of asphalt while incorporating a high proportion of recycled material, in: 5the Eurasphalt & Eurobitume Congress, 13-15th June 2012, Istanbul.
Van den bergh, W., Reynaert, R., De Jonghe, A.C., 2008. Aged-bitumen bound base structure (aB^3): state of the art 2007, in: 4th Euroasphalt and Eurobitume Congress 2008. Copenhagen, Denmark, pp. 1467–1474.
Van den bergh, W., Stoop, J., 2009. The Development of an aged-Bitumen Bound Base Structure with Roofing Waste and Reclaimed Asphalt Pavement: State of the Art 2009., in: Enviroad Congress. Warschau, Poland.
Van den bergh, W., Vuye, C., Swenters, F., 2013. The use of bituminous waste material in road construction (in Dutch), in: XXIIste Belgisch Wegencongres van de Belgische Wegenvereniging. Liège, Belgium.
van den Berk, M., 2004. Calculation of energy savings due to recycling of asphalt (Berekening Energiebesparing door Recycling van Asfalt). Utrecht.
Van Gelder, 2012. Analyse en detailanalyses van GHG genererende activiteiten.
Ventura, A., Jullien, A., 2009. Life cycle assessment applied to road pavements : an analysis of method and results relevancy, in: The Sixth International Conference on Maintenance and Rehabilitation of Pavements and Technological Control. Torino, Italy, pp. 1210–1219.
Ventura, A., Monéron, P., Jullien, A., 2008. Environmental Impact of a Binding Course Pavement Section, with Asphalt Recycled at Varying Rates. Road Mater. Pavement Des. 9, 319–338. doi:10.3166/RMPD.9HS.319-338
Ventura, A., Monéron, P., Jullien, A., Tamagny, P., Zavan, D., 2009. Environmental comparison at industrial scale of hot and half- warm mix asphalt manufacturing processes, in: Transportation Research Board 88th Annual Meeting. Washington DC, p. 12.

Vidal, R., Moliner, E., Martínez, G., Rubio, M.C., 2013. Life cycle assessment of hot mix asphalt and zeolite-based warm mix asphalt with reclaimed asphalt pavement. Resour. Conserv. Recycl. 74, 101–114. doi:10.1016/j.resconrec.2013.02.018

Vlaamse Overheid, 2014. Flemish Road Standard (Standaardbestek 250 voor de wegenbouw) versie 3.1.

Wayman, M., Andersson-Sköld, Y., Bergman, R., Huang, Y., Parry, T., Raaberg, J., Enell, A., 2012. Life Cycle Assessment of Reclaimed Asphalt.

Wen, H., Lu, J., VanReken, T.M., 2014. Modeling the Effects on Energy and Carbon Dioxide from the Use of Recycled Asphalt Pavement in Hot Mix Asphalt. Int. J. Sustain. Transp. 8, 249–261. doi:10.1080/15568318.2012.662579

Yildirim, Y., 2007. Polymer modified asphalt binders. Constr. Build. Mater. 21, 66–72. doi:10.1016/j.conbuildmat.2005.07.007

Yu, B., Lu, Q., 2012. Life cycle assessment of pavement: Methodology and case study. Transp. Res. Part D Transp. Environ. 17, 380–388. doi:10.1016/j.trd.2012.03.004

Zhang, J., 2010. Effects of Warm-mix Asphalt Additives on Asphalt Mixture Characteristics and Pavement Performance. University of Nebraska-Lincoln.

Zhao, S., Huang, B., Shu, X., Jia, X., Woods, M., 2012. Laboratory Performance Evaluation of Warm Mix Asphalt containing High Percentages of RAP. Transp. Res. Rec. J. Transp. Res. Board 98–105.

Zhao, S., Huang, B., Shu, X., Woods, M., 2013. Comparative evaluation of warm mix asphalt containing high percentages of reclaimed asphalt pavement. Constr. Build. Mater. 44, 92–100. doi:10.1016/j.conbuildmat.2013.03.010