SUSTAINABILITY ASSESSMENT OF RECYCLED ASPHALT MIXTURES IN TEXAS

by

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Abstract

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The pavement practitioners use more recycled materials in asphalt mixtures in order to compensate for the high price of petroleum products and save the limited resources of virgin materials. Reclaimed Asphalt Pavement (RAP) and Recycled Asphalt Shingles (RAS) have been in wide use in asphalt mixtures for several decades. Public perception on the utilization of recycled materials is that the mixtures become more cost effective and more environmental friendly. This is true when the initial stage of construction of pavements is assessed. However, a mixture that costs less and/or burdens the environment less at the beginning may require more frequent rehabilitation because of poor performance. Therefore, in order to have a comprehensive idea of the sustainability of a mixture, its entire life cycle should be evaluated.

The objective of this research was to assess the sustainability of three recycled asphalt mixtures and of a mix not containing recycled materials. The recycled mixtures were labeled as “High RAP”, “RAP&RAS-WMA” and “BMD”. The “High RAP” mixture had 19 percent fractionated RAP. The “RAP&RAS-WMA” had 15 percent RAP

and 3 percent RAS while the production technology was WMA. The “BMD” mixture had 15 percent RAP, 3 percent RAS and slightly higher binder content. The virgin mixture was “Type D” which is a common dense-graded mixture in Texas.

Twelve pavement sections were constructed from these four mixtures to evaluate their resistance to rutting, fatigue cracking and reflection cracking. The Accelerated Pavement Testing machine of the University of Texas at Arlington was employed to perform the full-scale testing. The results of field sections were then utilized to determine the service life of the mixtures for initial construction and subsequent required overlays. The life cycle environmental burden and cost of each mixture were also calculated.

Field results suggested that rutting is not a concern for these mixtures. The virgin control mixture had the second best performance in resistance to both fatigue cracking and reflection cracking. The life cycle environmental assessment of mixtures showed that the “BMD” mixture had the least environmental impacts and was followed by the “Type D”, the “RAP&RAS-WMA” and the “High RAP” mixtures. The same ranking of mixtures was observed in life cycle cost analysis. Among different construction phases, the “Materials Production” phase had the highest energy consumption and carbon dioxide emission, mainly due to the bitumen production process.

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List of Acronyms

AASHTO	American Association of State Highway Officials
APA	Asphalt Pavement Analyzer
APT	Accelerated Pavement Testing
ABR	Asphalt Binder Replacement
BBR	Bending Beam Rheometer
BMD	Balanced Mix Design
CDOT	Colorado Department of Transportation
CRCP	Continuously Reinforced Concrete Pavement
DSR	Dynamic Shear Rheometer
EIA	Energy Information Administration
EIO	Economic Input-Output
EPA	Environmental Protection Agency
EUAC	Equivalent Uniform Annualized Cost
FHWA	Federal Highway Administration
FWD	Falling Weight Deflectometer
GHG	Greenhouse Gases
GWP	Global Warming Potential
HMA	Hot Mix Asphalt
HWTT	Hamburg Wheel Tracking Test
IDOT	Illinois Department of Transportation
IDT	Indirect Tensile Strength
INDOT	Indiana Department of Transportation
IO	Input-Output
JCP	Jointed Concrete Pavement
JRCP	Jointed Reinforced Concrete Pavement
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LCCA	Life Cycle Cost Analysis
LCI	Life Cycle Inventory
LCM	Life Cycle Management
LTPP	Long Term Pavement Performance

M&R	Maintenance and Rehabilitation
MEPDG	Mechanistic Empirical Pavement Design Guide
MnDOT	Minnesota Department of Transportation
MWAS	Manufacturing Waste Asphalt Shingles
NAPA	National Asphalt Pavement Association
NCAT	National Center for Asphalt Technology
NESHAP	National Emissions Standards for Hazardous Air Pollutants
NMAS	Nominal Maximum Aggregate Size
NPV	Net Present Value
OAC	Optimum Asphalt Content
OT	Overlay Tester
PAH	Polycyclic Aromatic Hydrocarbon
RAP	Reclaimed Asphalt Pavement
RAS	Recycled Asphalt Shingles
SCB	Semi-Circular Bending
SMA	Stone Matrix Asphalt
TOAS	Tear-Off Asphalt Shingles
TRA	Total Recycle Asphalt
TTI	Texas A&M Transportation Institute
TXDOT	Texas Department of Transportation
WMA	Warm Mix Asphalt

CHAPTER 1

INTRODUCTION

1.1 Introduction

Discovery of oil in Pennsylvania, Texas and a few other states of the USA had been keeping the cost of virgin binder lower than the processing of reclaimed asphalt pavements (RAP) until 1970s, when the international oil crises quadrupled the price of crude oil (EIA 2015). This drastic increase coincided with the US oil production decline which made the asphalt industry seeking methods to incorporate RAP into construction and rehabilitation of pavements to cut the cost. By these methods, the new mixtures become cheaper as they need less virgin aggregates and bitumen, both to be produced and to be transported to plant. From the environmental prospect, less landfill space is occupied for disposal of used pavement materials, the demand for non-renewable resources becomes less, and also the reduction in energy consumption for extraction and transportation of virgin materials decreases the emission of greenhouse gases (GHG).

Another material for recycling and use in asphaltic pavements is asphalt shingles. These materials constitute two-thirds of the roofing market in the US, which is estimated to have an annual generation of 7 to 10 million tons of shingle tear-off wastes and 750,000 to 1 million tons of manufacturing shingle scraps. Since 19 to 36 percent of the total weight of them comes from asphalt cement, Recycled Asphalt Shingle (RAS) has emerged to be another source of black gold for paving industry (NAHB 1998). In 2013, National Asphalt Pavement Association (NAPA) estimated an annual production of 350

million tons of asphalt mixtures, out of which 68 and 1.6 million tons come from RAP and RAS, respectively. Considering only the recovered binder in the RAP and RAS, cost saving of about $2.23 billion is anticipated (Hansen and Copeland 2014).

Aside from the utilization of recycled materials, one of the sustainable practices in pavement industry is the Warm Mix Asphalt (WMA) technology which is currently used about 30 percent of asphalt mixtures. By either dispersing the bitumen (consequently improving the aggregate coating) or lowering its viscosity, WMA technology lowers the required compaction and mixing temperatures (50 to 100ºF) which reduces fuel consumption and consequently the emissions. Moreover, the exposure of mixture to lower temperatures reduces the aging of bitumen. This makes the incorporation of higher percentages of RAP and RAS feasible. Enhancing compaction, resisting longer haul distances and extending the paving season are other benefits of WMA technology.

Texas Department of Transportation (TXDOT) has been using asphalt recycling for a long time and has published special provisions for designing such mixtures. However, the performance of many in-service mixtures was not always satisfactory. When it comes to RAS and WMA mixtures, there are not even enough sections available to assess the long term behavior. It seems that there is an urgent need for comprehensive study of different RAP/RAS/WMA mixtures to validate the specifications of TXDOT.

1.2 Problem Statement

In spite of encouraging benefits of using RAP, RAS and WMA technology, some mixtures do not have satisfactory performance. Therefore, the specifications for the

design of these mixtures require thorough investigation. The inclusion of RAP and RAS in asphalt mixtures increases the rutting resistance due to the constituent stiff aged binder, while it makes the mixture more prone to cracking. In order to limit the further ageing of bitumen of RAP and RAS during production, these materials are introduced into the drum farther from the flame thus overheating of virgin aggregates should compensate this temperature deficiency. This practice necessitates excessive fuel consumption. Another problem with the use of recycled materials is the potential leachate of certain constituents into soil and groundwater. As it can be seen, some disadvantages of these mixtures can counterbalance their economic and environmental merits, making the assessment of cost and environmental burdens of recycled mixtures not very straightforward.

WMA is expected to improve the compactability of mixtures and hence achieving a uniform construction. However, the blending of aged RAP/RAS binder with virgin binder at lower temperatures may not be very effective. Clarifying this uncertainty demands more research as a variety of WMA technologies are currently approved by roadway officials.

Although the laboratory testing of mixtures is done under a fully controlled environmental condition and it is way less expensive than field testing, the outcomes are not always conclusive (if not contradictory) which raises doubts to repeatability of the results. This may happen due to the vast variability within recycled materials which come from various locations with different environmental conditions and degrees of ageing. Thus, it seems that the testing should be localized to a specific region which more or less has recycled materials with similar properties.

Aside from all of the technical advantages and disadvantages of recycled mixtures, one should pay close attention to the life-time of the pavement structure built with these mixtures. A mixture may seem to be more cost-effective and environmental friendlier than another while its service life is shorter. This means more maintenance and rehabilitation (M&R) activities would be needed during the analysis period. Therefore, the performance of different mixtures should be evaluated side-by-side to determine the frequency of M&R activities. Considering all of these aspects in a thorough environmental Life Cycle Assessment (LCA) and Life Cycle Cost Analysis (LCCA) can reveal the superiority of one mixture to another. As this is a rather new field of research in pavement engineering, there are very limited studies available in the literature and such studies are mostly based on hypothetical scenarios of pavement performance, rather than measured performance on real situations. Expanding the knowledge in this field can help the decision making officials evaluate the suitability of different approaches for the construction of pavements.

1.3 Research Objectives

This research aims to compare three asphalt mixtures containing recycled materials with a virgin control mixture in terms of field performance, environmental impacts and cost. The amount of recycled materials in each mixture is close to the maximum allowable values by TXDOT, which also allows the validation of TXDOT specifications.

With the help of the University of Texas at Arlington (UTA) Accelerated Pavement Testing (APT) facility, the performance of sections built with these mixtures

can be evaluated for resistance to rutting, fatigue cracking and reflection cracking. Moreover, LCA and LCCA of these mixtures will be investigated. At the end of testing, it will be possible to rank these mixtures based on their environmental impact and cost.

This study shows the environmental friendliness and cost effectiveness of multiple recycled asphalt mixtures for their entire life cycle. The performance of the mixtures during the analysis period is considered in the life cycle assessments. It includes the actual field performance of initially constructed sections as well as subsequent overlays. This aspect of pavements has been neglected in many former studies.

The share of each construction phase in the environmental burden of a pavement project is determined. The phase that has higher energy consumption or emits higher GHGs is spotted. The same is done for different constituents of an asphalt mixture. The share of the production of bitumen, aggregates or recycled materials is presented. This helps in identifying the section at which further optimization and investment can yield more influential results.

The outcomes of this study give a better insight of the sustainability of recycled asphalt mixtures to the paving industry of Texas.

1.4 Dissertation Organization

This dissertation is presented in six chapters. Chapter One introduces the need for research and states the current problems of this field of study, the objectives of research and how its results contribute to better understanding of the sustainability of recycled asphalt mixtures.

Chapter Two provides the characteristics of recycled materials of RAP and RAS and introduces some of the methods of Warm Mix Asphalt technology. Moreover, a review of the literature on lab testing and field testing of recycled asphalt mixtures is made.

Chapter Three explains the different approaches of life cycle assessment and introduces some of the available tools for environmental burden and cost analyses. It describes in detail the workflow of the programs used in this study for life cycle assessment. Additionally, a review of the published literature on life cycle analyses of the asphalt mixtures is provided.

Chapter Four introduces the UTA APT facility and provides the details of field sections and mixture compositions. It also presents the results of field testing of pavement sections as well as the post mortem investigations. This chapter includes the ranking of mixtures based on their field performance.

Chapter Five shows the frequency of required rehabilitation for each mixture. The energy consumption and emissions of a variety of GHG for the life cycle of mixtures are presented. The construction phase and the asphalt mixture components that incur more impact to the environment are introduced. The cost of mixtures in their entire life cycle is estimated. Finally, the mixtures are ranked based on their environmental friendliness and cost effectiveness.

Chapter Six summarizes the conducted activities for this research. It also includes the conclusions of the study along with the recommendations for future investigations.

CHAPTER 2

RECYCLED MIXTURES: BACKGROUND AND REVIEW OF LITERATURE

For the last four decades, RAP has been used extensively in the construction of new pavements. Therefore, numerous studies have been conducted to reveal the effects of RAP on the performance of new mixtures. However, the use of RAS and WMA technology are relatively new phenomena in asphalt industry. Consequently, high volume of current research projects is focused to determine the behavior and performance of such mixtures.

Results of some of studies suggest that the performance of asphalt mixtures may have been compromised by the introduction of recycled materials (Hajj et al. 2007, Mallick et al. 2008). This requires a new set of investigations to show if such mixtures are still economic and environmental friendly in a long run, rather than just looking at the initial construction level. LCA and LCCA studies are gaining more importance than before as a result of these concerns. The results of such analyses can provide a better picture of the advantages and disadvantages of these new practices.

In this chapter, the characteristics, design procedure, laboratory and field performance studies of mixtures containing RAP and RAS along with WMA technology are presented. This will provide better insight into current findings and existing uncertainties about the performance of various recycled asphalt mixtures.

2.1 Characteristics of RAP Materials

The variability in RAP materials was one of the main reasons for their limited use in asphalt mixtures by state DOTs, in spite of noticeable economic benefits. Zhou et al. (2010) studied the RAP stockpiles in Texas and described the potential sources of variability as following:

- RAP may constitute the materials from all layers of the old pavement (from surface course to even subgrade soil) plus any further maintenance treatments, such as chip seal, patches, etc.
- A stockpile may include materials from multiple projects with different design
- Waste trial batches of asphalt or deleterious materials may exist in any stockpile

Fortunately, space is not a limitation in Texas, thus materials from different projects are mostly collected in separate stockpiles. This is one of the best practices for eliminating variability.

Another useful practice in reducing variability is RAP fractionation. As stated in Zhou et al. (2010), "Fractionating RAP is the act of processing it to screen, crush, size, and separate the various sizes into stockpiles that are more consistently uniform in size and composition". In Texas, most contractors crush and fractionate RAP into single maximum size of either 3/8 inch or 1/2 inch so it can be used mostly for asphalt overlay mixes (dense-graded Type C or D). However, over-processing should be avoided as it generates too much fines (passing sieve #200) despite that it seems theoretically better to have finer RAP particles (Zhou et al. 2010).

2.1.1 Binder in RAP

The main problem associated with using RAP is the constituent stiff aged binder in the RAP. During the aging process, binder loses its lighter components. The increased proportion of asphaltenes results in significant rheological behavior change, including higher stiffness, higher viscosity, and lower ductility (Al-Qadi et al. 2007). The binder's life can be separated into two different periods. As the binder is mixed with the aggregates, transported to the site and laid down, which all happen under high temperatures, the major portion of aging is incurred (Zaumanis and Mallick 2015). This period is known as short-term aging and is considered to occur due to oxidation, volatilization and absorption of oily constituents, resins and asphaltenes by aggregates. The second period of binder aging, which is known as long-term, occurs during its service life. The mechanisms of aging at this stage include oxidation, polymerization, photo-oxidation (only for surface layers), thixotropy and syneresis (Read and Whiteoak 2003, Al-Qadi et al. 2007, Roberts et al. 2009). Some other influential factors in binder aging are the void content of mixtures, the layer position, the level of damage of the recycled pavement and stockpiling management (Al-Qadi et al. 2007, Zaumanis and Mallick 2015, McMillan and Palsat 1985, Zhou et al. 2010):

- Higher void content of asphaltic pavements facilitates the circulation of air through the mixture, hence increases aging.
- For surface courses, the exposure to fresh air is higher, thus their bitumen hardens faster than in the underlying layers.

- If the pavement prior to recycling had greater damages, the change in binder properties is higher.
- Large horizontal stockpiles trap moisture and have the RAP exposed to air more than tall conical stockpiles.

The aging process results in a PG grade for RAP binder that is higher than what it used to be prior to production. Based on the observations of multiple researchers, the high end PG grade of RAP binder should be expected to be between 82°C and 115°C (Romanoschi and Scullion 2014).

Zhou et al. (2013) reviewed three studies on RAP binder blending, performed by D' Angelo et al. (2011), Bonaquist (2007) and Copeland et al. (2010a), and inferred that, in most cases, the virgin binder coats RAP as a whole and forms a composite rather than having the RAP binder melt and blend with virgin binder. It was also inferred that the composite effect can provide properties similar to blended situation, thus 100% blending may not be necessary. In this case, the Bonaquist approach that compares the dynamic moduli of mixture and its recovered binder to determine 100 percent blending will be invalid as the comparison of such property cannot be a basis for determination of blending.

2.1.2 Compensating for Aged Stiff Binder of Recycled Materials

The aged stiff binder of recycled materials is usually addressed in several ways. The most common option is dumping the binder grade. It means that the desired grade is achieved by blending a softer binder with the recycled binder. This is usually based on the

assumption of full blending of recycled binder. Other practices include lowering the viscosity and restoring the properties of aged binder with the help of softening and rejuvenating agents, respectively (Roberts et al. 2009). Flux oil, lube stock and slurry oil are examples of softening agents while lubricating and extender oils with high maltene constituents are considered as rejuvenating agents (Terrel and Epps 1989).

Carpenter and Wolosick (1980) showed that the blending of rejuvenating agent and the aged binder is a time-consuming process which does not finish entirely in the mixing and construction stage. Due to great influence of this agent on asphalt mixture properties, special care should be given to HMA if it is expected to be in service in a short time.

The efficacy of rejuvenators in restoring the resistance to cracking of the recycled mixtures has been proven by Tran et al. (2012). They showed that for recycled mixtures including RAP and RAS, the optimum amount of rejuvenator is approximately 12% of the weight of the total binder. This percentage of rejuvenator restored the resistance to fatigue cracking, reflection cracking and top-down cracking while it did not jeopardize the performance in rutting or moisture damage tests.

2.2 Characteristics of RAS Materials

The asphalt roofing industry manufactures two primary roofing substrates of organic (paper felt) and fiberglass, each requiring a different saturation process (EPA 2015). Basic components of asphalt shingles are given in Table 2-1.

Since the shingles are expected to maintain their solid state under hot sunshine, the utilized asphalt cement is very stiff. However, the stiffness of typical asphalts (even AC-5) may not satisfy the requirements. To overcome this problem, air is bubbled through a liquid asphalt flux at 260°C (500°F) for 1 to 10 hours during the manufacturing process. The air blowing is continued until the desired properties are achieved. As the consequence of this process, chemical reactions which occur due to heat and oxygen age asphalt cement excessively and make it stiffer (Zhou et al. 2013, EPA 2015). Subsequently, the shingles become more oxidized and stiffer after several years of service under sun.

Table 2-1. Asphalt Shingles Components (NAHB 1998)

Material		**% by Weight**
Fiberglass or Cellulose Felt Backing		2 - 15
Asphalt Cement	Fiberglass Mat Base	19 – 22
	Cellulose Felt Base	30 - 36
Mineral Granules (Aggregate)		20 – 38
Mineral Filler/Stabilizer		8 – 40

2.2.1 RAS Characteristics in Pavement Engineering

The roofing industry still grades asphalt based on penetration and Ring-Ball softening point (Zhou et al. 2013). However, these approaches are no longer common in the pavement industry and have been mostly replaced by Superpave performance grading system (i.e. PG-System). Maybe the most comprehensive RAS characterization has been done by Texas Transportation Institute (TTI), which was published on July 2013. Zhou et al. (2013) investigated the HMA mixtures containing RAS for following purposes:

- Binder characterization and blending charts for virgin/RAS binders,
- Impact of RAS content on Optimum Asphalt Content (OAC) and engineering properties of RAS mixes, and
- Approaches for improving cracking resistance of RAS mixes.

They observed that extremely high mixing (or production) temperature is needed in order to have the binder of Manufacturing Waste Asphalt Shingles (MWAS) melt and coat virgin aggregates efficiently (around 130°C), while the Tear-off Asphalt Shingles (TOAS) did not show much melting and coating effect, even at temperature of 200°C (392°F). Nevertheless, they reported the average high temperature PG as 131°C (267.8°F) for MWAS and 178°C (352.4°F) for TOAS. This was made based on the results of 10 samples from different sources, as presented in Figure 2-1. Since MWAS and TOAS constitute binders with noticeably different grades, it is recommended that the contractors separate the stockpiles of these materials.

In order to investigate the blending of virgin and RAS binder, they evaluated blends of three virgin and four RAS binders in four different combinations with various

percentages through Dynamic Shear Rheometer (DSR) and Bending Beam Rheometer (BBR) tests. They concluded that linear blending can be assumed as long as the RAS recovered binder is below 30 percent of total binder. Approximately, adding 20 percent of RAS binder raises the low temperature PG for at least one grade, e.g. PG xx-22 changes to PGxx-16 (or even PGxx-10). Thus, PGxx-28 is recommended as virgin binder if PGxx-22 is finally desired.

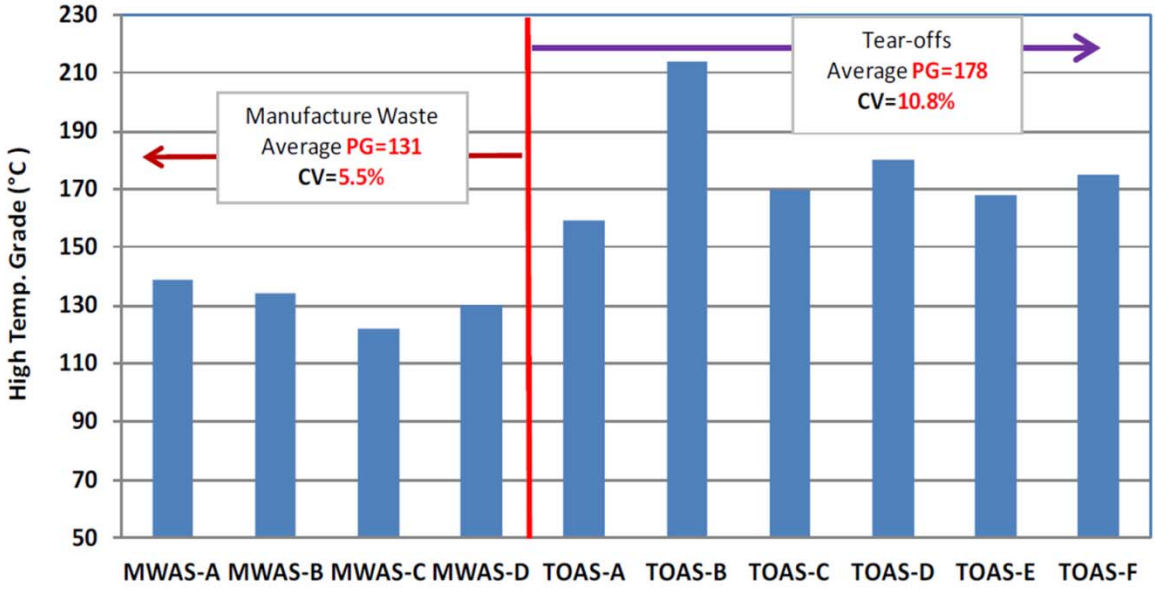


Figure 2-1. High Temperature Grades of RAS Binders: MWAS and TOAS (Zhou et al. 2013)

It should be mentioned that 20 percent RAS binder is achieved when roughly 5 percent of RAS material (by weight of total mixture) is added. The one grade loss at low temperature has also been observed in studies of other researchers (Maupin 2008, McGraw et al. 2010, Scholz 2010). However, at high end grade or whenever RAP is

added, results are no longer consistent (Williams et al. 2013). For mix design purposes, the percentage of RAS binder contributing to the final blended binder (i.e. the availability factor) may be assumed to be around 75%, as found by Tran et al. (2012).

Zhou et al. (2013) also investigated the effect of degree of blending on engineering properties. In order to get a mixture with 100% binder blending, they extracted and recovered the RAS binder in advance and then manually mixed with virgin binder. Additionally, they prepared a mixture through normal procedures in plant. The mixtures were then tested with Hamburg Wheel Tracking Tests (HWTT) and Overlay Tester (OT) to determine rutting and cracking resistances. They compared the results and observed no improvement in such properties for the 100% blending mixture.

They also investigated the impact of RAS on OAC through four different mixtures, made of three RAS percentages (0, 3% and 5%) and two different virgin binder grades (PG64-22 and PG70-22). They concluded that OAC increases as the RAS content increases. This is because the RAS binder is stiff and it leads to higher composite PG grade. In order to achieve the desired viscosity, if the same mixing and compaction temperatures are intended, the amount of virgin binder should be increased.

Zhou et al. (2013) evaluated the engineering properties of RAS mixtures through Dynamic Modulus tests, HWTT and OT. They observed that the use of RAS has no influence on dynamic moduli, improves the rutting/moisture resistance, but drastically decreases the cracking resistance. They found that using a soft binder and increasing the design density can improve the cracking resistance of RAS mixes to some extent. However from rutting/moisture damage perspective, using a soft binder was superior to

increasing the design density. It is noteworthy to mention, they observed the cracking resistance of MWAS mixtures to be much better than that of TOAS mixtures.

2.2.2 Environmental Concerns over RAS Usage in Pavement

There are no more environmental concerns over the constituents of MWAS as asbestos was banned to be used after mid-1980s (Townsend et al. 2007). However, post-consumer shingles from old buildings or the other products used in roofing such as mastic or roofing tar may still have some asbestos. National Emissions Standards for Hazardous Air Pollutants (NESHAP) does not allow ground recycling of any material with more than 1% asbestos. Therefore, shingle recycling facilities are required to obtain and test a sample from every 50 to 100 tons of materials (Williams et al. 2013). Table 2-2 shows the results of asbestos testing in multiple states. As it can be seen, the asbestos is no longer found very often in today's shingles.

Kriech et al. (2002) performed a laboratory research to evaluate the possibility of existence of other contamination in RAS. They found that the concentration of 29 tested Polycyclic Aromatic Hydrocarbons (PAHs) was below the detection limit of 0.1 mg/Lit as it is set forth by US Environmental Protection Agency (EPA). However, it still seems necessary to test at least post-consumer shingles prior to stockpiling with the already clean sources of RAS.

Table 2-2. Asbestos Testing Results (Townsend et al. 2007)

State	Date	Number of Samples	Number of Samples Detected Below 1%	Number of Samples Detected Above 1%	Total Percent of Samples Detected
Maine	1994-1995	146	2	2	2.70%
Iowa	1999-2001	1,791	0	0	0
Florida	2000-2001	591	3	2	0.80%
Missouri	2000-2001	51	0	0	0
Minnesota	2001-2002	206	1	0	0.50%
Massachusetts	2000-2007	25,296	12	404	1.60%

Wess et al. (2004) collected samples of run-off water from the surface of pavements containing RAS mixtures. PAH and some heavy metals were the tested factors in the samples. They found that the concentration of these particles is not above the detection limit of 0.5 μg/L in any of the samples. Several other researchers also found the same results (Brandt and De Groot 2001), (Grefe 2007).

2.2.3 Economic Incentives over RAS Usage in Pavement

The most important benefit of using RAS is the high amount of asphalt binder in it. Between 19 to 36 percent of RAS is composed of asphalt cement. It is predicted that the annual shingle wastes generation is about 11 million tons. Assuming a conservative amount of 20 percent binder in RAS, about 2 million tons of AC can be recovered which would replace approximately 9 percent of national needs (NAHB 1998 and Hansen

2009). This shows the importance of RAS incorporation in asphalt mixtures. However, in addition to the AC price as the main economic driver for RAS recycling, there are other major variables that affect RAS usage. Im and Zhou (2014) have listed these variables in potential cost saving as following:

- Type of the asphalt mixture produced.
- Price of neat liquid asphalt.
- Amount (%) of RAS used in the paving mixture.
- Type of RAS used (post-consumer or manufacturing waste).
- Cost of aggregates alternative to those contributed by the RAS.
- Landfill tipping fees.
- Capital cost of equipment for grinding/handling RAS.
- Expenses for acquiring, transporting, processing, and handling RAS.

2.3 Characteristics of Warm Mix Asphalt

The first attempts to lower the production and paving temperatures of asphalt mixtures started from 1970s with use of emulsified asphalts or foaming the binder with the moisture of aggregates (Zettler 2006). This reduction in temperature can range from 50°F to 100°F and it provides numerous benefits. Reduction in energy consumption and consequently lower emissions and costs, and exposure of workers to less fumes help the paving industry comply with strict environmental regulations and be less affected by rising fuel costs. For example, for serious to extreme ozone nonattainment areas such as

DFW, Houston and vast regions in California (FHWA 2015a), more plant operation and paving time will be available. Moreover, oxidative hardening and aging of binder which mostly occurs in the plant will be less as the production temperature is lowered. This keeps the pavement more flexible and thus less susceptible to cracking. In addition, the lower production temperature extends the paving season and provides more time to haul the mixture and compact the asphalt mat (Button et al. 2007). Another advantage of this technology is the improved workability. As a result of that, the requirement of compaction energy goes down and in-place density may increase (Hurley and Prowell, 2006), or the same density can be achieved with more passes of static rollers, rather than with expensive vibratory rollers (Hampton 2015). Higher workability also enables the designer to reduce the binder content in mix design which lowers the cost. Button et al. (2007) state that the OAC can go down by about 0.5% in the case of using WMA additives. Significant reduction of OAC has also been observed by Estakhri et al. (2010) for dense graded mixtures designed with three different WMA additives. However, one should perform further testing for durability and moisture susceptibility if lower AC is utilized.

Current WMA techniques fall into two main categories of foaming technology and use of additives. The foaming technology is the injection of a specific small amount of water into the foaming chamber where it will contact the hot bitumen. The water turns into microscopic vapor bubbles and gets thoroughly mixed with bitumen to achieve a mechanically foamed AC (Figure 2-2). The bitumen expands and its viscosity decreases as a result of combination with these bubbles (Astec Inc. 2015). Thus, the same amount

of bitumen coats the aggregates easier at lower temperature. Figure 2-3 illustrates the change in compaction range for liquid AC and foamed AC.

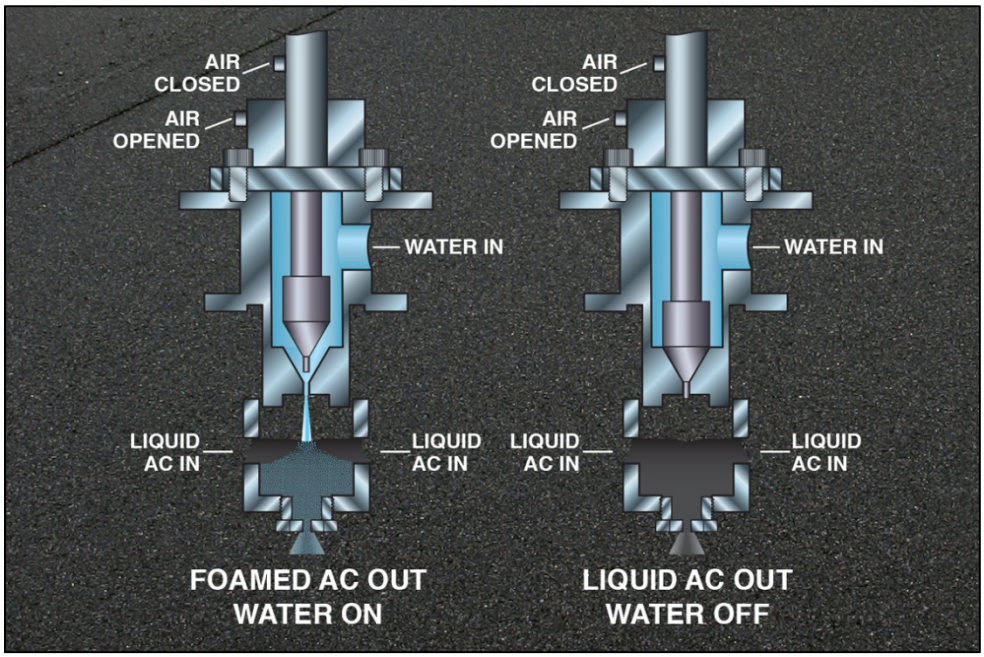


Figure 2-2. Green System Manifold (Astec Inc. 2015)

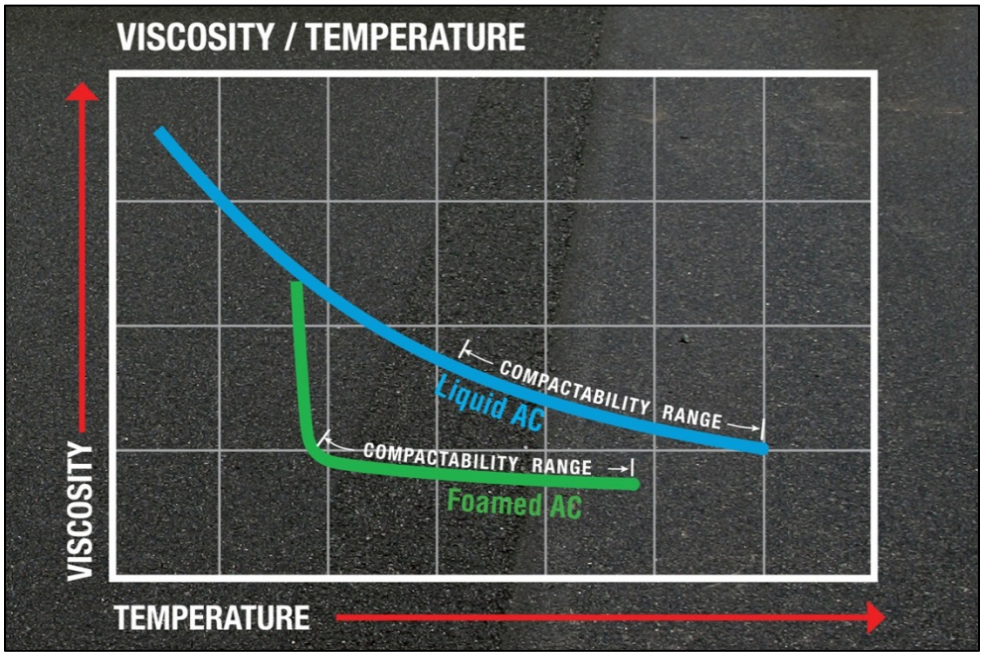


Figure 2-3. Compaction Chart (Astec Inc. 2015)

It should be mentioned here that this technology requires modification of the asphalt plants to accommodate the new system of nozzles and the chamber, which obviously incurs cost to the plant owners. Other alternatives include the introduction of additives. The additives can be organic or chemical. Sasobit and Asphalten-B waxes are examples of organic additives that can be added at the plant or by the binder provider. Figure 2-4 shows a sample of organic wax. These waxes chemically change the temperature-viscosity curve of AC by providing liquid in the AC above their low melting point (i.e. around 210°F). Blending with 2 to 4 percent (by weight of binder) of these granules, typically called "flow improvers", provides up to 54°F reduction in production temperature. However, there is always the possibility of sudden decrease in the viscosity of bitumen due to melting of crystallized wax at high ambient temperatures (Button et al. 2007 and Estakhri et al. 2010). This suggests prior laboratory testing of samples produced with each individual product.

Figure 2-4. Sasobit WMA Additive (Estakhri et al. 2010)

Any additive which is not organic is categorized as chemical. The chemical water-bearing additives such as Aspha-min or Advera provide foaming, similar to injection of water. These additives are finely powdered synthetic zeolites (Figure 2-5) that have been hydro-thermally crystalized and give up 18-21 percent water by mass when exposed to temperature above 185°F to 360°F. Simultaneous introduction to the mix with the binder results in microscopically foaming the binder which temporarily increases workability and better coats the aggregates. A dosage of 0.25 to 0.3 percent by weight of the asphalt mix is typically recommended for such additives (Button et al. 2007 and Estakhri et al. 2010).

Figure 2-5. Advera WMA Additive (Estakhri et al. 2010)

For these additives that use moisture to enhance aggregate coating and workability, some curing time may be required prior to opening to traffic. This time is needed for the moisture to be expelled from the additive and perform the function it is expected to (Button et al. 2007).

Another popular chemical additive is Evotherm. The most recent version is Evotherm 3G (also branded as REVIX^{TM}) which has been co-developed by MeadWestvaco Asphalt Innovations, Paragon Technical Services Inc & Mathy Technology and Engineering Services. It is a liquid additive that does not need any plant modification and can be introduced at mix plant or asphalt terminal. It also acts as anti-strip agent and can replace lime (MeadWestvaco 2015). Unlike two former versions (i.e. Evotherm ET and Evotherm DAT), the Evotherm 3G is water free and does not provide foaming of asphalt binder or any other viscosity reduction methods. However, it promotes adhesion by reducing the internal friction between the aggregates and the binder film that generally exists during mixing and compaction processes. The mixing and compaction temperatures are determined after rheological testing (FHWA 2015b). Evotherm 3G can lower the paving temperature by 60°F to 90°F. Typical dosage range for Evotherm 3G is 0.25% to 0.75% by weight of total binder, including virgin binder and the binder recovered from recycled materials (MeadWestvaco 2015a). In order to show the usefulness of Evotherm 3G, MeadWestvaco (2015b) reports a case study of paving over a bridge deck in highway I-35 in downtown San Antonio, Texas. The mixture contained PG 64-22 binder, 16% RAP and 4% RAS. With the use of Evotherm 3G, it became possible to reduce the mix temperature by 70°F and achieve densities of around

94% with only static rollers and not the vibratory rollers which can damage the bridge. Wisconsin Department of Transportation also evaluated the effect of Evotherm on mixtures performance. Evotherm had been used only as compaction aid for paving of recycled mixtures (13% RAP and 3% post-consumer RAS) and the mixtures were produced as HMA. They observed that the introduction of Evotherm provided a softer (better) mixture to compact and also improved the resistance to fatigue cracking while did not jeopardize rutting resistance (Williams et al. 2013).

New WMA technologies are being introduced every year. TXDOT placed its first WMA trial in 2006 and allowed further use of this technology. As of January 2015, 17 different WMA technologies are approved by TXDOT (Table 2-3).

Table 2-3. TXDOT Approved WMA Technologies (TXDOT 2015)

WMA Technology	Process Type	WMA Supplier
Advera (Synthetic Zeolite)	Chemical Additive	PQ Corporation
ALmix WarmWare	Foaming Process	ALmix
Aspha-Min (Synthetic Zeolite)	Chemical Additive	Aspha-Min
Astech PER (Hydrogreen)	Chemical Additive	Meridian Technologies
Cecabase RT	Chemical Additve	Arkema Inc.
Double Barrel Green	Foaming Process	Astec Industries, Inc.
Evoflex	Chemical Additive	MeadWestvaco Asphalt Innovations
Evotherm	Chemical Additive	MeadWestvaco Asphalt Innovations
HydroFoam IEQ	Foaming Process	East Texas Asphalt Co., Ltd.
QPR QualiTherm	Chemical Additive	QPR Quality Pavement Repair

Table 2-3. Continued

WMA Technology	Process Type	WMA Supplier
Rediset WMX	Chemical Additive	AkzoNobel Surface Chemistry
Rediset LQ	Chemical Additive	AkzoNobel Surface Chemistry
Sasobit	Organic Additive	Sasol Wax Americas, Inc.
Terex	Foaming Process	Terex Roadbuilding
Maxam	Foaming Process	Maxam Equipment
Ultrafoam GX	Foaming Process	Gencor Industries
ZycoTherm	Chemical Additive	Zydex Industries

2.4 Design of Asphalt Mixtures with Recycled Materials

As a part of the Strategic Highway Research Program (SHRP) in 1993, the Superpave mix design was introduced (Asphalt Institute 1995) but it did not consider RAP incorporation. This made the state DOTs unwilling to allow RAP usage (Hansen and Newcomb 2011) until McDaniel et al. (2000) developed procedures for RAP incorporation through National Cooperative Highway Research Program (NCHRP project D9-12). The guideline she proposed for RAP binder adjustment is as follows (AASHTO 2010):

- For RAP content of less than 15 percent, there is no need to change the binder grade.
- For RAP content between 15 to 25 percent, the virgin binder should be one grade softer than desired final grade. This is sometimes called grade dumping.

- For RAP content of more than 25 percent, blending charts should be used to determine the grade of virgin binder.

However, this guideline is subject to change where the state departments of transportation have adjusted the percentages for local conditions.

In the appendix of AASHTO M 323 (AASHTO 2010), the blending chart for RAP content of more than 25% is defined as one of the following two options. First, when the desired final binder grade, the percentage of RAP, and the properties of recovered RAP binder are known, the required properties of the virgin binder grade should be determined at every temperature separately:

$$T_{virgin} = \frac{T_{blend} - (\%RAP \times T_{RAP})}{(1 - \%RAP)} \quad \text{(Eq. 2.1)}$$

Where,

T_{virgin} = Critical temperature of virgin asphalt binder (high, intermediate, low)

T_{blend} = Critical temperature of blended asphalt binder (final desired; high, intermediate, low)

$\%RAP$ = Percentage of RAP (in decimal)

T_{RAP} = Critical temperature of recovered RAP binder (high, intermediate, low)

Second, when a specific virgin asphalt binder grade must be used and the final desired binder grade and recovered RAP properties are known, the allowable percentage

of RAP should be calculated for high, intermediate and low temperatures, and the range of content satisfying all three requirements should be selected as:

$$\%RAP = \frac{T_{blend} - T_{virgin}}{T_{RAP} - T_{virgin}} \quad \text{(Eq. 2.2)}$$

In designing the RAP content, one should consider the ability of the plant to superheat the aggregates. For example, for 50% RAP content and 138°C (280.4°F) desired discharge temperature, the aggregates with 5% moisture content should be heated to 438°C (820.4°F), as recommended by Virginia Department of Transportation (1996). Not all plants are able to maintain such a high temperature, thus corrective measures should be taken to avoid further mixture problems.

The incorporation of RAP in the design procedure is done by simply considering it as another stockpile. However, the presence of binder in the RAP influences the weight of RAP aggregates and should be corrected as follows (Al-Qadi 2007):

$$M_{dryRAP} = \frac{M_{RAPAgg}}{(100 - P_b)} \times 100 \quad \text{(Eq. 2.3)}$$

Where,

M_{dryRAP} = mass of dry RAP;

M_{RAPAgg} = mass of RAP aggregate and binder; and

P_b = RAP binder content.

This procedure has its own setbacks. Aside from the fact that it is time consuming, the use of hazardous solvents and disposal issues discourage the asphalt practitioners. Several alternatives were proposed which require determination of the Dynamic Modulus, Indirect Tension and Bending Beam Rheometer (Bonaquist 2007, Stephens et al. 2001, and Zofka 2004). However, none of them require performance tests such as tests for fatigue cracking or rutting, which leaves the estimation of the performance of the mixtures upon the local experience from previously constructed sections. For RAS, there is no mix design procedure available as its incorporation in recycled asphalt mixtures is relatively recent.

TXDOT has published special specifications that set limits on maximum allowable percentage of recycled binder, fractionated and unfractionated RAP and RAS. Table 2-4 shows such limitations for dense graded mixtures. As it can be seen, the TXDOT allows the incorporation of RAS of up to 5%. However, because of the high angularity of RAS particles, most asphalt producers are not willing to use more than 3%.

Table 2-4. The Maximum Allowable Amounts of Recycled Binder, Fractionated and Unfractionated RAP and RAS for Dense Graded Mixtures (TXDOT 2013)

Mixture Description and Location	Maximum Ratio of Recycled Binder to Total Binder (%)	Maximum Allowable % (Percent by Weight of Total Mixture)		
		Unfractionated RAP	Fractionated RAP	RAS
Surface Mixes	20 (30[I])	10	20	5
Non-Surface Mixes < 8 in. From Final Riding Surface	20 (35[I])	10	30	5
Non-Surface Mixes > 8 in. From Final Riding Surface	20 (40[I])	10	40	5

I. Allowed when using WMA or softer low temperature binder grade.

2.4.1 Concept of Balanced Mix Design

Generally, current asphalt mix designs result in mixtures which are rut resistant but susceptible to cracking (Zhou et al. 2006). The addition of RAP and RAS with their stiff aged binder increases the resistance to rutting, while reduces the cracking resistance. Moreover, it is well understood that one of the consequences of placing excessive amount of asphalt in the mixture is the higher vulnerability to rutting. In contrary, lack of enough binder also results in short cracking life due to limited flexibility that the asphalt mix will have. Therefore, for any aggregate structure, there may be a range in which the lower bound is the minimum level of asphalt to provide satisfactory cracking resistance, and the upper bound is the maximum asphalt content that does not cause excessive rutting. Following this principle, Zhou et al. (2006) have suggested a procedure to find an OAC that satisfies both criteria. The concept of this procedure, called Balanced Mixture Design (BMD), is depicted in Figure 2-6.

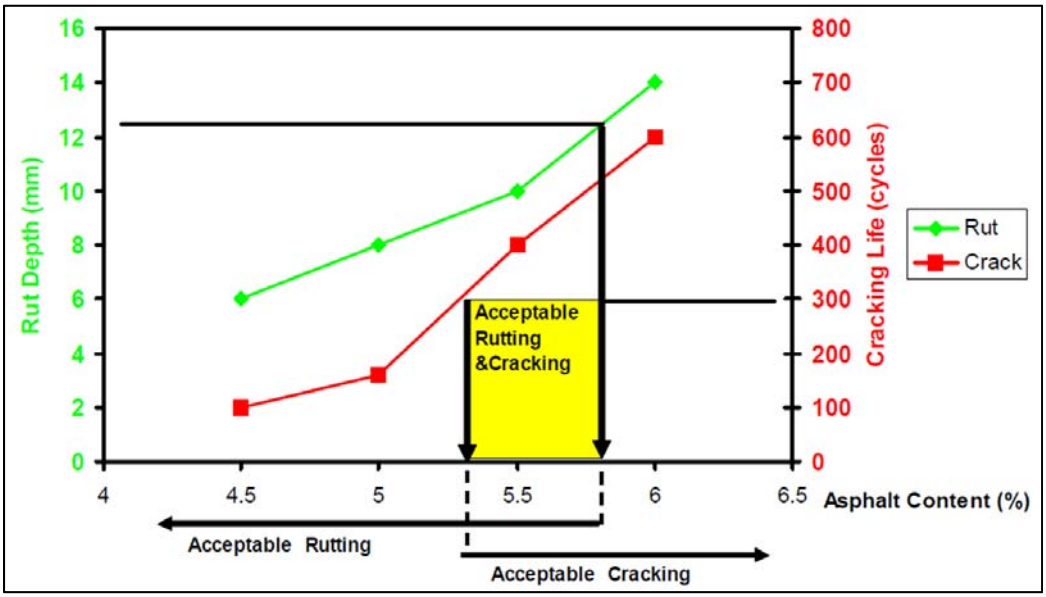


Figure 2-6. The Balanced Mixture Design Concept (Zhou et al. 2006)

The procedure relies on the use of HWTT and OT to determine rutting and cracking resistance. However, the same principle can be used if any other acceptable tests are utilized. Then it will be just the matter of setting an acceptable threshold or limit for the corresponding test.

The proposed BMD procedure of Zhou et al. (2006) includes the following steps:

1) Selection of asphalt binder and aggregates

2) Preparation of laboratory mixed samples

It is done through either the Superpave Gyratory Compactor (SGC) or the Texas Gyratory Compactor (TGC). Two samples for three to four asphalt contents.

3) Determination of OAC

This is done at a target density (typically 96 percent of maximum theoretical density). Then, VMA and VFA are checked to see if they are within the allowable range. If not, the design should be started over from step 1.

4) Evaluation of mixture properties

Four test specimens are molded to 93 ± 1 percent density at each of three asphalt contents (OAC, OAC + 0.5%, and OAC + 1.0%). Note that the interval of these three asphalt binder contents may vary based on binder's PG and the type of aggregates. Two test specimens for the HWTT and two for the OT are needed. The HWTT and the OT are performed according to the test protocols.

5) Determination of balanced asphalt content

The results are plotted similar to Figure 2-2 to determine the acceptable range. The criteria currently in use are successfully passing 300 cycles in OT for

cracking, and a maximum of 0.5 inch deformation in HWTT. If either of the criteria (or both) cannot be met, the design process should be started over from step 1.

2.5 Laboratory Evaluation of Recycled Asphalt Mixtures

McDaniel and Shah (2003) studied the applicability of Federal Highway Administration (FHWA) tiered approach and Superpave RAP specifications for materials collected from Indiana, Michigan and Missouri. They compared laboratory and plant produced mixtures with varying RAP content up to 50% with the SuperPave™ Shear Tester for materials from each state independently. They observed that the stiffnesses of mixtures are the same for Michigan and Missouri samples, while the plant-produced mixtures from Indiana materials showed significantly higher stiffnesses than its laboratory mixes. In addition, they noticed that the mixtures get stiffer as the RAP content increases. Although this increased the rutting resistance, the fatigue and thermal cracking resistance was compromised. This has been already observed in their testing for NCHRP Project D9-12 when the recycled mixtures with greater than 20% RAP content showed less fatigue life than virgin mixtures (McDaniel et al. 2000). They also stated that for mixtures with RAP content above 40 to 50%, conforming to Superpave specifications may not be feasible as the fine content (passing sieve #200) is relatively high.

The laboratory fatigue performance of HMA recycled mixtures with RAP contents from 0 to 30% was investigated by Huang et al. (2004). They tested the mixtures

through indirect tensile strength, semi-circular bending, and four-point beam fatigue. Following the Marshal Mix Design, researchers strived to have the same aggregate structure and asphalt content. However, the research report stays unclear on how the residual binder was considered in the mix process. They concluded that the tensile strength and fatigue life of mixtures increase with the incorporation of RAP material. However, this conclusion may be contrary to the general perception about the effects of recycled materials.

Hajj et al. (2007) investigated the influence of recycled asphalt pavements in HMA mixtures from the standpoint of mixture resistance to rutting, fatigue cracking, thermal cracking, as well as moisture sensitivity in laboratory. They used the Marshal Mix Design with the blending chart approach to select the grade of required virgin binder. They used 15 and 30 percent of RAP from three different sources, at two binder grades. The majority of mixes performed satisfactorily in the moisture sensitivity tests. They evaluated the resistance of mixtures to rutting by the Asphalt Pavement Analyzer (APA). The inclusion of RAP materials decreased rutting up to 33 percent, comparing with the control mix with virgin materials. They evaluated the resistance to fatigue cracking by flexural beam fatigue test with constant strain at three different levels. The results were not conclusive enough, although it was mentioned that the introduction of RAP decreased the fatigue resistance of mixtures, specifically at higher strain levels. However, it should be kept in mind that stiffer mixtures will produce lower tensile strains under field loading. This necessitates testing the samples at similar strain levels in laboratory to replicate field conditions.

Maupin et al. (2008) studied the effect of increased RAP percentages on performance of some Virginia Department of Transportation (VDOT) paving projects. Samples of mixes containing 21 to 30 percent RAP as well as a sample with less than 20 percent RAP (as the control mixture) were collected and tested. Mixtures were designed through Superpave method with the binder grade of PG 64-22 and Nominal Maximum Aggregate Size (NMAS) of 9.5 mm to 19.0 mm. Tests included beam fatigue, APA and Tensile Strength Ratio on various samples. They concluded that no significant statistical difference exists between the higher RAP mixes and the control mixes for fatigue, rutting, and susceptibility to moisture.

Two experiences in western Canada have been reported by Forfylow and Middleton (2008) and Reyes et al. (2009). They used field cores and laboratory compacted plant produced specimens of WMA mixtures. The WMA was produced with foaming technology of Double Barrel Green (DBG) at 265°F to 274°F with different percentages of RAP and RAS. Based on Tensile Strength Ratio (TSR) tests, they concluded that the DBG mixes are not susceptible to moisture damage and the performance of mixtures containing up to 15% RAP and 5% RAS are similar to that of virgin mixes. Moreover, after two years of monitoring, the field performance of all sections was favorable.

Mallick et al. (2008) investigated the feasibility of incorporating high RAP contents with WMA additive of Sasobit and multiple soft binders. They tested Superpave gyratory compacted laboratory samples for Indirect Tensile Strength, APA and seismic modulus. They observed that if an appropriate binder grade is mixed with the right

amount of WMA additive, the stiff binder of recycled mixtures can be rejuvenated to a comparable level with that of a virgin mixture. They concluded that the Sasobit additive improves the uniformity in mixtures and similar air voids to that of conventional mixes are achieved. In their study, for 75% RAP content, they found that very soft binders, such as PG 42-42 should be used to achieve satisfactory results.

Copeland et al. (2010b) evaluated plant produced asphalt mixtures from field project in State Route 11, Deland, Florida. The production of mixtures performed through both HMA and WMA. The mixtures were Superpave 12.5mm and contained 45 percent minus 1/4 inch fractionated RAP. Total binder content was 5.6 percent and the virgin binder was recycling agent-RA800 (i.e. PG 52-28). The temperatures for HMA were 310°F-300°F and for WMA were 270°F-260°F. Lower viscosity for WMA mixtures were achieved through foaming technology, i.e. injection of 2% water by the weight of binder. They conducted performance grading of the binder, dynamic modulus and flow number tests on the mixtures. They found that the RAP-HMA mixture was stiffer than the RAP-WMA (PG 64-16 vs. PG 52-22). This conclusion was further confirmed by the dynamic modulus and flow number tests. They compared the measured dynamic modulus results with predicted values from Hirsch and Witczak models and concluded that the blending of virgin and recycled binders in RAP-HMA was complete while it was incomplete for RAP-WMA.

In order to evaluate the effect of RAP amount on rutting resistance, Apeagyei et al. (2011) investigated the performance of 19 plant-produced HMA mixtures containing 0 to 25 percent of RAP through dynamic modulus and Flow Number tests. The samples

included 16 dense-graded surface and base mixtures and three Stone Matrix Asphalt (SMA) with three binder grades (PG 64-22, PG 70-22 and PG 76-22). They observed that the performance of 25 percent RAP mixtures was similar to that of virgin mixtures containing no RAP. Surprisingly, the mixtures with the highest RAP content (25 percent) showed less rutting resistance than mixtures with 10-15 percent RAP content. They concluded that the practice of binder grade change, which means using softer asphalt binder for higher RAP contents, may be responsible for it.

Aurangzeb et al. (2012) studied the moisture susceptibility, dynamic modulus, wheel tracking and beam fatigue of HMA mixtures with 0% (control), 30%, 40%, and 50% RAP content from two different districts of Illinois. The NMAS of mix designs was 19mm and the RAP binder grades were PG 82-10 and PG 88-10. The mixtures were designed based on the Bailey method. By using this method, the volumetrics of the mixtures were kept similar in order to have the performance properties solely dependent on mechanical properties. They concluded that the achievement of similar volumetrics (i.e. VMA) comes from fractionating RAP material in a manner as controlling the gradation of virgin aggregate. They also stated that the tensile strength, complex moduli and rutting resistance of mixtures increased as the RAP content increased. When single-grade dumping was used, the fatigue life improved. However, double-grade dumping did not show the same improvement. Overall, it was concluded that all the mixtures with RAP had equal or better performance than virgin mixtures. They mentioned proper processing and fractionation of RAP as the key approaches to design high quality asphalt mixtures.

The studies which were discussed herein have been brought as examples of numerous published works on the laboratory evaluation of RAP mixtures. The results are mixed and sometimes even contradictory. It seems that the performance of RAP mixtures depends on a myriad of factors which cannot be always fully simulated in the laboratory. That is why Al-Qadi et al. (2007) summarized their literature review on RAP mixtures with the statement that inconsistent results have been achieved at times, in spite of considerable research in this field. They believed that the three tier system of FHWA is suitable for low to moderate RAP contents. At higher blend percentages, uncertainty in binder properties is accompanied by concerns over aggregates gradation as the fine content increases. In addition to inconsistent lab results, the construction process brings another level of complexity to prediction of binder blending. The temperatures and times that the mixtures are held at those elevated temperatures are different from the laboratory conditions. Therefore, transition of similar performance from laboratory to field may not be a wise assumption.

The conclusion of Zaumanis and Mallick (2015) for their state-of-the art review of high RAP content mixtures best describes the current situation:

> " The design of mixture needs more effort to evaluate the RAP aggregate and binder properties, select the best RAP processing method, address the increased dust content, choose the most appropriate technique(s) for reducing the aged binder stiffness and perform the mix design without knowing the actual amount of blending between the RAP and virgin binder "

2.6 Field Performance of Recycled Asphalt Mixtures

The history of recycled mixtures dates back to the 1970s when FHWA conducted a field demonstration project in New Jersey. The project included paving of a shoulder with asphalt mixtures containing 50% RAP and the "extremely well" performance of it encouraged further experimentation with recycled materials (Hellriegel 1980).

2.6.1 Field Performance Studies in the US

Kandhal et al. (1995) compared the performance of five test sections with RAP content ranging from 10 to 25 percent and virgin materials in the state of Georgia. After one to two and a half years in service, they observed that all recycled and virgin mixtures performed equally well and no significant rutting, raveling or fatigue cracking had occurred in any of the test sections.

Paul (1996) evaluated the field performance of 6 to 9 years old conventional and recycled asphalt pavements with 20 to 50 percent RAP in Louisiana. He found no significant difference in terms of the pavement conditions and serviceability ratings.

National Center for Asphalt Technology (NCAT 2009) studied 18 projects across the US to compare paired sections of virgin and recycled asphalt mixtures containing 30 percent RAP. The projects were 6 to 17 years old. The distresses for comparison were rutting, fatigue cracking, longitudinal cracking, transverse cracking, block cracking, and raveling. They concluded that in most cases the performance of recycled mixes with 30 percent RAP was very similar to that of virgin mixes.

Musselman (2009) reported on a Florida Department of Transportation investigation of pavements constructed between 1991 and 1999 with 30 to 50 percent RAP content and virgin mixes as benchmark for comparison. The age at which the pavement became deficient from cracking standpoint was compared. He concluded that there is no significant difference between that of virgin mixes and of mixes with 30 percent RAP content. However, the performance decreases for mixes with more than 30 percent RAP.

West et al. (2011) reviewed the asphalt overlay section of Specific Pavement Study Experiment 5 (SPS5) for pavements built in 18 states and provinces of North America between 1989 and 1998, including mixtures with different RAP content and virgin mixtures. They found that in terms of International Roughness Index (IRI), rutting, block cracking and raveling, overlay mixes with 30 percent RAP performed as well as virgin mixes, but virgin mixes exhibited better performance in fatigue cracking.

Williams et al. (2013) reported a field and laboratory demonstration project of recycled mixtures for Minnesota Department of Transportation (MnDOT). The sections were paved in Fall 2008 and included three mixes containing either 5% post-consumer RAS, or 5% manufacturing scraps RAS, or 30% RAP. Almost 100% of RAS and RAP materials passed sieves #4 and 3/4", respectively. All the mixtures produced and paved as 3 inch thickness HMA and were used for shoulder and traffic transition lanes in 3.5 miles of highway I-94 in Minnesota. Low temperature and reflective cracking of pavement sections were the distresses of interest. Total AC for RAS mixtures were 4.8% and 5.0%, and for RAP mixture was 5.3%. Virgin blended binder for all the mixtures was

PG 58-28. From the standpoint of performance grade, they found out that 30% RAP can be replaced with 5% RAS, if the same grade is expected to be achieved. They performed the dynamic modulus, flow number, beam fatigue and Semi-Circular Bending (SCB) tests in the laboratory. The dynamic modulus test results showed that there is no statistical difference between the stiffness of mixtures. In the flow number test, they observed that the best performance is exhibited by the post-consumer RAS mixture, then the post-manufacture RAS while the RAP mixture was the most susceptible mixture to permanent deformation. In the beam fatigue test, the performance of both RAS mixtures was better than that of RAP mixture which is counterintuitive as the binder in RAS is stiffer and the RAP mixture had higher asphalt content. However, the authors hypothesized that the presence of fiber in ground RAS may be the reason for better tensile strength. From SCB test, they did not find any difference in low temperature cracking resistance of these three mixtures. After four years surveying the field condition of sections, they observed that the performance of post-consumer RAS sections was similar to that of RAP sections and superior to that of post-manufacture RAS sections everywhere. However, since the condition and underlying layers for all the sections were not identical, it was not possible to make a conclusion based on field observations.

A field demonstration project for Indiana Department of Transportation (INDOT) was conducted in US Route 6 in Elkhart County of Indiana in 2009. Williams et al. (2013) reported the project as a replacement for a 1.5 inch milled HMA overlay with varying thicknesses on top of a concrete pavement. Three different recycled mixtures with 15% RAP-HMA, 3% post-consumer RAS-HMA, and 3% post-consumer RAS-

WMA (foaming technology) were used to pave 6.8 miles. Better compaction (higher field density) was achieved with the use of WMA technology. The effective asphalt content was almost the same for RAP and RAS mixtures, 5.1% and 5.2% respectively. The virgin asphalt binder was PG 70-22. Laboratory tests were the same as for the aforementioned MnDOT project. In all the lab tests, the three mixtures performed rather similar and no statistical difference could be observed. However, the RAS mixtures showed slightly better rut resistance in the flow number test. Field surveys were performed within three years after construction of the project. The total length of reflective cracks in RAS-WMA mixture was more than that in the other two sections which had comparable crack lengths. However, the severity of those cracks was less than for other sections. Figure 2-7 shows the severity of cracks for these sections at the end of third year survey.

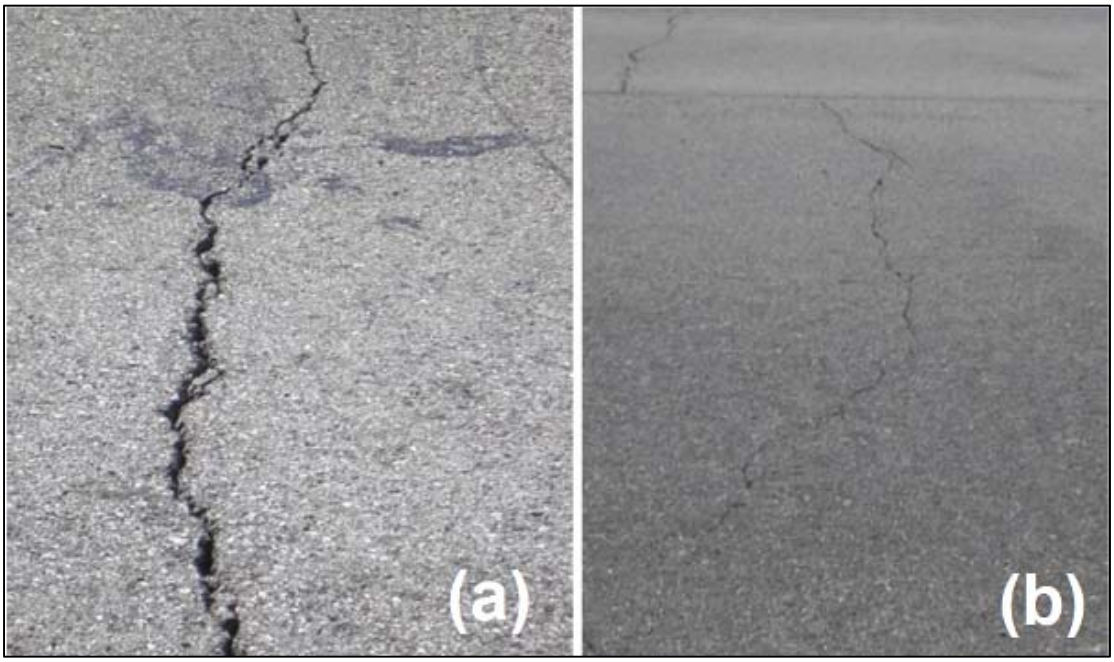


Figure 2-7. INDOT Project: (a) High Severity Transverse Cracks in HMA-RAS (b) Low Severity Transverse Cracks in WMA-RAS (Williams et al. 2013)

They also reported the greatest amount of longitudinal fatigue cracking in RAS sections. Length of this type of cracks in RAS sections was 6 to 9 times the length of cracks in RAP section.

Colorado Department of Transportation (CDOT) constructed a field demonstration project in August 2011, as reported by Williams et al. (2013). The objective of project was to compare the performance of a typical CDOT HMA mixture with 20 percent RAP (CDOT Superpave No.2 mix) with the same mixture design when 5 percent of RAP has been replaced by 3 percent post-manufacture RAS (i.e. 15% RAP and 3% RAS). Temperatures of RAP mixture were 300°F-285°F while RAP/RAS mixture had higher range of 335°F-315°F. Both the RAS and the fractionated RAP were processed minus ½ inch. However, visible individual tabs of RAS during paving revealed the necessity for finer processing of shingles. The total asphalt content for RAP mixture was 5.1 percent and for RAP/RAS mixture was 5.2 percent. Virgin binder of PG 64-28 was used in both mixtures. The existing pavement was 6 inch HMA on top of a concrete pavement. Two inches of it was milled and replaced by 2 inches of each of the mixtures. Ambient temperature during paving was 69 to 95 °F and humidity was moderate to high. Same laboratory tests for MnDOT project were also performed. Last field condition survey was conducted one winter after the construction, in March 2012. From dynamic modulus and flow number tests, it was observed that both mixtures have the same resistance to rutting. The RAP/RAS mixture showed a better fatigue life in the controlled strain, four-point fatigue beam test. Low temperature cracking resistance was the same for both mixtures in SCB test. Field survey revealed that the transverse cracks are minor

for RAP/RAS mixture and very little for RAP mixtures. Also low severity raveling was observed in RAP section (Figure 2-8). However, the pavement was not in service for sufficient time to make a precise judgment on the field performance of mixtures.

Figure 2-8. Low Severity Raveling (RAP), (Williams et al. 2013)

Williams et al. (2013) reported the construction of a demonstration field project with recycled materials for Illinois Department of Transportation (IDOT) during July-October 2011. The goal of project was to evaluate the performance of SMA mixtures containing RAS, RAP and ground tire rubber (GTR), both plant produced and laboratory

mixed. Two mixtures with 5 percent RAS or 5% RAS and 11% RAP with binder PG 70-28 were produced in plant for field demonstration project. The same mixtures with binder PG 58-28 and 12% GTR have also been prepared in the lab for performance comparison purposes. The 5% post-consumer RAS was added to the mixtures to replace the entire fiber that is normally used in SMA mixes. The SMA with 5% RAS was used to pave 14 miles in highway I-80 and the SMA mixture with 5% RAS and 11% RAP was used to pave 9.5 miles of highway I-90. The existing pavement in I-80 had 3 ½ inches of SMA on top of 9 ¼ inches of CRCP. The entire SMA layer was milled and replaced with 4 inches of SMA in two equal lifts. The existing pavement in I-90 had 2 ¼ - 5 ½ inches of HMA on top of 10 inches of jointed reinforced concrete pavement (JRCP). The entire HMA layer was milled and replaced with 4 inches of SMA in two equal lifts. The ambient temperature during paving was 40°F to 96°F and the humidity was moderate. The plant produced the mixtures at the high temperature of 360°F. The post-consumer RAS was grinded and screened to minus 3/8 inch. The total asphalt content in SMA with 5% RAS (highway I-80) was 6.2% and in SMA with 5% RAS and 11% RAP (highway I-90) was 6.0%. The immediate benefit of using RAS in these mixtures was controlling the draindown below 0.02%. This satisfied the IDOT required limit of 0.3% for SMA mixes which is typically achieved by using more expensive material of cellulose or mineral fiber. All the mixtures showed excellent rutting resistance and fatigue properties in laboratory tests. Results of SCB test revealed that low temperature cracking performances of RAS-SMA and RAS&RAP-SMA mixtures were not statistically different. The last

reported field condition survey in March 2012 showed no distress on any kind on these pavement sections.

2.6.2 Field Performance Studies in Texas

Chen and Daleiden (2005) reported two RAP overlay projects. One of them was a hot in-place recycled (i.e. 100% RAP) and the other was from the Long Term Pavement Performance (LTPP) SPS5 sections. These projects are located on US175 in Dallas district and experienced the same environmental and traffic conditions. As can be seen in Figure 2-9, for 100% RAP overlay, reflection cracks occurred after two weeks of opening to traffic. While for the overlay with 30% RAP and a soft virgin binder (AC5), no crack was observed on the travel lanes, even after a 10-year period.

Figure 2-9. 30% RAP vs. 100% RAP Overlays on US175, Dallas District (Chen and Daleiden 2005)

Hong et al. (2010) studied 16 years performance monitoring of test sections with 35% RAP in Texas, as a part of LTPP-SPS5. The criteria were IRI, transverse cracking, rut depth, and ride quality. Comparing with virgin sections, the high RAP sections had

higher cracking amounts, less rut depth, and similar ride quality change over time. However, the overall performance of all the sections was satisfactorily.

Another experience from Austin District in FM 2439 is shown in Figure 2-10. The asphalt mix incorporated 20% RAP. The longitudinal cracking in surface mix was observed only a few months after placement.

Figure 2-10. Early Cracking in a Surface Mix Incorporating 20% RAP

Estakhri et al. (2010) reported construction of a WMA project in BU 287 Fort Worth, Texas in 2008. The project was 4.8 miles long with average daily traffic of 24,100 vehicles. The old pavement had 8 inches of crushed stone flexible base and a variety of surface layers, such as CRCP with 3.5 inches HMA overlay or jointed concrete pavement (JCP). Former district experiences had shown that overlaying JCP with hot mix results in

expansion of sealant or entrapped water and causes heaving and consequently rupturing the wearing course. Therefore, WMA was specified to have lower placement temperature and reducing this phenomenon. The WMA placement included dense-graded Type B with 20% RAP for shoulder rehabilitation and dense-graded Type D as an overlay for the entire project. Mixture details are shown in Table 2-5. Producing the mixtures as WMA rather than HMA resulted in about 0.8 gallon reduction of fuel consumption per ton of mix.

Table 2-5. Fort Worth BU 287 Project Details (Estakhri et al. 2010)

Mixture (Item 341)	**Dense-graded Type B**	**Dense-graded Type D**
WMA Tonnage (tons)	20,000	32,000
Binder Grade	PG 64-22	PG 76-22
Aggregates	75% Limestone	90% Limestone
	5% Field Sand	10% Field Sand
	20% RAP	0% RAP
Anti-strip	1% liquid	
AC Content (%)	4.3	5.0
WMA Additive	Evotherm DAT	
Mat Thickness (in.)	10	3.5
Haul Distance (miles)	50	
Cost ($/ton)	52	63

Ground Penetration Radar (GPR) was employed to evaluate the uniformity of compaction right after construction. They observed that even at shoulder location where the thickness of WMA layer was 14 inches, the compaction was uniform in depth and no defect existed. They used a HMA section in SH 114 Fort Worth with similar pavement

structure and mixture as the control section. Falling Weight Deflectometer (FWD) testing two months after construction showed no significant difference in structural strength characteristics between that of WMA and of HMA sections. Additionally, after one year of service, no evidence of rutting or cracking had been observed (Figure 2-11).

Figure 2-11. Fort Worth BU 287 WMA Project after One Year of Service (Estakhri et al. 2010)

Zhou et al. (2011) reported four test sections of an overlay rehabilitation project on IH 40 in Amarillo, TX in 2009. Figure 2-12 shows the existing pavement condition prior to overlay placement. The design required 4 inches milling and replacing with an

asphalt overlay. The pavements were subjected to cold weather, heavy traffic and severe existing cracks. The four sections were built with dense-graded Type C mixtures. The mix designs of four sections are shown in Table 2-6.

Figure 2-12. Existing Pavement Conditions of IH40 after Milling (Zhou et al. 2011)

Table 2-6. Mix Design Information of the Four RAP Test Sections on IH40 near Amarillo, Texas (Zhou et al. 2011)

Section	RAP (%)	Virgin Binder	Designer	Mix Design Method	OAC (%)
0	20	PG 64-28	Contractor	TXDOT's Tex-204-F	5.0
1	0	PG 64-28	Contractor	TXDOT's Tex-204-F	4.8
2	35	PG 58-28	TTI	BMD	5.5
3	20	PG 64-28	TTI	BMD	5.3

After 2 years of service, all sections had no measurable rutting but very visible reflective cracking. At the time of report publication, the 35 percent RAP section showed the least reflective cracking. It should be mentioned that this mixture had also resisted the highest cycles in the OT.

Construction of three RAP sections on FM1017 in south of Texas was reported by Zhou et al. (2011). The pavement was a new construction of 1.5 inch (37.5 mm) surface asphalt layer. The mixtures used were all dense-graded Type D. The mix designs are shown in Table 2-7.

Table 2-7. Mix Design Information of the Three RAP Test Sections on FM1017 near Pharr, Texas (Zhou et al. 2011)

Section	RAP (%)	Virgin Binder	Designer	Mix Design Method	OAC (%)
1	20	PG 64-22	Contractor	TXDOT's Tex-204-F	5.0
2	35	PG 64-22	TTI	BMD	6.4
3	0	PG 76-22	Contractor	TXDOT's Tex-204-F	4.9

After one year of service, no rutting or cracking had been observed. As it seems the performance was better than RAP sections of IH40. The researchers attributed their superior performance to multiple factors, including lighter traffic, milder weather condition, less rainfall and of course no pre-existing cracks. However, one year is not a long period for pavements and future surveys may provide more reliable information on their performance. Following the comparison of performance results of these two

experiences (i.e. IH40 and FM1017) and NCAT 2006 test tracks, Zhou et al. (2011) concluded that the cracking criteria for recycled mixtures should depend on the existing condition of underlying layers. Different designs should be considered if the project is an overlay and not a new construction.

Zhou et al. (2013) reported a new construction with 15 percent RAP and 5 percent tear-off RAS on SH146 in Houston in October 2010. The mixture was dense-graded Type C with virgin binder of PG 64-22. The mix was used as the top 2-inch surface layer on a good foundation. The main features of the section were new construction, hot summer and mild winter weather condition, light traffic (1.5m ESAL). Laboratory testing of mixture indicated excellent resistance against rutting, but poor against cracking. However, in the last reported survey which was conducted on May 2013, no distress had been observed (Im and Zhou 2014).

Zhou et al. (2013) tested the effectiveness of increasing the design density on improving the cracking resistance of RAS mixes through construction of two test sections on US87 in Amarillo, TX in October 2010. Five percent tear-off RAS was used in the mixtures. Sections were subjected to hot summer and cold winter weather with numerous freeze-thaw cycles and light traffic of about 5 million ESALs in 20 years. The RAS mixture used in these sections were different in the OAC and design density. The OAC for control section was 4.6 percent with 96.5 percent design density and for the other one was 5.0 percent with 97.3 percent design density. The virgin binder grade was PG 64-28. The existing asphalt pavement had severe transverse cracking. Therefore, the reflection cracking was the anticipated distress. After 2.5 years monitoring, no rutting had been

observed. However, the reflection cracking was evident in this period in both sections (Im and Zhou 2014). Comparison of the development of cracking in two sections shows that the section with higher OAC and design density suppressed the reflection cracking better (Figure 2-13).

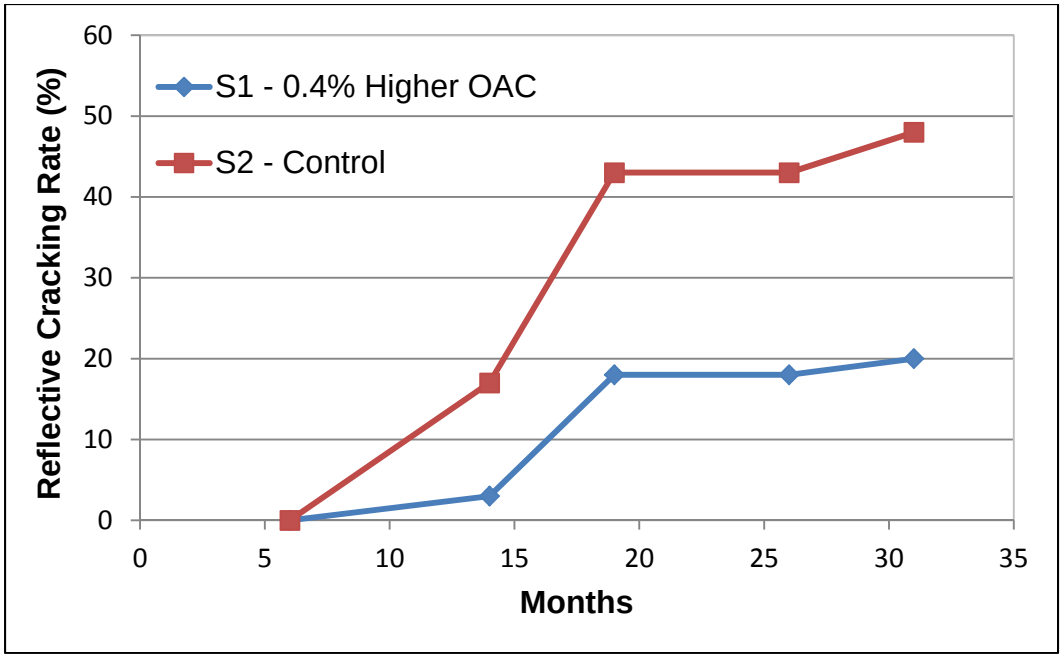


Figure 2-13. Reflective Cracking Development History of the RAS Test Sections on US 87 (Im and Zhou 2014)

Zhou et al. (2013) reported the performance of nine test sections built between Dec. 2011 and Jan. 2012 on FM973 in Austin TX. The project required the construction of a 2 inch overlay in an area with warm weather and very heavy truck traffic. The purpose of construction of these pavement sections was to evaluate the effectiveness of using soft binder on improving the cracking resistance of RAP/RAS mixes. The existing

pavement condition was reported “not bad”. However, severe longitudinal and fatigue cracks along the wheel path were observed in limited areas. These test sections have been trafficked for 18 months (Im and Zhou 2014). The latest reported survey was conducted in April 2013 and lots of cracks were observed for the first time (Figure 2-14). Details of each section with reflection cracking rate are brought in Table 2-8.

Table 2-8. Test Sections on Fm973, Austin, Texas (Im and Zhou 2014)

Section #	Type	Virgin Binder	RAP	RAS	Reflective Cracking Rate (%)
1	HMA	70-22	0	0	0
2	HMA	64-22	30	0	8
3	HMA	64-22	15	3	75
4	HMA	64-22	0	5	100
5	HMA	58-28	30	0	6
6	HMA	58-28	15	3	1
7	WMA Foaming	70-22	0	0	25
8	WMA Evotherm	70-22	0	0	8
9	WMA Evotherm	64-22	15	3	3

Since the authors have not provided enough information on the asphalt content and underlying condition of each section, it was not possible to compare the mixtures performances.

Figure 2-14. Observed Cracks on Sections 5 and 6 (Im and Zhou 2014)

Im and Zhou (2014) reported the construction of four field sections on Loop 820 in Fort Worth, Texas on July 2012. The pavement was subjected to hot summer and mild winter weather and a moderate traffic of 15 million ESALs in 20 years period. The sections were built as a 2 inch WMA overlay on top of finely cracked CRCP. The mixtures contained 15% RAP and 5% manufacture waste shingles. The researchers were interested to see the performance of RAP/RAS mixtures with different introduction form of Advera additive. Moreover, they added more virgin binder in one of the mixtures to evaluate if this can increase the resistance to cracking. Table 2-9 shows the details of each section. After a year of monitoring, none of the sections have shown any distresses. Figure 2-15 illustrates the condition of pavement before and one year after the placement of the overlay.

Im and Zhou (2014) concluded their report with stating that the cracking performance of recycled mixtures depend on many factors including traffic, climate, existing pavement condition (for overlay projects), pavement structure and layers thicknesses. They also made a comparison between their findings and the results of

NCAT 2006 test tracks in which 7 sections with different binder grade and RAP contents had been built.

Table 2-9 Four Field Test Section on Loop 820 (Im and Zhou 2014)

Section	Virgin Binder	OAC (%)	WMA Additive: Advera
0	PG 64-22	5.1	Advera as external additive
1	PG 64-22	5.1	Advera pre-blended with processed RAS
2	PG 64-28	5.1	Advera as external additive
3	PG 64-22	5.5	Advera as external additive

Figure 2-15. RAP/RAS Test Sections on Loop 820, Fort Worth (Im and Zhou 2014)

At the time of report publication, those sections have had 10 million ESALs in 2 years. Among them, only the section with highest RAP content (i.e. 45 percent), stiffest virgin binder (i.e. PG 76-22) and Sasobit additive had reflective cracks and the rest

showed no cracks at all (refer to Im and Zhou 2014 for NCAT test tracks references). They concluded that the RAP/RAS mix design and laboratory performance evaluation system should be "project-specific", considering all the aforementioned influential service conditions.

2.7 Summary and Remarks

This chapter provided the background of recycled asphalt mixtures as well as review of the literature on this topic. RAP has been used in asphalt mixtures for a long period of time and hence its properties and performance are better known. However, RAS is a new material for paving industry, thus the long term performance of its mixtures is not clear to the practitioners. The same problem exists for the relatively newly introduced technology of WMA. Therefore, the need for further research on these mixtures is urgent.

After reviewing the provided literature, it is obvious that the lab performance of mixtures may not be the same as in the field which makes the researchers unwilling to rely much on the lab results. However, the field testing has also its own limitations. Aside from the higher costs, the results of an actual field section are available at the end of its service life. This is usually a long period of time. By that time, the state DOT may have constructed or rehabilitated many other projects with that mixture of interest. It is clearly irrecoverable if the performance of that mixture is not satisfactory. Therefore, an accelerated way of testing on smaller scale controlled field sections can provide fast and

reliable results on the performance of recycled mixtures. This enables the decision makers of asphalt industry to select the best mixture for future projects.

CHAPTER 3

LIFE CYCLE ASSESSMENT: BACKGROUND AND REVIEW OF LITERATURE

3.1 Introduction

The US Environmental Protection Agency describes Life Cycle Assessment as a "cradle-to-grave" approach for evaluation of industrial systems. "This begins with the gathering of raw materials from the Earth to create the product and ends at the point when all materials are returned to the Earth. The term "life cycle" refers to the major activities in the course of the product's life-span from its manufacture, use, and maintenance, to its final disposal, including the raw material acquisition required manufacturing the product" (EPA 2006). Figure 3-1 illustrates the stages that can be considered in a LCA with typical inputs and outputs.

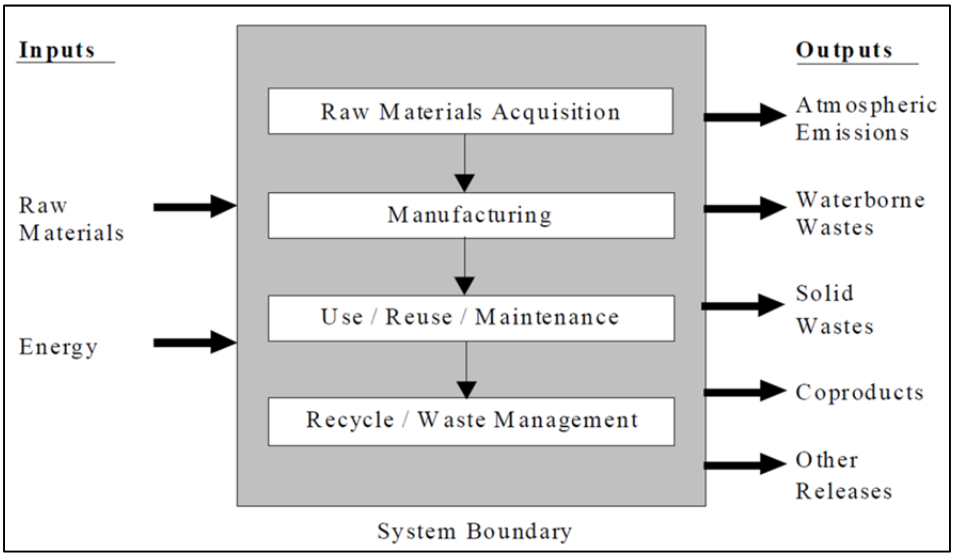


Figure 3-1. Life Cycle Stages (EPA 1993)

The LCA technique is a systematic phased approach with four major components as defined by the Environmental Protection Agency (EPA 2006):

1. *Goal Definition and Scoping*

The process or product should be defined and described. Boundaries and environmental effects of the assessment should be established. The type of information and required specificity, the method of organizing the data and displaying of results should be determined.

2. *Inventory Analysis*

The usage of energy, water and materials along with environmental releases (e.g. air emissions) should be identified and quantified. This step provides a basis for comparative evaluation of environmental impacts.

3. *Impact Assessment*

The potential human health and ecological effects of items described in phase 2 should be assessed. This phase should also address resource depletion. It establishes a linkage between the product or process and its environmental impacts. For example, what will be the impact of a certain amount of carbon dioxide emission into atmosphere?

4. *Interpretation*

At the end, the preferred process or product should be selected based on the results of phases 2 and 3. This should be done with taking into account all the uncertainties and assumptions, made to achieve those results.

The LCA technique can help the decision-makers to study the entire life of a process and come up with a more informed decision. By employing this technique, the

probable transfer of environmental impacts from one media to another and/or from one life-cycle stage to another can be identified. For example, if controlling air emissions results in creation of waste water, or saving of raw materials in initial construction stage causes more frequent maintenance and rehabilitation. In such scenarios, simply looking at one stage or one media does not reflect the entire impact of the process.

However, an LCA may have some limitations. Its accuracy relies on thoroughness and precision of collected data. Since there are numerous influential factors in a process, the user should determine in advance that to what extent he/she would like to conduct the analysis. A comprehensive LCA can be very time and resource intensive. Therefore, one should evaluate the financial benefits of the assessment against the cost of performing such analysis. Moreover, it should be kept in mind that LCA does not determine the cost effectiveness or satisfactory performance. It can only be a component of a broader decision making procedure (e.g. Life Cycle Management, LCM). Jensen and Remmen (2004) describe LCM as "the application of life cycle thinking to modern business practice, in order to manage the total life cycle of a product or service towards more sustainable consumption and production".

3.2 Different Approaches of Life Cycle Assessment

An LCA can be done through multiple methods, including the classical method or the Process-based (PLCA), streamlined, Economic Input-Output (EIO-LCA) and hybrid. The advantages and disadvantages of each method will be briefly explained further.

3.2.1 Process-based Life Cycle Assessment

The PLCA is a technique that considers the entire process (i.e. main functional unit) by narrowing it down into smaller processes until it reaches the very basic processes (i.e. unit processes) which cannot be further reduced (ISO 2006). For example, the construction of HMA pavement section can be broken down into material production, transport of materials to plant, mix production, transport of the mix to site, placement and compaction. Then, each phase can be narrowed down more. For example, the compaction phase consists of passing of breakdown roller, intermediate roller and then finish roller. In this manner, if all the unit processes are defined, then the PLCA can be very precise. However, the collection of data for every small process can be very time and cost consuming. Because of that, the LCA practitioners of a field may not include all the processes in the assessment, making the comparison of final results futile. This can be the case for considering user costs in LCA of pavements. It is very likely that one modeler does not include the tear and wear of vehicles tire or the wasted fuel in a traffic queue, while the other one does. Therefore, the system boundaries can be at the modeler's discretion, which may cause inconsistency.

3.2.2 Streamlined Life Cycle Assessment

Streamlined LCA was developed to reduce the load of data collection and missing processes in PLCA (Lin 2012). The objective of performing LCA is well defined in advance to decide the level of significance of each process in achieving the final goal. Subsequently, the researcher categorizes those processes and more time and energy will

be spent on sound data collection for the more important processes. Processes of less importance may be excluded from the assessment or replaced by similar process with known information (Curran and Young 1996). This method can save resources and provide some regulation or structure for setting the boundaries (i.e. data cut off). However, replacement of seemingly less important processes with some standard ones will result in uniform outcomes for different projects and also the chance that some important impacts will be eliminated.

3.2.3 Economic Input-Output Life Cycle Assessment

EIO-LCA was developed based on an Input-Output (IO) model that categorizes similar industries of an economy into one specific sector. In this approach, the outputs of one sector can be the input of another. The public agencies such as the U.S. Department of Commerce collect the data in a specific period of time and provide a national average for each sector. The interaction of different sectors of an economy is provided in a monetary form. Therefore, a researcher can trace back all the pre-required stages and products for an output of one sector and also determine the cost. This methodology was later adopted by Green Design Institute of Carnegie Melon to present the EIO-LCA. The prediction of noneconomic impacts in this method is done through addition of data on energy and environmental flows to the IO table. This method is quick and inexpensive and does not require a specific boundary as it covers the entire economy. However, since it uses a national average for a sector rather than detailed data of a specific process, the level of uncertainty is high. For example, the IO table in a country may not distinguish between

the sources of crude oil or the technology used to produce the bitumen while the pollution emission may not be the same in different approaches. Thus, this model is more of screening tool for various approaches rather than providing a concrete answer to LCA concerns. Moreover, for a specific product, it can show where the greatest impact occurs to invest more time in optimization of that sector (Matthews et al. 2015). Another major disadvantage of this method that comes from IO tables is that the phases of use, operation and end of life of a product or process are not covered (Lin 2012).

3.2.4 Hybrid Life Cycle Assessment

The hybrid LCA combines the benefits of PLCA and IO-based LCA. While the core model of it can be either of those two methods, utilizing the elements of the other approach improves the overall model (Matthews et al. 2015). Different versions of hybrid LCA exist, including tiered, IO-based, and integrated (Suh 2004).

In tiered hybrid, the significant steps of a product system are modeled with the detailed data of the process, while the remaining components are analyzed with the IO method. The researcher determines which boundaries to use, depending on the availability of data. The IO-based hybrid analysis is performed through disaggregation of IO model into smaller sectors. For some of these smaller sectors the process data are available to be used in modification and improvement of the IO model. The integrated hybrid models contain a technology matrix to account for physical flow between processes and an economic IO matrix to account for monetary flow between sectors. In cases when the IO data are not up to date or too aggregated, the hybrid model is

employed through the use of process data to overcome such problems. Because of the necessity of managing both physical and monetary units, the integrated models are the most time and data intensive among hybrid LCAs (Matthews et al. 2015).

3.3 Tools for Life Cycle Cost Analysis

Historically, the life cycle assessment was vastly performed for cost estimation by the state DOTs. It was used to determine for example which rehabilitation method is more cost effective. The environmental assessment was not very popular until recent years. Due to the scarcity of environmental assessment tools or lack of precise data, the LCCA is more popular (Santero et al. 2010).

3.3.1 RealCost

Among LCCA tools, the FHWA developed program *RealCost* (Rangaraju et al. 2008) which is maybe the most widely used. In addition to agency costs, the program is able to estimate user costs. The delay to travelers is calculated based on traffic characteristics under normal and construction conditions and a value of time is applied to this delay to provide user costs. However, among the myriad of user cost factors, this program only considers traffic delay time but not the other costs to the users, such as noise, safety, excess fuel consumption, and vehicle wear (Santero et al. 2010).

3.3.2 MnLCCA

Some of state DOTs have come up with their own local LCCA spreadsheets. For example, the Minnesota Department of Transportation has developed *MnLCCA* (MnDOT 2015). There are eight different Excel spreadsheets for various districts of the state, as the pricelist varies between those districts. The program covers both the routine costs of initial construction activities and subsequent rehabilitations strategies for analysis periods of either 35 or 50 years.

Since the regional costs of materials and labor can vary noticeably, it is a wiser decision to perform LCCA with the local pricelists. Therefore, general programs or local spreadsheets of other states are of little help.

3.4 Tools for Life Cycle Environmental Impact Assessment

In recent years, researchers are focusing on assessment of environmental impacts of pavements more than before. Several tools and models have been developed in UK, Denmark, Canada and USA.

3.4.1 ROAD-RES (Birgisdóttir 2005)

The *ROAD-RES* model was developed in Denmark to compare the life cycle environmental impacts of a pavement with municipal solid waste incineration (MSWI) as subbase and a pavement with virgin materials in subbase while the MSWI is deposited in landfill. It includes the phases of material production, construction, maintenance, and

end-of-life, as well as limited leachate information for the use phase. This model covers the environmental burdens to air, soil and water with a special focus on residues and water pollution. These burdens are identified through various factors, such as GWP, photochemical ozone formation, acidification, stratospheric ozone depletion, nutrient enrichment, human toxicity and eco-toxicity. An overview of the *Road-Res* model is presented in Figure 3-2.

3.4.2 BenReMod-LCA (Apul 2007)

This process-based model was introduced in the U.S. to evaluate the environmental impacts of industrial by-products and recycled materials in pavement life cycle. RAP, recycled concrete pavement (RCP), steel slag, fly ash and bottom ash are included in this model. However, the phases of material production and transportation are only considered. The output of the model covers impacts such as GWP, acidification, human toxicity and eco-toxicity.

3.4.3 Project Emission Estimator, PE-2 (Mukherjee 2012)

PE-2 is a hybrid LCA program that provides carbon dioxide footprint of pavement construction phases. Information is obtained from Michigan Department of Transportation data. It includes production of materials, construction, use and maintenance. The emissions related to transportation are also included in the material production phase. In the use phase, the effect of detours and traffic delays are calculated from another simulation package, called "*MOVES*".

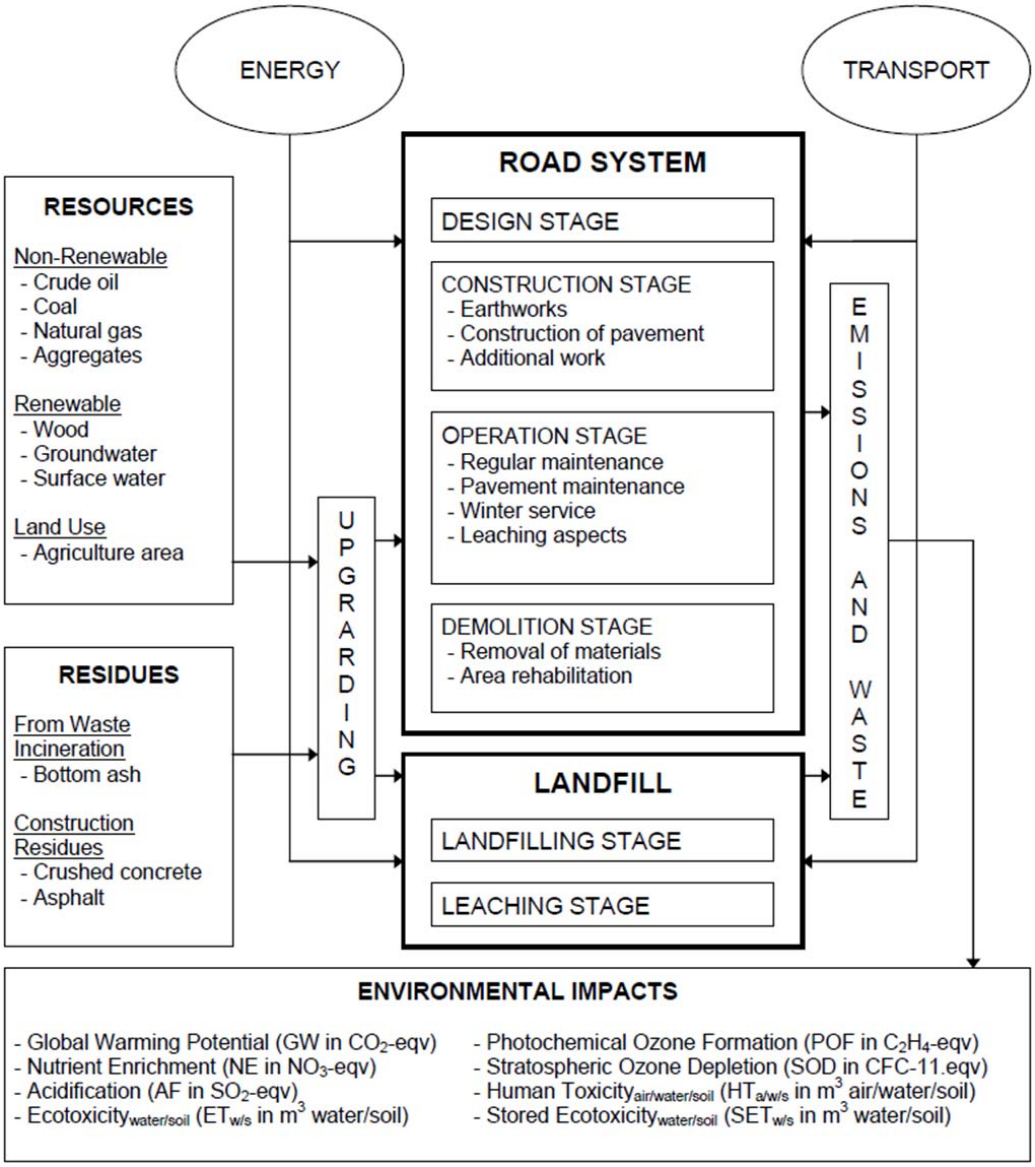


Figure 3-2. Overview of *Road-Res* Model (Birgisdóttir 2005)

3.4.4 Huang's Model (Huang et al. 2009)

Huang developed a PLCA tool in Excel to estimate the environmental impacts of HMA pavements construction and maintenance. The model considers production of materials, transport, construction, maintenance and end-of-life. The environmental impacts are

determined based on UK and European database. It can consider recycled materials, such waste glass, incinerated bottom ash, and RAP. The structure of the model is depicted in Figure 3-3. The model provides depletion of minerals and fossil fuels, GWP, acidification, ozone depletion, photochemical smog, human toxicity, eco-toxicity, noise, depletion of landfill space and eutrophication. However, the environmental burden is presented for the entire life cycle of pavement and not for individual phases separately. Moreover, since the model is not available to public, it is not possible to further evaluate the results (Lin 2012).

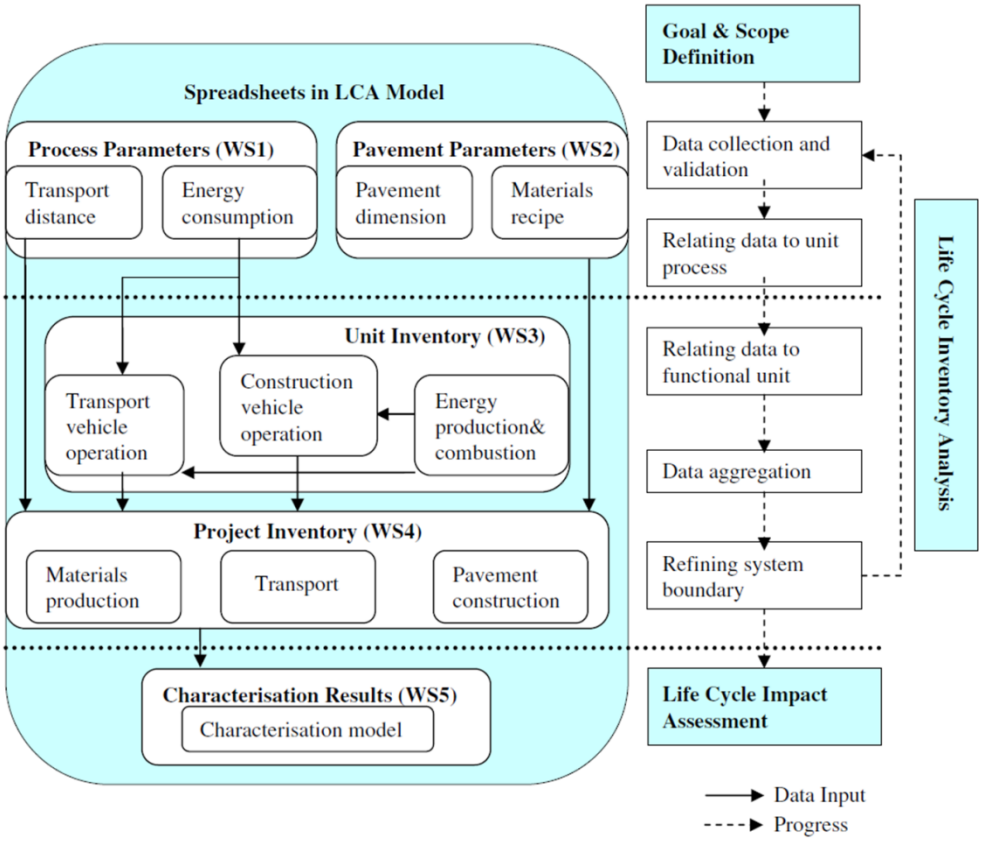


Figure 3-3. Structure of the LCA Model and Procedures for Inventory Analysis (Huang et al. 2009)

3.4.5 Athena Pavement Life-Cycle Assessment (Athena Institute 2013)

Athena Impact estimator for highways was developed in Canada to perform LCA for different stages of pavements life. It covers materials manufacturing, construction, use and rehabilitation stages. This estimator uses the data from nine regional locations of Canada and includes a wide variety of roadway designs from arterial design to multilane highways. It also has a very large database of materials and equipment. It is one of the few tools that compute the increase in fuel consumption based on stiffness and roughness of the pavement surface. The outputs of the program are GWP, acidification, human health criteria, ozone depletion, smog and eutrophication, as well as fossil fuel consumption.

3.4.6 Pavement Life-Cycle Assessment Tool for Environmental and Economic Effects, PaLate (Horvath 2004)

The University of California-Berkley developed *PaLate* as a hybrid LCA. It is an Excel spreadsheet program that provides both the cost estimation and the environmental impacts of pavement construction. It allows the inclusion of virgin and recycled materials. Initial construction, maintenance and equipment use are considered in this tool. Figures 3-4 and 3-5 show the overview and covered activities in *PaLate*. The program is composed of multiple worksheets that require the user's input.

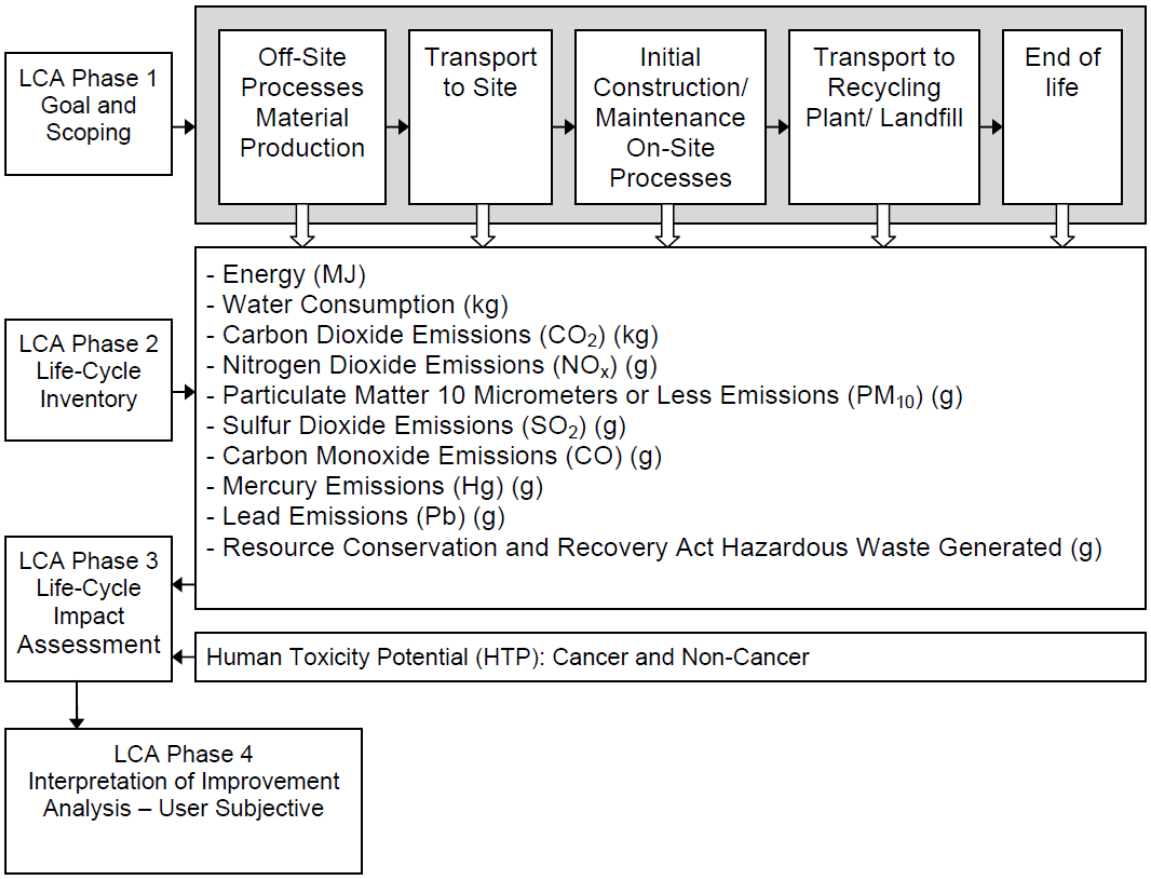


Figure 3-4. Overview of the *PaLate* Model (Nathman et al. 2009)

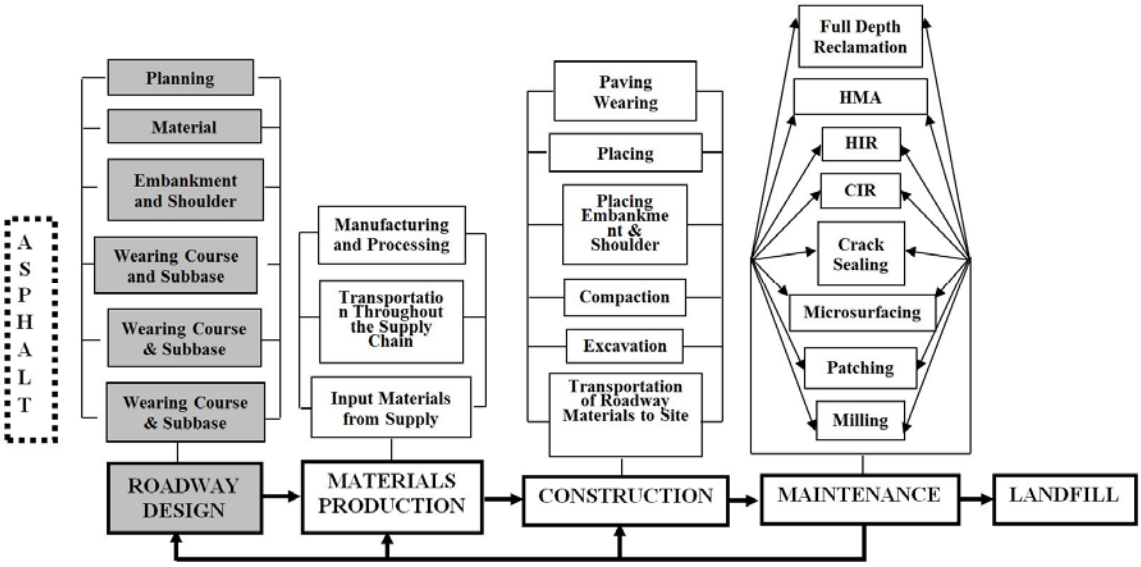


Figure 3-5. Flowchart of the Covered Activities in the *PaLate* Program

- Geometrical parameters of roadway design

This worksheet allows the user to enter width, length and depth of each layer of the pavement section. Up to three wearing courses and four subbase layers can be considered in the program. However, for embankment and shoulder, the total volume should be entered directly. The analysis period is another input in this worksheet. A screenshot of the design worksheet is shown in Figure 3-6.

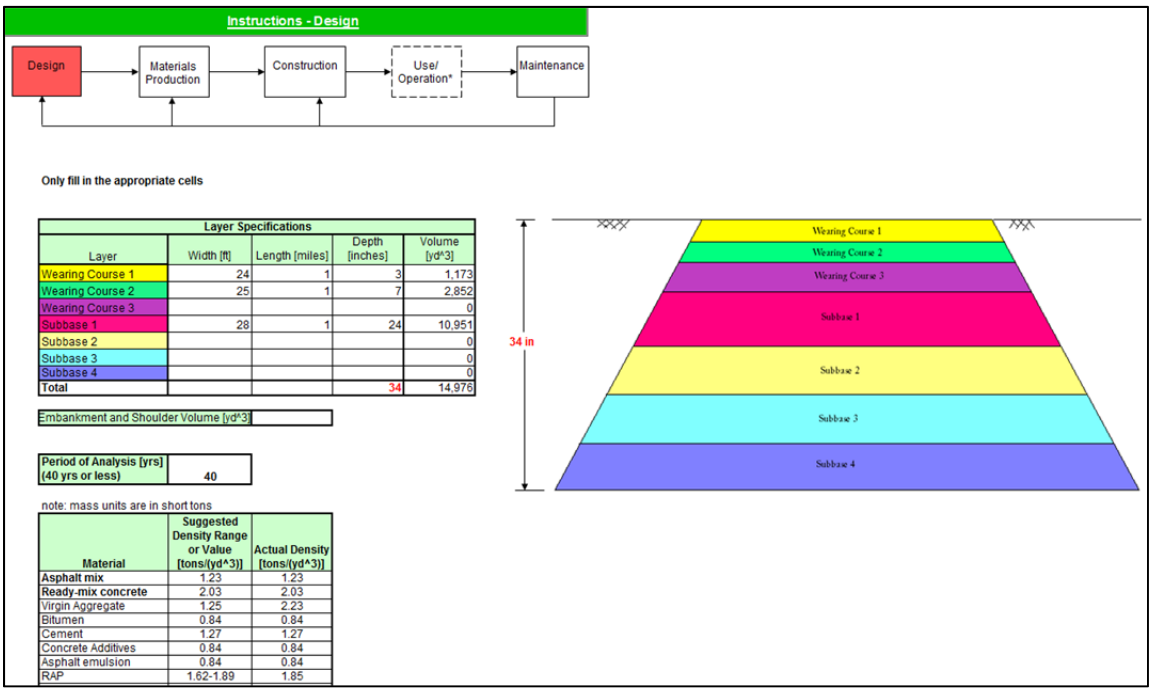
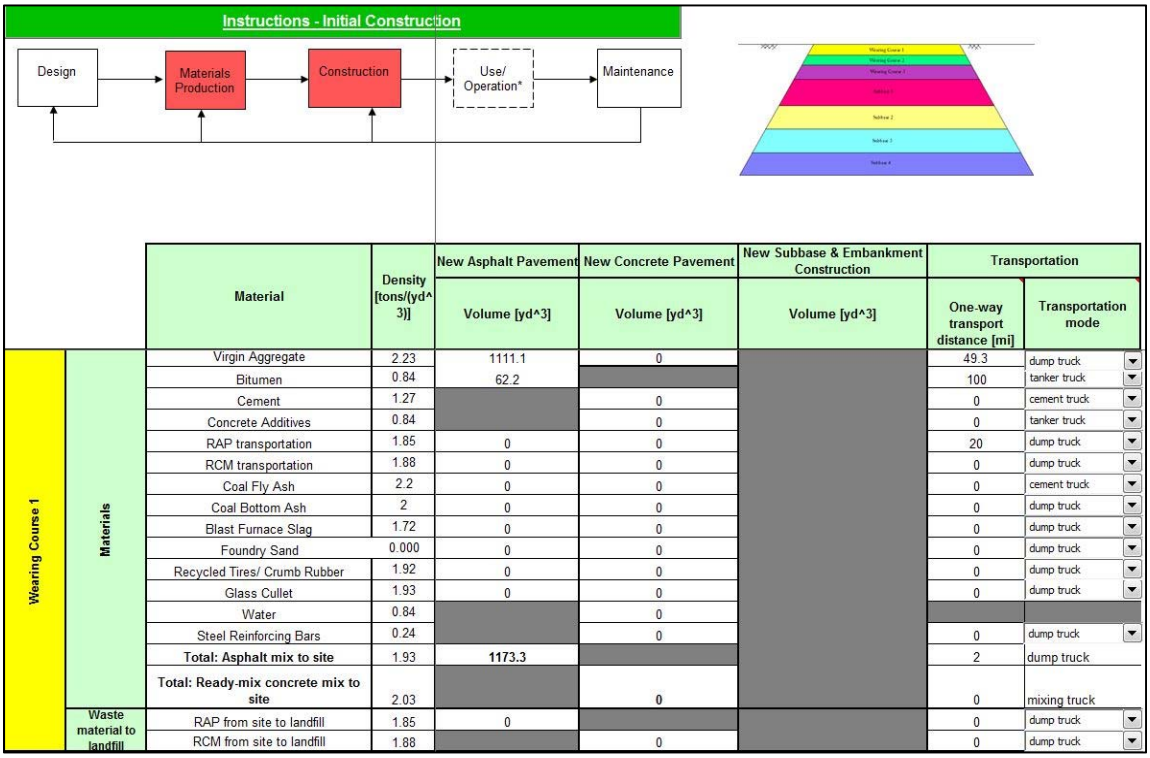


Figure 3-6. User Inputs in the Design Module of *PaLate*

- Initial construction and maintenance

Two separate worksheets for initial construction and maintenance need the user to enter the total volume of required materials in each activity. The densities of the materials are already included in the program. However, these values can be changed at the users'

discretion. The user can enter the distance of transport and select its mode from five different options of dump truck, tanker truck, cement truck, rail and barge. Figure 3-7 shows a screenshot of the initial construction worksheet.

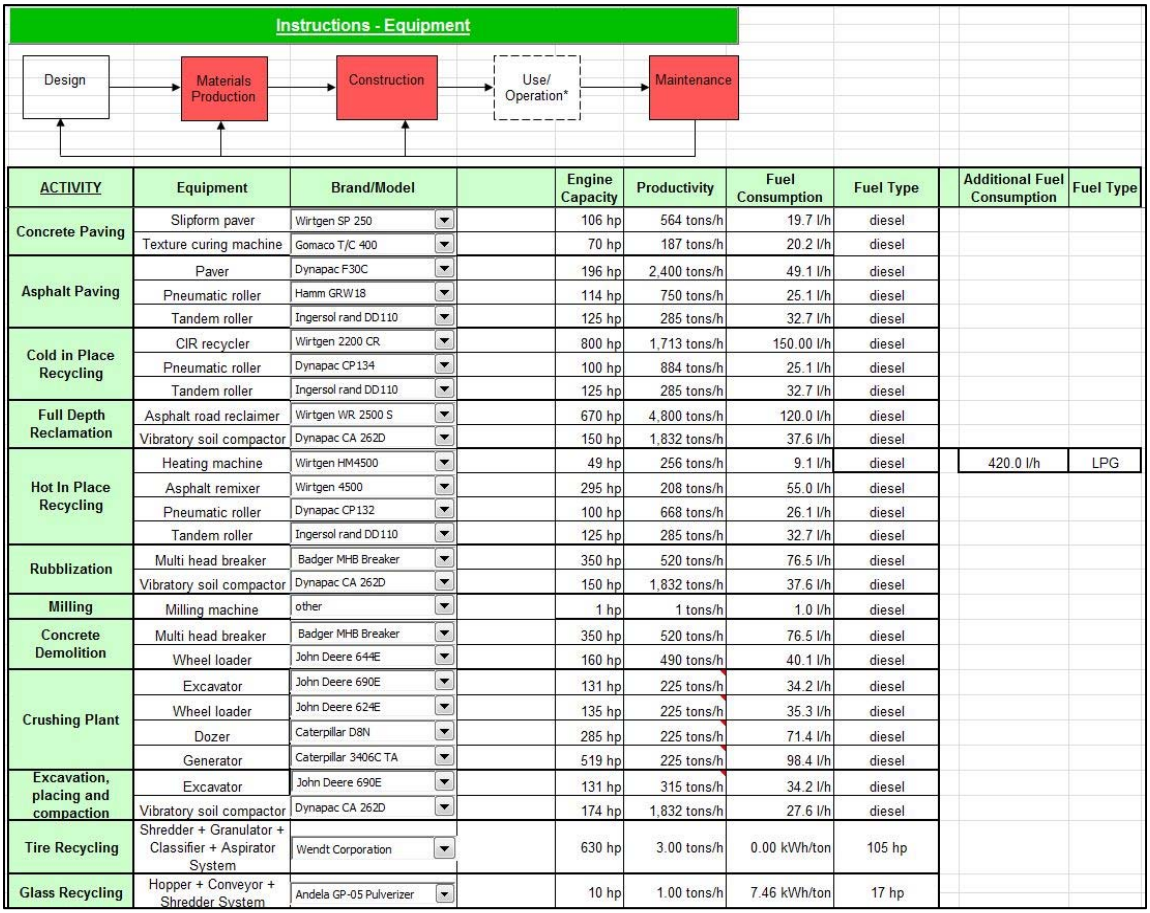


		Material	Density [tons/(yd^3)]	New Asphalt Pavement Volume [yd^3]	New Concrete Pavement Volume [yd^3]	New Subbase & Embankment Construction Volume [yd^3]	Transportation One-way transport distance [mi]	Transportation mode
Wearing Course 1	Materials	Virgin Aggregate	2.23	1111.1	0		49.3	dump truck
		Bitumen	0.84	62.2			100	tanker truck
		Cement	1.27		0		0	cement truck
		Concrete Additives	0.84		0		0	tanker truck
		RAP transportation	1.85	0	0		20	dump truck
		RCM transportation	1.88	0	0		0	dump truck
		Coal Fly Ash	2.2	0	0		0	cement truck
		Coal Bottom Ash	2	0	0		0	dump truck
		Blast Furnace Slag	1.72	0	0		0	dump truck
		Foundry Sand	0.000	0	0		0	dump truck
		Recycled Tires/ Crumb Rubber	1.92	0	0		0	dump truck
		Glass Cullet	1.93	0	0		0	dump truck
		Water	0.84		0			
		Steel Reinforcing Bars	0.24		0		0	dump truck
		Total: Asphalt mix to site	1.93	**1173.3**			2	dump truck
		Total: Ready-mix concrete mix to site	2.03		**0**		0	mixing truck
	Waste material to landfill	RAP from site to landfill	1.85	0			0	dump truck
		RCM from site to landfill	1.88		0		0	dump truck

Figure 3-7. User Inputs in the Initial Construction Module of *PaLate*

- Definition of equipment

On-site construction and maintenance equipment as well as off-site processing equipment can be defined in this worksheet. A variety of equipment types are already defined in the program for each activity. However, if one would like to add a different equipment type, it can be done in the "equipment details" worksheet. Figure 3-8 shows the equipment definition worksheet.



ACTIVITY	Equipment	Brand/Model		Engine Capacity	Productivity	Fuel Consumption	Fuel Type		Additional Fuel Consumption	Fuel Type
Concrete Paving	Slipform paver	Wirtgen SP 250		106 hp	564 tons/h	19.7 l/h	diesel			
	Texture curing machine	Gomaco T/C 400		70 hp	187 tons/h	20.2 l/h	diesel			
Asphalt Paving	Paver	Dynapac F30C		196 hp	2,400 tons/h	49.1 l/h	diesel			
	Pneumatic roller	Hamm GRW18		114 hp	750 tons/h	25.1 l/h	diesel			
	Tandem roller	Ingersol rand DD110		125 hp	285 tons/h	32.7 l/h	diesel			
Cold in Place Recycling	CIR recycler	Wirtgen 2200 CR		800 hp	1,713 tons/h	150.00 l/h	diesel			
	Pneumatic roller	Dynapac CP134		100 hp	884 tons/h	25.1 l/h	diesel			
	Tandem roller	Ingersol rand DD110		125 hp	285 tons/h	32.7 l/h	diesel			
Full Depth Reclamation	Asphalt road reclaimer	Wirtgen WR 2500 S		670 hp	4,800 tons/h	120.0 l/h	diesel			
	Vibratory soil compactor	Dynapac CA 262D		150 hp	1,832 tons/h	37.6 l/h	diesel			
Hot In Place Recycling	Heating machine	Wirtgen HM4500		49 hp	256 tons/h	9.1 l/h	diesel		420.0 l/h	LPG
	Asphalt remixer	Wirtgen 4500		295 hp	208 tons/h	55.0 l/h	diesel			
	Pneumatic roller	Dynapac CP132		100 hp	668 tons/h	26.1 l/h	diesel			
	Tandem roller	Ingersol rand DD110		125 hp	285 tons/h	32.7 l/h	diesel			
Rubblization	Multi head breaker	Badger MHB Breaker		350 hp	520 tons/h	76.5 l/h	diesel			
	Vibratory soil compactor	Dynapac CA 262D		150 hp	1,832 tons/h	37.6 l/h	diesel			
Milling	Milling machine	other		1 hp	1 tons/h	1.0 l/h	diesel			
Concrete Demolition	Multi head breaker	Badger MHB Breaker		350 hp	520 tons/h	76.5 l/h	diesel			
	Wheel loader	John Deere 644E		160 hp	490 tons/h	40.1 l/h	diesel			
Crushing Plant	Excavator	John Deere 690E		131 hp	225 tons/h	34.2 l/h	diesel			
	Wheel loader	John Deere 624E		135 hp	225 tons/h	35.3 l/h	diesel			
	Dozer	Caterpillar D8N		285 hp	225 tons/h	71.4 l/h	diesel			
	Generator	Caterpillar 3406C TA		519 hp	225 tons/h	98.4 l/h	diesel			
Excavation, placing and compaction	Excavator	John Deere 690E		131 hp	315 tons/h	34.2 l/h	diesel			
	Vibratory soil compactor	Dynapac CA 262D		174 hp	1,832 tons/h	27.6 l/h	diesel			
Tire Recycling	Shredder + Granulator + Classifier + Aspirator System	Wendt Corporation		630 hp	3.00 tons/h	0.00 kWh/ton	105 hp			
Glass Recycling	Hopper + Conveyor + Shredder System	Andela GP-05 Pulverizer		10 hp	1.00 tons/h	7.46 kWh/ton	17 hp			

Figure 3-8. User Inputs in the Equipment Module of *PaLate*

- Definition of cost parameters

The program provides two options for the input of the cost parameters. The first option is to enter the final cost of each activity per cubic yard of the mixture that was used. The second one is to enter separately the cost of each component of the mixture (e.g. virgin aggregates, bitumen, etc.) per cubic yard along with the costs associated with labor, equipment, overhead and profit. In both options, the cost of transporting RAP (or Reclaimed Concrete Material, RCM) to landfill and its tipping fee is determined based on

the state in which the project is selected to be constructed. Figure 3-9 illustrates a portion of "Costs" worksheet.

BASE SCENARIO	
Period of Analysis [yrs] (40 yrs or less)	40
Discount Rate [%] (e.g., 5.00)	4.00%
UCRF	0.0505

Enter the discount rate in the blue table AND fill out EITHER the green table OR the orange table.

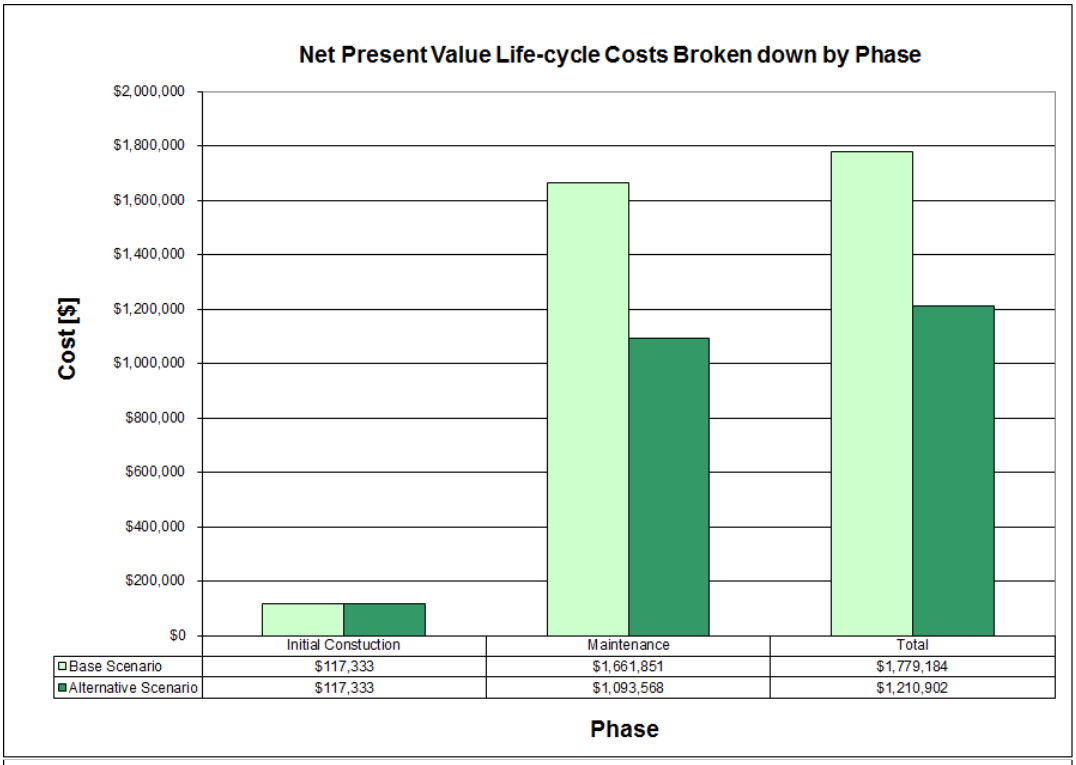
BASE SCENARIO

Installed Asphalt Paving Cost			Installed Concrete Paving Cost		
Expected Cost:	0		Expected Cost[$/yd^2]:	31	
Initial Construction Volume [yd^3]:	1173.3		Initial Construction Volume [yd^3]:	0	
Total Maintenance Volume [yd^3]:	32853.3		Total Maintenance Volume [yd^3]:	0	
Year	Volume [yd^3]	Unit Cost [$/(yd^3)]	Actual Cost [$]	Volume [yd^3]	Unit Cost [$/(yd^3)]	Actual Cost [$]
0	1173.3	100	117333.3	0	0	0
1	0	0	0	0	0	0
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	0	0	0	0	0	0
5	0	0	0	0	0	0
6	0	0	0	0	0	0
7	0	0	0	0	0	0
8	0	0	0	0	0	0
9	0	0	0	0	0	0
10	16426.7	100	1642666.7	0	0	0
11	0	0	0	0	0	0
12	0	0	0	0	0	0
13	0	0	0	0	0	0
14	0	0	0	0	0	0
15	0	0	0	0	0	0
16	0	0	0	0	0	0
17	0	0	0	0	0	0
18	0	0	0	0	0	0
19	0	0	0	0	0	0
20	16426.66667	100	1642666.667	0	0	0

Virgin Aggregate		Bitumen		Cement	
Expected Cost: 9.33		Expected Cost: 0		Expected Cost: $100.00 /ton	
Total Initial Construction Volume [yd^3]: 1111.146667		Total Initial Construction Volume [yd^3]: 62.18666667		Total Initial Construction Volume [yd^3]: 0	
Total Maintenance Volume [yd^3]: 15556.05333		Total Maintenance Volume [yd^3]: 870.6133333		Total Maintenance Volume [yd^3]: 0	
Year	Volume [yd^3]	Actual Cost [$]	Volume [yd^3]	Actual Cost [$]	Volume [yd^3]	Actual Cost [$]
0	1111.146667	48000	62.18666667	20000	0	0
1	0	0	0	0	0	0
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	0	0	0	0	0	0
5	0	0	0	0	0	0
6	0	0	0	0	0	0
7	0	0	0	0	0	0
8	0	0	0	0	0	0
9	0	0	0	0	0	0
10	0	0	0	0	0	0
11	0	0	0	0	0	0
12	0	0	0	0	0	0
13	0	0	0	0	0	0
14	0	0	0	0	0	0
15	0	0	0	0	0	0
16	0	0	0	0	0	0
17	0	0	0	0	0	0
18	0	0	0	0	0	0
19	0	0	0	0	0	0
20	0	0	0	0	0	0

Figure 3-9. User Inputs in the Cost Module of *PaLate*

The outputs of program are presented in two worksheets of "Cost Results" and "Environmental Results". *PaLate* employs a life cycle cost (LCC) framework that combines the cost of construction, maintenance and salvage value as agency cost, and the cost of traffic delays, damage to vehicles and accidents as user cost. It can consider two scenarios for construction and maintenance in parallel for comparison purposes. The "Cost Results" worksheet provides the Net Present Value (NPV) and the Equivalent Uniform Annualized Cost (EUAC) of each defined scenario. The EUAC is superior to the NPV whenever the alternatives do not have the same analysis period. The output charts include the cost broken down by either construction phases, or by materials and processes (Figure 3-10).



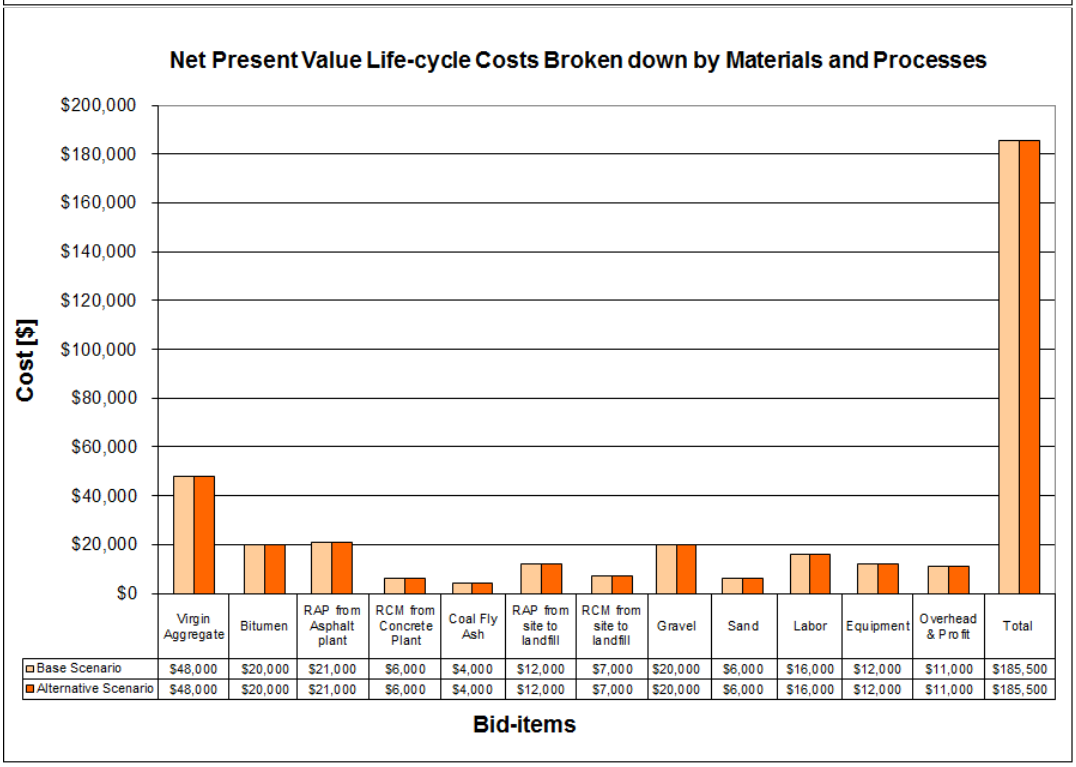


Figure 3-10. The Cost Results Worksheet of *PaLate*

The "Environmental Results" worksheet provides a variety of environmental impacts, including energy and water consumption, potential leachates, RCRA hazardous waste generated, human toxicity potential, and emissions of Mercury, Lead, CO_2, NO_X, PM_{10}, SO_2, and CO. For PM_{10} emission calculations, *PaLate* also considers aggregates and RAP truck loading and unloading and transporting (not fuel related) from site to landfill or plant. The output of program for environmental analyses separates the burden of materials production, materials transport and processes (equipment). Figure 3-11 shows an example of outputs for energy consumption.

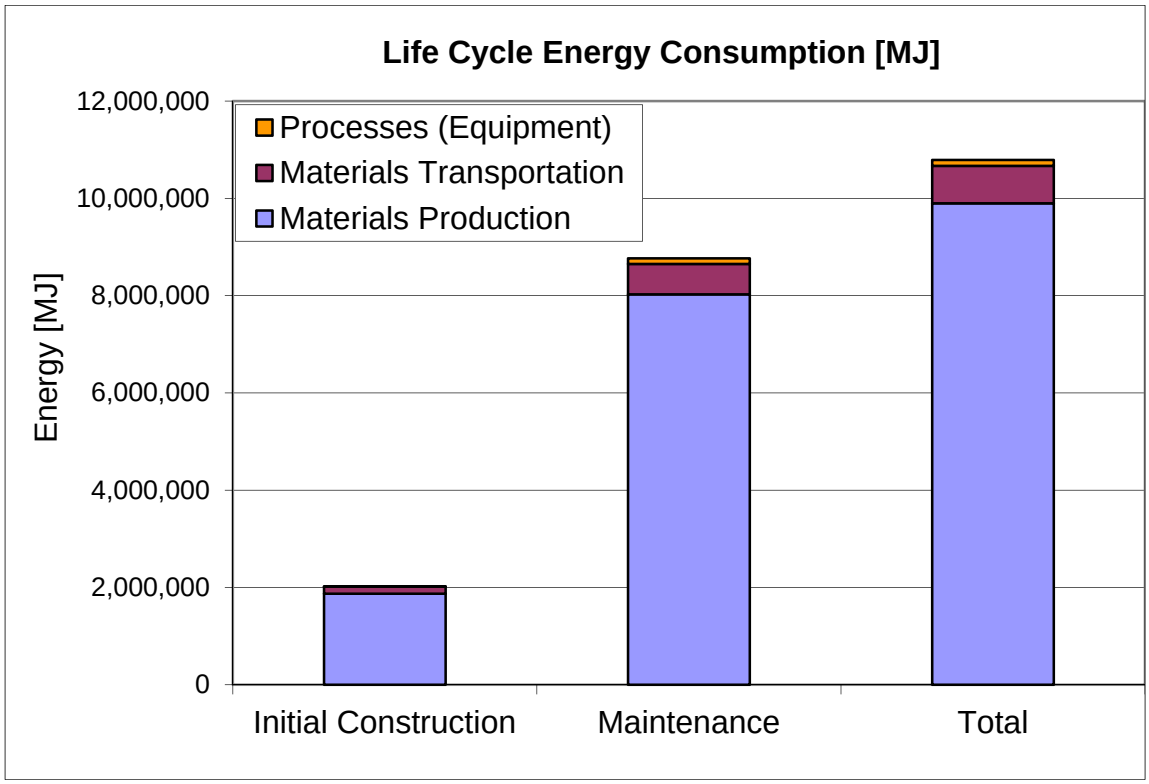


Figure 3-11. Energy Consumption Output in *PaLate*

As it can be seen, the program is very transparent and allows the user to modify the basic parameters. The downside of the program is that the implemented LCA model is not very up to date. A further refinement of database can make the program a very strong tool for life cycle assessments (Nathman et al. 2009).

3.4.7 Roadprint (Lin 2012)

Roadprint was developed at the University of Washington for both probabilistic and deterministic LCA of pavements. It was originally an Excel spreadsheet and later became available as an online tool. This is the most recent LCA tool for pavements. *Roadprint* covers material production, transport, construction, maintenance, and end-of-life phases of a pavement's life. The following information has been considered in the development of HMA part of Life Cycle Inventory (LCI).

- Energy Production
- Transport Activities
- Production of Bitumen (controversial feedstock energy is presented separately)
- Production of Aggregate
- HMA Plant Operation
- HMA Milling as RAP Production
- Operation of Construction and Rehabilitation Equipment

However, less significant processes such as signage, lighting or stripping, and processes with uncertain data such as traffic or pavement condition were ignored. Figure

3-12 illustrates the system boundary of the program including unit processes, scope, and exclusions.

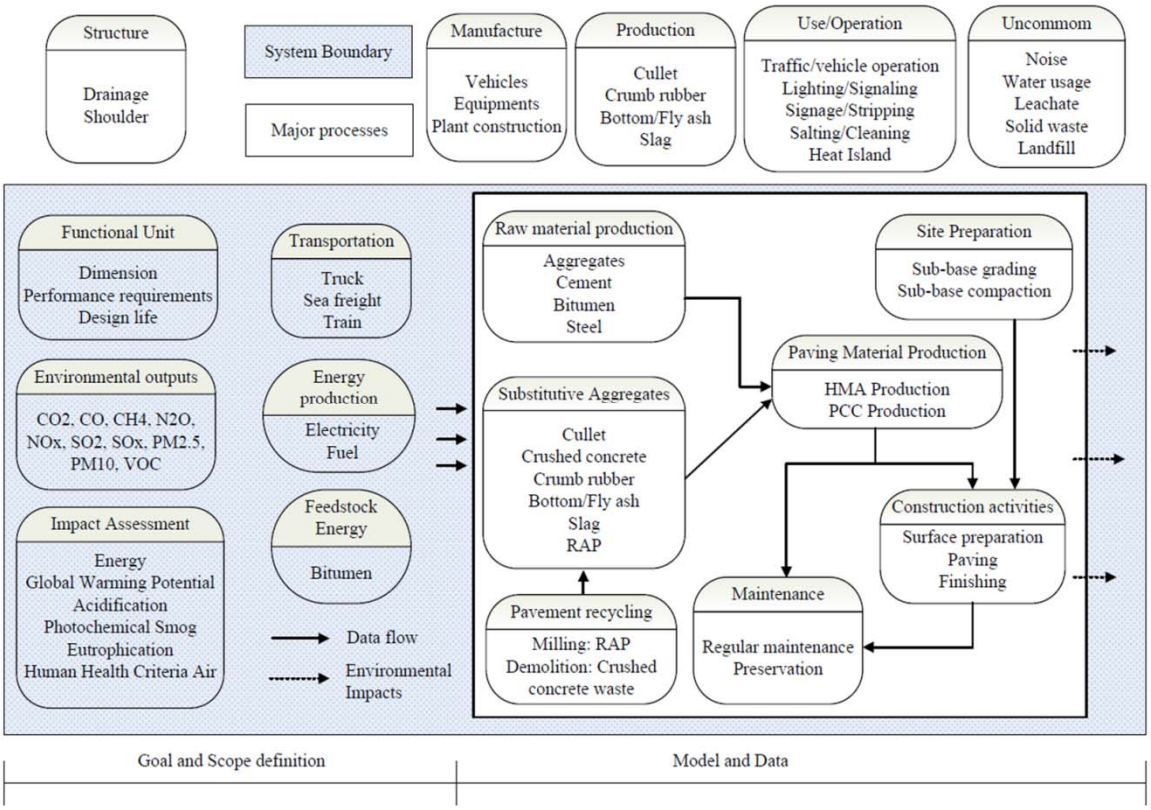


Figure 3-12. System Boundary of *Roadprint* Program (Lin 2012)

The online tool consists of five different sections/tabs. The first tab allows the user to enter the basic road information. It includes the selection of the state in which the project is constructed, the analysis period, the number of M&R and the pavement geometry (Figure 3-13).

The input of road materials for both initial construction and maintenance is done in the second tab. Depending on the type of pavement (flexible or rigid), the components of base and surface courses are entered separately from a list of available materials,

including virgin aggregates, sand and gravel, bitumen, etc. Figure 3-14 illustrates the second tab of the program.

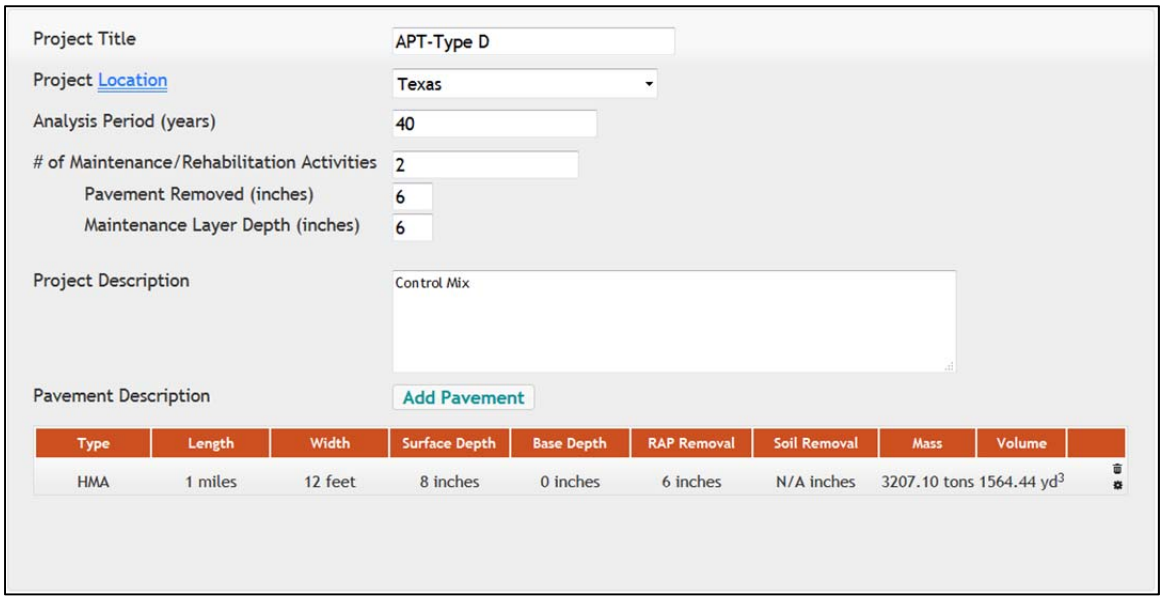


Figure 3-13. *Roadprint* Basic Road Information Tab

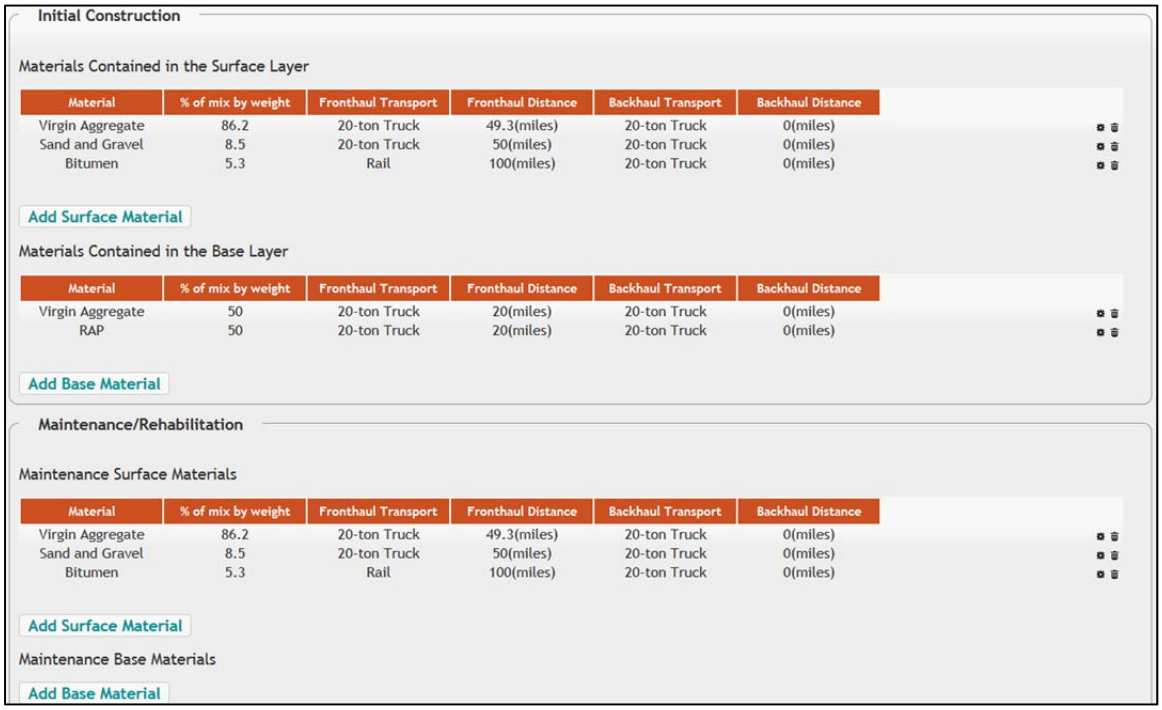


Figure 3-14. *Roadprint* Materials Input Tab

Roadprint splits the third tab into two parts to allow the input of equipment for initial construction and maintenance phases. After selection of the appropriate equipment, its characteristics (e.g. engine horsepower and efficiency) will be entered. This tab also provides this opportunity for the user to include the burdens of HMA plant. A list of defined equipment for asphalt pavements in *Roadprint* is presented in Figure 3-15.

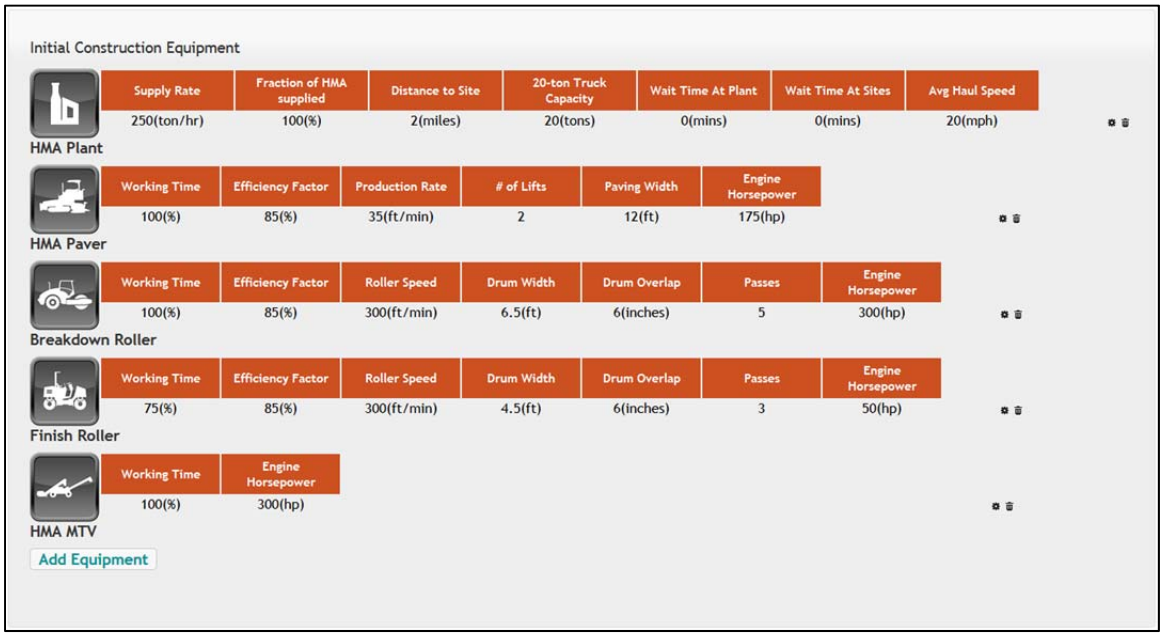


Figure 3-15. *Roadprint* Equipment Definition Tab

The fourth and fifth tabs of the program provide the outputs in graphical and tabular forms, respectively. These outputs include the energy consumption and emissions of CH_4, CO, CO_2, SO_2 (acidification), NO_X (photochemical smog), PO_4 (eutrophication), PM_{10}, PM_{25}, N_{20}, VOC, GWP, smog and human health criteria. A sample of graphical output is shown in Figure 3-16. In addition to the presentation of these outputs, the

Roadprint online tool allows the user to export the data as an Excel spreadsheet which facilitates further processing.

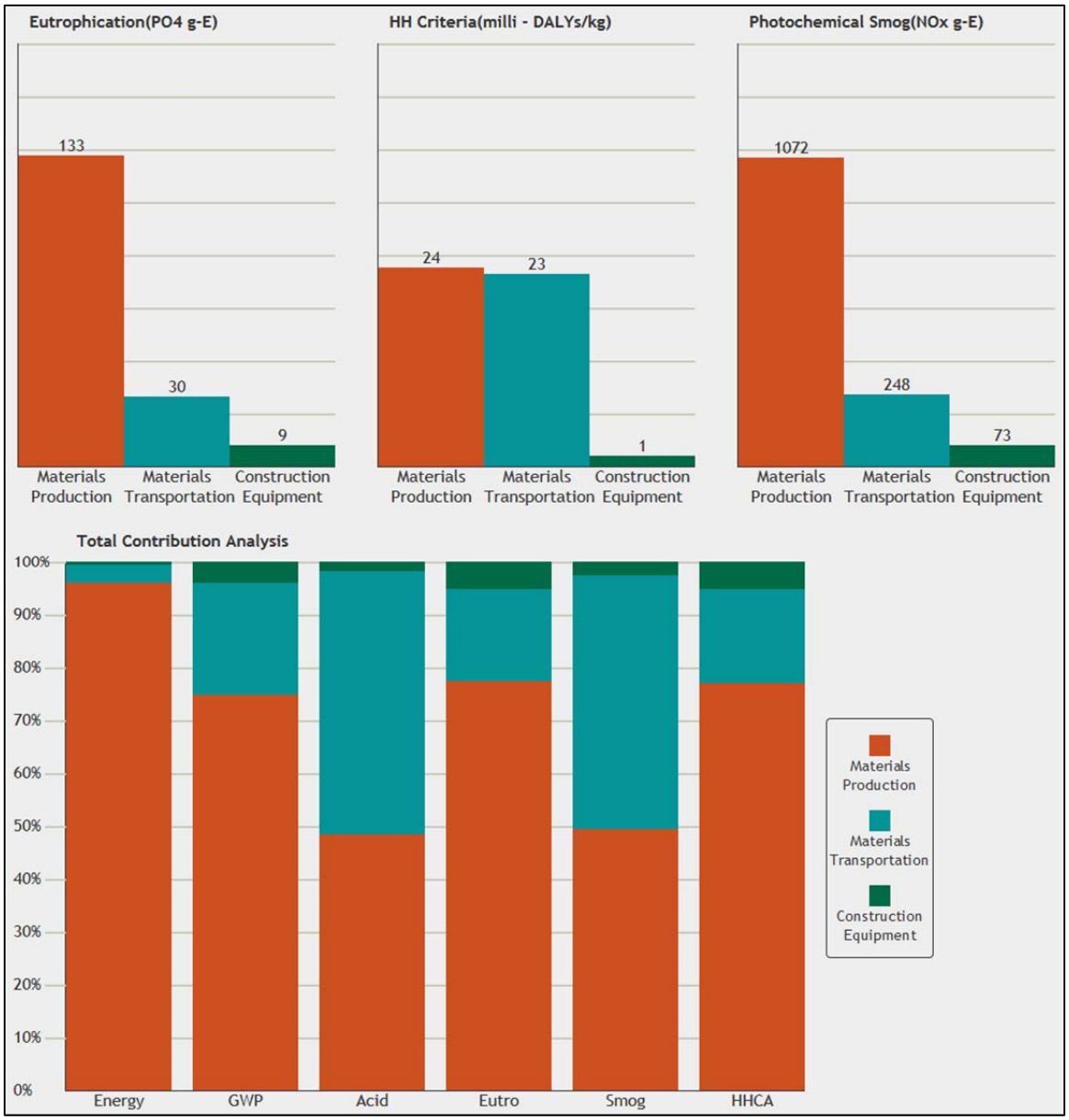


Figure 3-16. *Roadprint* Graphical Data Output Tab

Regarding the Roadprint program it should be mentioned that:

1) The feedstock energy of produced bitumen is provided separately, as it is still undecided among the researchers (Santero 2010 and Kang et al. 2014) that bitumen should be considered as a source of energy or not.
2) If no recycling information (e.g. milling) is provided in the program, the RAP will be treated as free product. It means that it will be considered with no consumed energy or environmental burden.
3) Pavement construction equipment is selected based on the engine size (HP). It is assumed that the equipment with the same engine size will consume same amount of energy and have same amount of air emissions.
4) The *Roadprint* program has adopted the method developed by Heijung and Suh (2002) to perform inventory calculations. This method considers a comprehensive matrix for all the unit processes of a functional unit. The matrix is then subdivided into two smaller matrices. One of them accounts for economic inflows and outflows and the other one accounts for environmental effects and resource usage. An example of calculation for this method is given in Appendix A.

3.4.8 Selection of Superior Tools for Assessment of Environmental Impacts

Several factors influence the selection of an appropriate tool for LCA. The most important one is its availability to general public. Some of the aforementioned models are not accessible for everyone (e.g. Huang's Model). In addition to that, the tool should provide the required output for a comprehensive assessment. Some of the programs

calculate only a few parameters (e.g. PE-2). Another important factor is the region in which the program has been developed. The results of LCA greatly depend on the data inventory which has been collected in a specific region. Therefore, the assessment should be done with a tool that includes the on-site and off-site equipment and processes, similar to the ones that are used in the actual project. Based on this, even a comprehensive tool such as Athena cannot be a reliable program for LCA in the U.S., as it was developed in Canada.

Among the current tools, *PaLate* and *Roadprint* are the two that are available to the public, provide comprehensive output regarding energy consumption and emissions, and also have been developed in the U.S. Between these two, Roadprint should provide more reliable results as its inventory is more up to date.

3.5 Studies of Life Cycle Analyses of Environmental Impacts and Cost

The pavement service life is analyzed both for its environmental burdens and cost. This section provides the recent findings of researchers on LCA and LCCA of asphalt concrete pavements.

3.5.1 Studies of Life Cycle Environmental Impacts

Cochran (2006) compared the environmental impacts of recycling of asphalt shingles with their disposal. The comparison was in terms of potentials of global warming, human toxicity, material depletion and acidification. She concluded that the inclusion of RAS in

HMA saves energy and adds less environmental burdens compared with disposing shingles in landfills and utilizing all virgin materials.

Button et al. (2007) reviewed several publications on WMA mixtures and concluded that the utilization of WMA technology in general results in 30 percent less emission of CO_2, 40 percent reduction in fumes, and 50 to 60 percent less generated dust. For a few jobs where energy consumption has been measured (e.g. Kristjansdottir et al. 2007), the production of WMA needed 20 to 75 (mostly in the range of 30 to 50) percent less energy when compared with the HMA production.

Chiu et al. (2008) evaluated the environmental impacts of different methods of rehabilitation for flexible pavements. They considered typical HMA, RAP included HMA, asphalt rubber and glassphalt as rehabilitation techniques. They found that the production of virgin asphalt is the main carrier of environmental burden. Based on that, they stated that the reduction of asphalt content can significantly decrease the emissions. However, one should be aware that this can affect the performance of pavement which in long term results in higher energy consumption and emissions. They also concluded that using recycled HMA cuts 23 percent of environmental burden while glassphalt increased that by 19 percent.

Hassan (2009) developed a life cycle inventory (LCI) for energy, material inputs and emissions for the entire material production and construction phases of flexible pavements. Based on the inventory, she compared the LCA of WMA technology (WAM®-foam) with that of a conventional HMA. She found that the WMA pollutes the air 24 percent less than HMA and the fossil fuel consumption is also 18 percent less. She

concluded that the overall environmental impact of WMA is about 15 percent less than that of HMA.

Tatari et al. (2012) also evaluated the environmental benefits of three WMA technologies against HMA. Four pavement sections with similar structures have been designed with the Mechanistic Empirical Pavement Design Guide (MEPDG) program. Three WMA technologies of Aspha-min, Sasobit and Evotherm were considered versus conventional HMA. All the sections were designed with 9.5 mm (3/8 inch) NMAS of Marshal mix with OAC of 6.1 percent and 15 percent RAP. Aside from energy consumption and multiple emission factors, the authors also calculated the resource consumption for HMA and WMA with an Eco-LCA methodology. They found that material extraction and production is the phase that consumes the highest amount of resources. They also stated that the Aspha-min WMA was the least sustainable when total energy, emissions and ecological resources are considered all together. WMA with Sasobit had the lowest CO_2 emission. They did not consider any actual field project. However, based on their analyses, they concluded that WMAs do not perform significantly better than HMA if a hybrid LCA is utilized.

Zhou et al. (2013) conducted a literature review on the economic factors of RAS recycling. Based on the publications, they concluded that the potential savings by using RAS in HMA will be even more in the future as the price of liquid AC and landfill tipping fees will increase. Therefore, more investment should be made in equipment and training of asphalt practitioners to incorporate RAS into HMA.

A report published by Environmental Protection Agency (EPA 2013) analyzed the life cycle of RAS in pavement mixtures. Studied mixtures contained different amounts of RAS and RAP with or without WMA technology. It was concluded that the introduction of RAP and RAS to their maximum allowed amount will reduce the GHG considerably. For mixes with 20% RAP, by changing the production from HMA to WMA, 12 percent energy can be saved at the asphalt plant. Additionally, to improve the asphalt life cycle, it was recommended to focus more on efficiency of plant, as it is responsible for nearly 21 percent of the gross GHG emissions in recycled HMA cases, about 16 percent in the virgin case, and 15 percent in WMA case.

Yang (2014) developed a software tool based on her LCA framework that evaluates the environmental effects of five major phases of pavement life, including material production, construction, maintenance, use, and end-of-life. She considered a case study in Illinois with 11 SMA and HMA mixtures in a 60 years analysis period. In the material production phase, she found that both in terms of energy consumption and GWP, plant operation to produce asphalt mixture is responsible for nearly 50 percent of the burden while binder production incurs 33 percent. The contribution of crushed aggregate was 16 to 19 percent and other materials such as RAP had negligible influence. Results of her study indicated that the use phase is the dominant phase, responsible for almost 92 percent of energy consumption and GWP while material and maintenance phases each contribute only 3-4 percent. In her study, construction and end-of-life phases were liable for only 1.2 and 0.3 percent, respectively.

Lin (2012) evaluated the life cycle of a standard Washington DOT pavement designs as an assessment for *Roadprint* program. The considered pavement was one mile long, 12ft wide for 25,000,000 to 50,000,000 ESALs traffic and analysis period of 50 years. The pavement structure consisted of 11 inch HMA over 7 inch crushed rock base. He assumed that the flexible pavement requires three times maintenance of replacing 1.8 inch of surface HMA. The HMA mix design included 5 percent bitumen, 85 percent crushed rock, and 10 percent sand by weight. All the materials transportation distance was considered 50km (31 miles). The impact assessment results of his study are depicted in Figures 3-17 and 3-18.

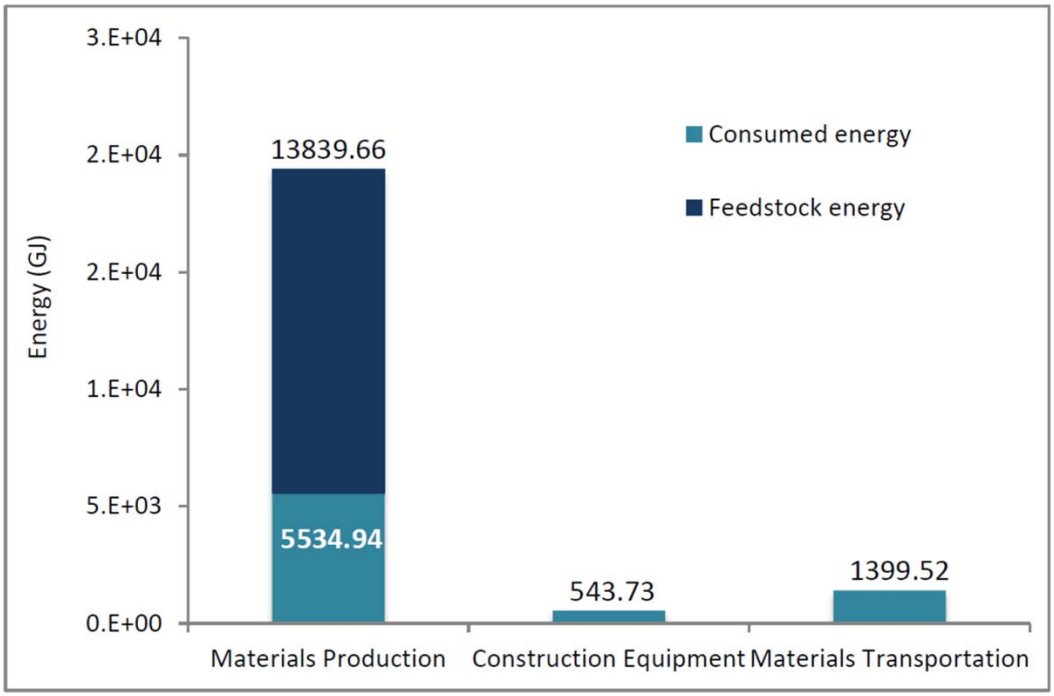


Figure 3-17. Energy Consumption Results for HMA (Lin 2012)

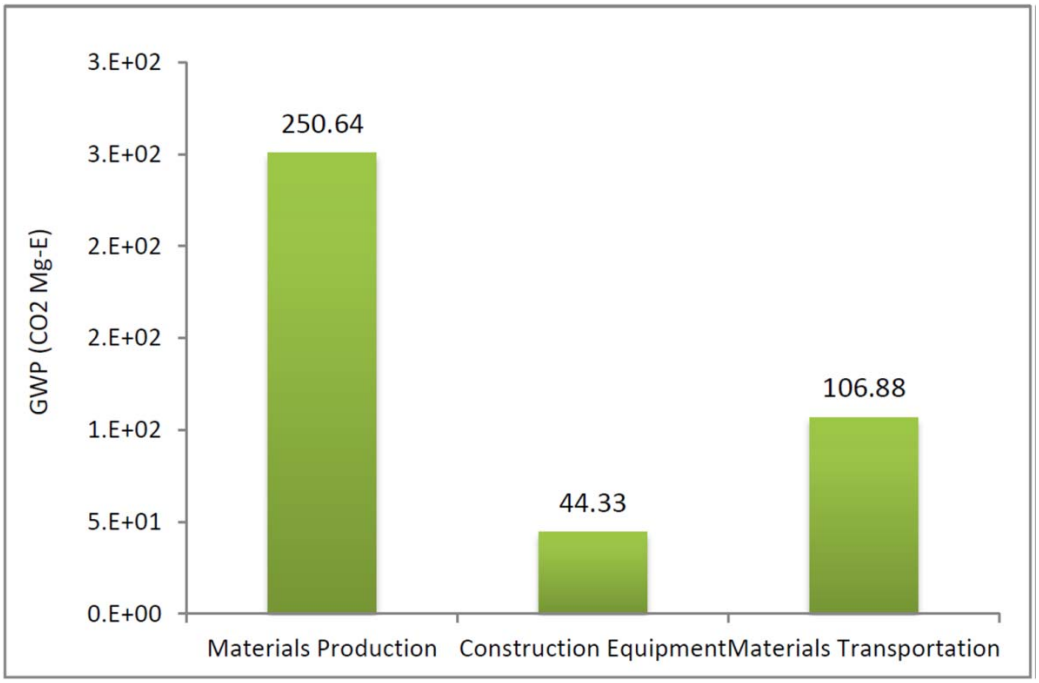


Figure 3-18. GWP Results for HMA (Lin 2012)

As it can be seen, material production was the most energy intensive and also yielded the highest GWP while the construction phase was insignificant. The deconstruction of material production stage is presented in Table 3-1 for further evaluation.

If the controversial feedstock energy is set aside, then the HMA mixture production and bitumen production are the top two energy consuming processes, 68 percent and 25 percent, respectively. The same is true for GWP results. The aggregate production is responsible for 7 percent energy consumption while the major constituent of HMA is the virgin aggregate.

Based on his findings, it can be concluded that in terms of mix design, lower bitumen content can significantly reduce the energy consumption and environmental

burden. Additionally, In terms of mixture production, newer technologies such as WMA should be used to decrease this noticeable burden of plant operation.

Table 3-1. Energy and GWP Deconstruction of Material Production (Lin 2012)

	Energy* (GJ)		Energy (GJ)		GWP(CO_2 Mg-E)	
	Value	%	Value	%	Value	%
HMA/WMA	3742.8	19.3	3742.8	68	136.5	54.4
PCC	0.0	0	0.0	0	0.0	0
Virgin Aggregate	400.4	2.1	400.4	7	17.2	6.9
Sand and Gravel	22.7	0.1	22.7	0	0.4	0.2
Bitumen	1369.1	7.1	1369.1	25	96.6	38.5
Feedstock	13839.7	71.4	0.0	0	0.0	0.0
Cement	0.0	0	0.0	0	0.0	0
RAP/RAC to Plant	0.0	0	0.0	0	0.0	0
Aggregate Substitutes	0.0	0	0.0	0	0.0	0
Steel	0.0	0	0.0	0	0.0	0

He also compared the results of different LCA tools for three real projects in US. The details of these projects are brought in Table 3-2. In addition to *Roadprint*, he employed *PaLate*, *Oasis*, and *EIOLCA* to generate GWP and energy consumption. Figure 3-19 shows the results for material production phase. The author did not have enough information to perform a meaningful LCA comparison between the projects. However, his aim was to show the inappropriateness of using multiple tools for one process. He claimed that this arises from the fact that different tools have different inventories and it is not wise to rely on such comparisons as the difference of multiple processes or products will be lost in the variability among the inventories.

Table 3-2. Details of Projects Used in LCA Comparison (Lin 2012)

Project Location	Details
Keolu Drive, Hawaii	• Milling 6 in. of existing HMA • Resurfacing with 2 in. of HMA over 4 in. asphalt concrete base • Recycled material used: 10% Cullet • Maintenance Schedule: Mill and fill of 2 in. HMA at years of 10, 20, 30, and 40
US-97, Oregon	• Expansion of an existing highway • Milling 2in. of existing HMA • Original structure: Not mentioned • Recycled material used: 20% RAP • Maintenance schedule: Adding 2 in. of HMA every 15 years
SR-240 & I-182, Washington	• Expansion of an existing highway • Using HMA and PCC • No mix design details available. Values were assumed. • No scheduled maintenance

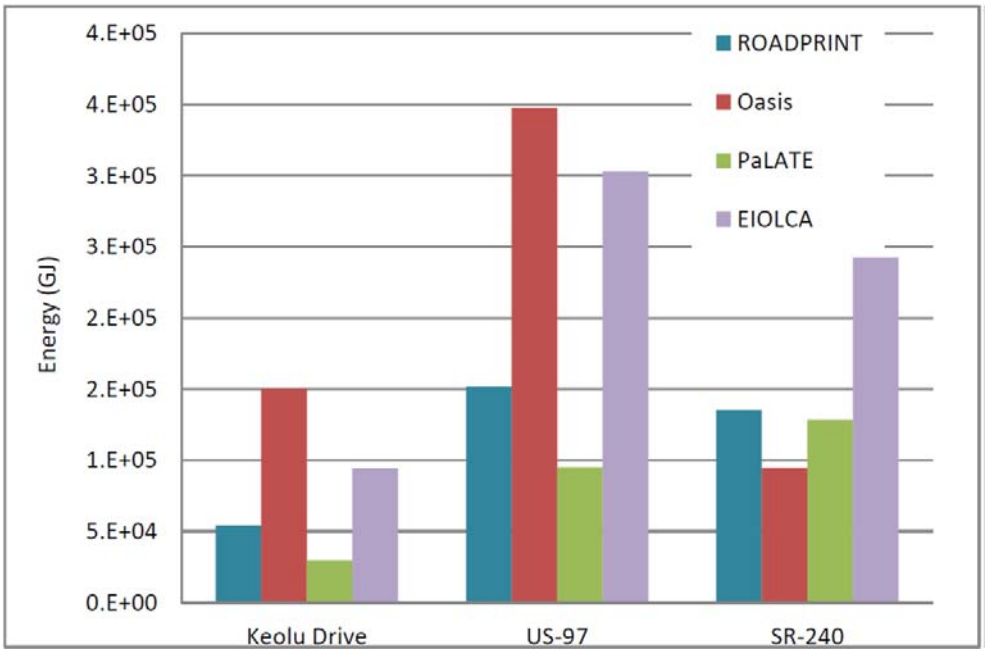


Figure 3-19. Comparison of the Energy Use in Material Production – No Feedstock Energy (Lin 2012)

Willis (2014) conducted a LCA on the Green Group experiment test sections of 2012 and compared the results to those of an asphalt mixture containing only virgin materials (from 2009 test sections) produced at common production-mixture temperatures. The four sections of 2012 contained a variety of material types in addition to virgin materials, such as RAP, RAS, fly ash, hydrated lime and cellulose. WMA with either foaming technology or chemical additives had been used for different layers of 2012 sections. The LCA was done using the *Roadprint* program and included material extraction, production, and construction phases. He concluded that using recycled materials saved 9 to 26 percent energy and decreased the CO_2 emission by 5 to 29 percent. Also, depending on the temperature reduction, using WMA technologies cut the energy consumption and CO_2 emission in plant by 12 to 17 percent and 6 to 9 percent, respectively.

In order to estimate the environmental burdens in asphalt paving, Lippert et al. (2014) calculated the quantities of required materials for 16 mixtures including SMA, Asphalt Binder Replacement (ABR) and Total Recycle Asphalt (TRA) which have been used in 3 demonstration projects in Illinois. They concluded that even though the binder is 5% to 7% of mix design by weight, 30% to 50% of the total environmental burden of producing HMA mixtures come from production of binder. However, the exact amount of that burden depends on the region and the fact that binder is modified or not. They also mentioned that the environmental benefits of ABR and TRA can be significant if the performance of roads with such mixtures are not worse than that of virgin mixtures and suggested to consider the pavement life for environmental calculations.

Aurangzeb and Al-Qadi (2014) evaluated the economic and environmental feasibility of mixtures with high RAP content through LCCA and LCA in Illinois. They considered mixtures with 30%, 40%, 50% RAP and a control mixture of all virgin materials. In LCA, the life-cycle of the pavement for phases of material, construction, maintenance and rehabilitation were assessed. In LCCA, the costs associated with the initial construction, and M&R for agency costs, as well as construction work zone for user costs were included in the study. The Illinois DOT's Bureau of Design and Environment Manual was used to schedule the activities of maintenance and rehabilitation. While the initial construction costs of mixtures were different, the maintenance costs were considered identical. They hypothesized different scenarios for the performance of RAP mixtures in such a way that the life of pavement sections built with recycled materials is assumed to be either similar as of control mixture or a fraction of that (i.e. 90%, 80% and 70% of the life of control mixture). This allowed the authors to determine up to what performance level the RAP mixtures are still economically beneficial. They found significant reduction in cost when high percentage of RAP is used and recommended to incorporate both agency and user costs into the analysis, as the user cost was nearly 50% of the total cost. Moreover, they calculated up to 28% reduction in environmental burden of the mixture if recycled materials are used. Although they mention the necessity of field performance evaluation to determine the schedule of M&R to be included in LCA and LCCA, their analyses for "break-even performance levels" were based on assumed scenarios which obviously lack actual field results.

Kang et al. (2014) assembled a regional LCI database of energy consumption and GHG emissions, and a sub-life-cycle binder model for material phase of flexible pavements in northern Illinois. The database was developed from literature sources and regional questionnaires. The sub-life-cycle model was generated for a specific type of crude oil source with considering a market value based allocation of resources for asphalt production in refineries. This helped the determination of indirect energy consumptions in LCA. The model then was used for a case study in a project in Illinois. The project consisted of 7.6 miles full depth HMA reconstruction for two out of three lanes of a major Interstate. The new pavement structure was built in total thickness of 15 in., from 11 mixtures containing either 6 or 8.5 percent RAP. They found that approximately 80 percent of the total energy is attributed to direct consumption, i.e. the HMA mixture production, and the other 20 percent is related to raw material production, such as binder, aggregate and RAP. In GWP calculations, the share of HMA mixture production was about 70 percent. They considered three scenarios for reconstruction of pavement to calculate the burden of traffic delay. The first scenario assumed four 1.9-mile work zones with a nighttime closure strategy that avoids peak traffic. Second case included two 3.8-mile work zones with 16-hour closure, still avoiding peak traffic. The last case assumed the entire 7.6-mile work zone with a 32-hour closure time. They used the EPA's simulator MOVES. The first two cases that did not caused any traffic queue had relatively close energy consumption and CO_2 emissions. However, the third scenario had these factors almost 4 to 5 times higher than the first two cases. This shows the importance of traffic queue occurrence in traffic delay calculations. In general, their

calculations showed that the material phase had 19 to 29 times greater GWP and 21 to 34 times greater energy consumption than that of the combination of construction phase and traffic delay.

3.5.2. Studies of Life Cycle Cost Analysis

Maupin et al. (2008) performed a laboratory and statistical investigation on the performance and bid pricing of mixtures with high RAP content (more than 20 percent RAP) in Virginia. Multiple plant produced Superpave mixtures from resurfacing projects were sampled and tested in fatigue beam, APA and TSR. They did not find any significant difference in the results of these tests. Moreover, no construction problems had been reported in placement and compaction in field. These observations made the authors to rely solely on contractors' bid prices for economical comparison, as the M&R become similar to control mixture. Data collection included tonnage of asphalt mixture, total number of contractors' bids, the winning bid, mix designation, and the mixtures binder grade. Their statistical analysis showed that bid prices were significantly related to mixture tonnage and number of received bids. They stated that the statistical analysis for the impact of high RAP content on bid prices was inconclusive. However, in none of the projects the cost increased and in a few ones, the unit cost decreased with the introduction of more than 20 percent RAP.

Hansen (2009) conducted a simple cost analysis to show the potential savings in asphalt mixtures when RAS is introduced. For the assumptions he made (Table 3-3), he

found a savings of $6.80 per ton of HMA. The majority of this cost saving came from the replacement of virgin binder with the recycled binder of RAS.

Table 3-3. Assumptions for Cost Analysis (Hansen 2009)

RAS in Mix	Recoverable Asphalt Content of RAS	Virgin AC Price	Fine Aggregate in RAS	Value of Fine Aggregate in RAS
5%	20%	$600 /ton	30%	$10 /ton
Landfill Tipping Fee	**Acquisition Cost**	**Processing Cost**	**Capital and Miscellaneous Costs**	
$25 /ton	$0 - Paid by Generator	$12 /ton	$0	

Rand (2011) conducted cost estimation for asphalt mixtures in Texas. The focus of his study was on substitute binders, RAP, and RAS as three issues that significantly reduce the cost of HMA. The mix design was a dense-graded Type D with 5 percent total asphalt content. Table 3-4 shows the assumptions he made for the analysis. For a typical binder grade, the production cost of mixtures with different compositions was considered. This included mixtures made of all virgin materials, or with 20 percent RAP, or 5 percent RAS, or 15 percent RAP and 5 percent RAS.

Table 3-5 illustrates the cost of each mixture. He found that the introduction of RAP and RAS can significantly reduce the price of mixture. This is about 32 percent for PG 76-22. Moreover, he showed that the cost saving can be further increased if binder substitution (grade dumping) is employed. The grade dumping eliminates the need for using more expensive polymer modified binders like PG 76-22 or PG 70-22.

Table 3-4. Assumptions Used for Asphalt Pavement Cost Estimates (Rand 2011)

MATERIAL	COST PER TON	NOTES
Aggregate	$22	Includes processing & freight
PG 76-22	$538	Based on September 2009 *Index (freight not included)
PG 70-22	$480	Based on September 2009 *Index (freight not included)
PG 64-22	$377	Based on September 2009 *Index (freight not included)
RAP	$15	Contains 5% AC, includes processing & freight
RAS	$20	Contains 20% AC, includes processing & freight

* Source: Louisiana Asphalt Pavement Association

Table 3-5. Asphalt Pavement Cost Estimates (Rand 2011)

COST OF MIX ($ PER TON)					
Binder Grade	Virgin Mix	20% RAP	5% RAS	15% RAP + 5% RAS	*One Grade Substitute
PG 76-22	47.80	41.24	42.54	37.64	35.74
PG 70-22	44.90	38.92	40.22	35.74	32.39
PG 64-22	39.75	34.80	36.10	32.39	NA

* Includes 15% RAP and 5% RAS

Mirzadeh et al. (2013) suggested a framework for LCCA of asphaltic pavements in Sweden that considered the energy and time related costs based on separate inflation rates. They calculated the unit price for multiple asphalt mixtures and compared with the average winning bid price for a particular case study. They assumed a design life of 25 years for one lane and 1 km (1.6 miles) long asphalt pavement which has 50mm (2 in.) wearing course of dense-graded mixture on top of 100mm (4 in.) binder course made of gravel-asphalt. They also considered a 4 percent discount rate. They found that in most of the cases, the calculated prices were good representatives of the laid asphalt prices. From their analysis, they also concluded that more than 50 percent of the total costs of construction and rehabilitation come from cost of oil products. They performed a sensitivity analysis on the effect of transportation distances and found that it plays an important role in high variation of final mixture costs. Regarding the user costs, their analysis showed that the costs of user delay and vehicle energy loss constitute 25 percent and 3 percent of the entire rehabilitation costs, respectively. This latter analysis was based on the assumption that the traffic level is below the work zone capacity, otherwise the contribution of user costs would dramatically increase.

Im and Zhou (2014) performed a cost analysis to evaluate the cost benefit of recycled HMA mixtures with and without rejuvenators. They only considered the cost of asphalt binder, rejuvenator, recycled materials and virgin aggregates as the production materials and ignored further steps of trucking and compaction. They compared three mixtures, one with virgin materials (obviously no rejuvenator), another with virgin aggregates plus 19 percent RAP and virgin binder without any rejuvenator and another

one with 0.6% rejuvenator (case 3). Based on the unit costs that they assumed (Table 3-6), they found that using RAP can reduce the cost up to 17.5 percent. However, the use of rejuvenator did not show any savings. Authors claimed that the use of rejuvenator will improve the performance of pavement which makes the mixture cost-effective if the entire life cycle of the pavement is considered in the analysis.

Table 3-6. Price of Materials in HMA (Im and Zhou 2014)

Price $/ton			
Virgin Aggregates	Virgin Binder	RAP	Rejuvenator
13.6	621.4	4.6	1500

DeDene et al. (2015) performed a cost assessment of different WMA mixtures based on their laboratory performance. The performance criteria they looked at were the rutting resistance from APA, fatigue resistance from four-point beam test, and moisture susceptibility from TSR. Four WMA technologies of Advera, Cecabase, Sasobit and direct injection (Double Barrel Green) were tested versus a control mixture of HMA produced at 150°C (302°F). Mixtures were designed based on Superpave method with 9.5mm (3/8 inch) NMAS, binder of PG 58-34, air void of 4 percent and less than 3 million ESALs traffic. They assumed the cost of construction as twice the material cost. They performed analysis of variance (ANOVA) to determine significant variables for each performance response. Mixing temperature and amount and type of WMA additive were primary variables in ANOVA. They found that the mixing temperature is the

dominant factor in reduction of cost. However, lower dosages of WMA additives could also reduce the cost. This reduction of cost was in the range of 2 to 7 percent. In general, they concluded that all the employed WMA technologies are capable of improving performance and thus reducing the cost.

TXDOT uses approximately 10 million tons of HMA and WMA every year (Hansen and Copeland 2014). Since the most expensive category of production is the materials, almost 70 percent of asphalt mixture production cost (Copeland 2011), if replacing the virgin materials by RAP and RAS can only save $10 per ton of mixture, an annual saving of $100 million is anticipated. In addition to direct savings, there are other parameters that affect the cost indirectly. For example, when the control of emissions can constitute up to 50 percent of overhead costs (Hampton 2015), lower emissions result in lower cost. Therefore, a thorough cost analysis on the use of recycled materials or new technologies such as WMA will demonstrate the real extent of savings which may in turn persuade the asphalt industry to utilize these practices extensively.

3.6 Summary and Remarks

In this chapter, different methodologies of LCA have been discussed. Some of the available tools for LCA and LCCA were briefly introduced. The two more relevant programs of *PaLate* and *Roadprint* were described in more detail. Moreover, the literature on performing such assessments for asphalt pavements was reviewed. Although the results are more project-specific and variability is high, it can be concluded that the

introduction of recycled materials in asphalt mixtures as well as utilization of WMA technology will lower the environmental footprint and cost of mixture production and compaction.

Very limited studies considered the performance of the sections in calculating the life cycle burden of the pavement. This is a very important issue as it can change the relative superiority of one mixture to another. For example, a mixture that costs less and incurs less pressure to the environment may deteriorate faster which requires more frequent rehabilitation. In this case, the mixture may make the project even more costly with more environmental burden during the service life. Therefore, in determining the suitability of a specific mixture, the factors of interest should be calculated for the initial construction as well as any subsequent M&R for the entire life cycle of the pavement section.

CHAPTER 4

PERFORMANCE OF FIELD SECTIONS AT APT FACILITY

4.1 Introduction

The objective of this research is to estimate the sustainability of asphalt mixtures with RAP and RAS when the LCA is included in the analysis. The field performance of pavement sections is an essential component in conducting a comprehensive LCA as it allows determination of frequency of required M&R after the initial construction. To evaluate the performance of four asphalt mixtures containing RAP and RAS, several pavement sections were constructed at the UTA APT facility. This chapter provides the details of the APT testing.

4.2 Accelerated Pavement Testing Facility

The UTA APT facility is located near SH-820 on the east side of Fort Worth, TX. The site is also in the proximity of an asphalt plant owned by Austin Bridge and Road Inc., the contractor used for the construction of the pavement sections. Layout of the site is shown in Figure 4-1.

The APT machine is shown in Figure 4-2. This machine is of linear type and includes a bogie with dual wheels that can move forward and backward. At the ends, an energy absorption and release system stops the bogie and pushes it back in the opposite direction. This assembly applies an 18 kips (81kN) single axle load. This is the legal axle

load in Texas. Lateral wander movement to the maximum position of ± 12 inches (305 mm) from the centerline is another capability of this machine. In order to measure the temperature for testing, several thermocouples have been installed at different depths of the surface layer of all sections. In addition, two load cells are installed on the axle to ensure the uniformity of the applied load on various pavement sections.

Figure 4-1. Layout of UTA-APT Site

Figure 4-2. The APT Machine

4.3 Details of Pavement Sections and Mixture Types

Twelve pavement sections were built at the APT facility. These sections allowed the field evaluation of four different surface asphalt mixtures for resistance to fatigue cracking, reflection cracking and rutting. The Figure 4-3 illustrates the layout of sections. Same structural design was considered for the sections tested for similar performance criterion. The design and loading conditions of sections are in such a way that specific mode of failure occurs. For example, the structure of sections of E, F, G, and L is designed to provide enough flexibility for wearing course to show fatigue failure and not permanent deformation. The temperature is also kept at intermediate level (i.e. 20°C/68°F), so the bitumen is stiff enough to resist rutting.

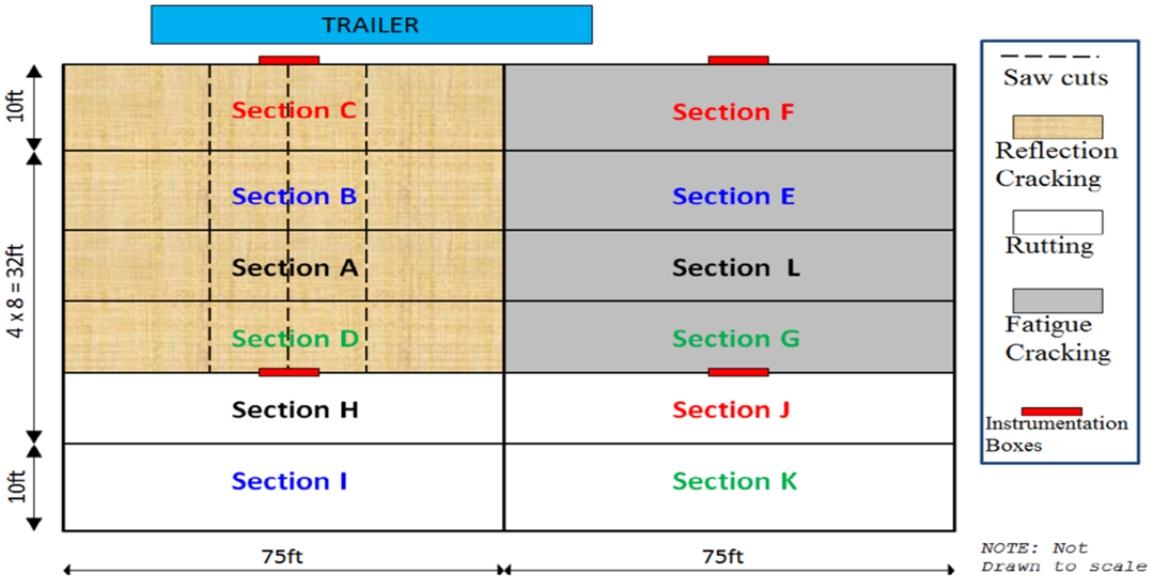


Figure 4-3. Test Sections Built at UTA-APT Facility

It should be mentioned that the design of sections was for a life of approximately 500,000 repetitions of axle load. Table 4-1 shows the mixture types and the designed

thickness of different layers for each section. For further information on construction sequences and testing conditions, the reader is referred to Romanoschi and Scullion (2014).

Table 4-1. Details of the Mixtures at APT Site (Romanoschi and Scullion 2014)

Reflection Cracking Experiment			
Test Section	Surface 2in.	Intermediate 2in.	Base 8in.
A	**Type D**	Type C	Cement (3.5%) Treated base
B	**High RAP**		
C	**RAP&RAS**		
D	**BMD**		
Rutting Experiment			
Test Section	Surface 2in.	Intermediate 6in.	Base 7in.
H	**Type D**	Type B	Cement (3.5%) Treated base
I	**High RAP**		
J	**RAP&RAS**		
K	**BMD**		
Fatigue Cracking Experiment			
Test Section	Surface 3in.	Base 8in.	Subbase 8in.
L	**Type D**	Bridgeport Rock	Cement (2%) Treated Subbase
E	**High RAP**		
F	**RAP&RAS**		
G	**BMD**		
Type D contains no RAP/RAS **High RAP = 19% RAP** **RAP&RAS = (15% RAP + 3% RAS) w/ WMA** **BMD = (15% RAP + 3% RAS) TTI Design**			

Table 4-2. Initial Design Information for the Mixtures (Romanoschi and Scullion 2014)

Mixture	% Rock				RAP %	RAS %	TD %	OAC %	PG
	BPD	BPMS	MCMS	FS					
Type D	61	-	30	9	-	-	96.5	4.8	64-22
High RAP	46	29	-	6	19	-	96.5	4.8	
RAP/RAS-WMA	48	29	-	5	15	3	96.5	5	
BMD	48	29	-	5	15	3	97.5	5.5	64-28
Type C	50	27.6	-	5	15	2.4	97	4.7	64-22
Type B	38	32	-	-	30	-	97	4.1	

Abbreviations used in table:
- BPD: Bridgeport Type D Rock
- BPMS: Bridgeport Manufactured Sand
- MCMS: Mill Creek Manufactured Sand
- FS: Field Sand
- TD: Total Density

The Bridgeport aggregates were used in the asphalt mixtures. These aggregates are of good quality with LA abrasion number of 27, magnesium sulfate soundness of 11, and very little bitumen absorption. Therefore, the performance of mixtures is not affected by the aggregates.

The HMA wearing courses were produced, delivered, and compacted at the temperature range of 320°F to 270°F. The "RAP/RAS-WMA" mixture was produced using the WMA technology with Evotherm-3G additive. The temperature range for this mixture was 255°F to 230°F.

The collected trial batches from plant produced mixtures showed that the target binder content has been only achieved for “High RAP” mixture. The binder content for mixtures of “Type D”, “RAP/RAS-WMA”, and “BMD” were 5.3%, 4.9%, and 5.2%, respectively. This will influence the relative performance of mixtures. In any further analysis, these values are taken into account.

4.4 Performance Evaluation of Mixtures in Lab

Texas Transportation Institute collected multiple cores from the APT project right after construction (Figure 4-4) for further lab testing. They performed HWTT, OT, Resilient Modulus (Mr), and Indirect Tensile Test (IDT). Table 4-3 shows the results of these tests.

Figure 4-4. Section Coring for Lab Testing

Table 4-3. Lab Tests Results on APT Field Cores (Romanoschi and Scullion 2014)

Mixture Type	HWTT Passes to Failure	Rank in Rutting Resistance	OT Cycles to Failure	Rank in Cracking Resistance	Mr (ksi)	IDT (psi)
Type D	4600	**4**	383	**2**	416.7	120.9
High RAP	11216	**2**	108	**4**	478.1	117.75
RAP&RAS-WMA	5350	**3**	175	**3**	385.7	106.7
BMD	11400	**1**	442	**1**	354.7	121.1

If the results of HWTT are used for evaluation of rutting resistance and the results of OT for evaluation of cracking resistance, it seems that the "BMD" mixture performs the best at both criteria. The "RAP&RAS-WMA" mixture is always the third, while the "High RAP" and the "Type D" mixtures are in the middle. Between the latter two, the "High RAP" has better rutting resistance and the "Type D" mix has better cracking resistance. These rankings will later be compared with the field results of APT experiment which will reveal the extent of usefulness of current lab tests in predicting field performance.

The results of IDT are in agreement with OT for "BMD" and "Type D" mixtures. However, the other two mixtures will switch the place in the cracking resistance ranking, if only the IDT is considered.

From the results of the Resilient Modulus test, it can be concluded that the "High RAP" is the stiffest mixture and the "Type D", "RAP&RAS-WMA", and "BMD"

mixtures are in subsequent orders, respectively. It should be mentioned that these values will be used in estimation of layer coefficients to calculate the Structural Number (SN) of pavement sections with these mixtures as the surface course.

4.5 Performance Evaluation of Mixtures in Field

The pavement sections at APT project were tested for three performance criteria from February 2014 to August 2015. In this period, the sections were subjected to more than 2,500,000 passes of standard single axle. Figure 4-5 shows the periods that each pair of sections was tested, along with the measured temperature.

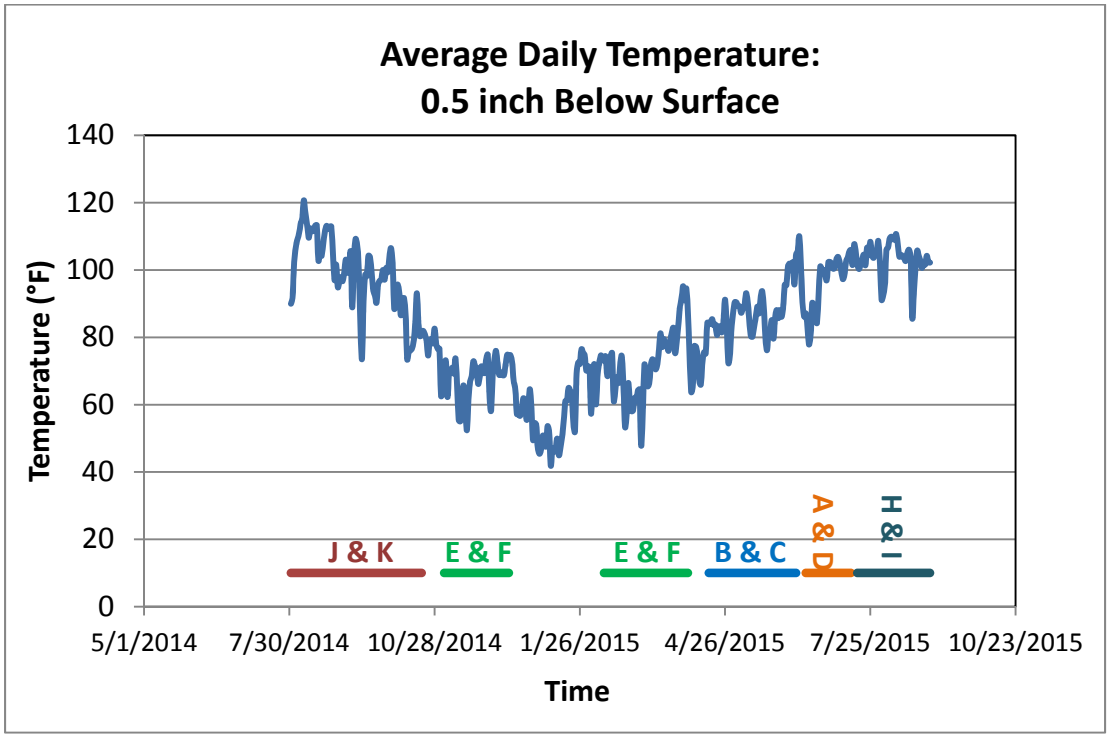


Figure 4-5. Testing Period and Measured Temperatures on Sections

The on-site performance evaluation of sections included the running of a profiler, a crack mapping frame and visual inspection. The profiler was utilized to record the transverse profile of surface layer at five transverse locations in order to calculate the permanent deformation. The extent of fatigue cracks in the sections was measured with the help of a crack mapping frame. The propagation of reflective cracks was measured only by a simple tape measure over the existing saw cuts of the underlying layer.

4.5.1 Fatigue Cracking Performance of Field Sections

Sections E, F, G and L were tested to determine the resistance of mixtures to fatigue cracking. The pavement temperature during testing was maintained around 68°F (20°C) at all times.

More than 400,000 passes were performed over sections G and L from February to April 2014. Figure 4-6 shows the condition of these sections at the end of testing period. As it can be seen, the condition of Section L (i.e. Type D mixture) is much better than Section G (i.e. BMD mixture). The pumping of fine materials into the surface layer of Section G was observed after 300,000 passes (Figure 4-7). The occurrence of fatigue cracks was first observed on Section G. After 320,000 passes, 31% of the inspected area of Section G was cracked while no cracks were observed for section L. At 416,000 passes, the percent cracked area increased to 51% for Section G and 25% for Section L. Fifty percent cracked area had been determined as the threshold of failure in fatigue. Therefore, testing was not continued after that. Figure 4-8 shows the pattern of fatigue cracks for these two sections at the end of testing.

Figure 4-6. After Testing Condition of Sections G and L

Figure 4-7. Pumping of Fine Materials into Surface Layer of Section G

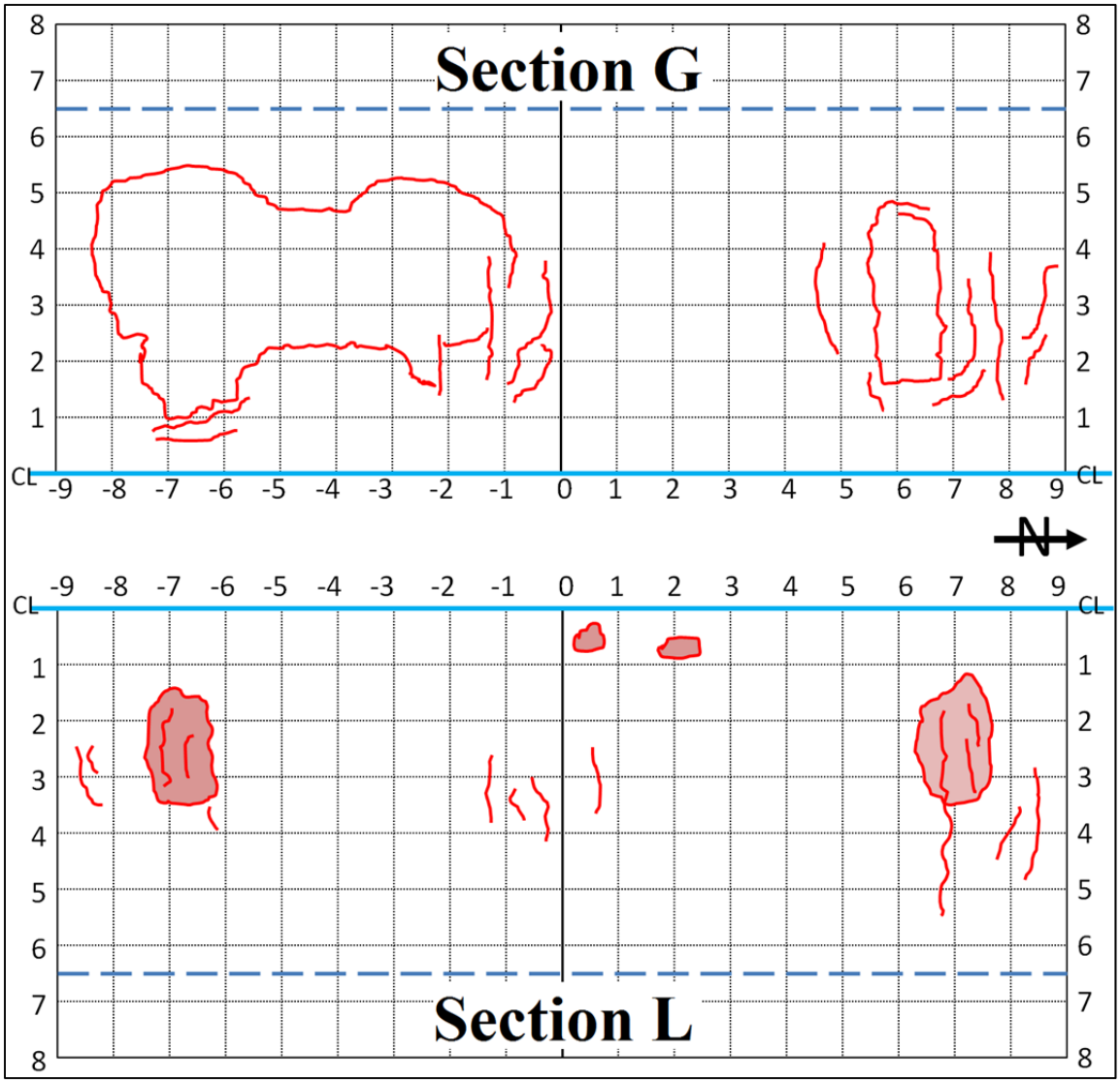


Figure 4-8. Pattern of Fatigue Cracks for Sections G and L after 416,000 Passes

Sections E and F experienced more than 500,000 passes in two periods, from November to December 2014 and from February to April 2015. The condition of these sections at the end of testing is shown in Figure 4-9. Section E (i.e. High RAP mixture) had numerous cracks while the number of cracks in Section F (i.e. RAP&RAS-WMA) was very limited. In fact, Section E showed early signs of cracking right after 400,000

passes and by 500,000 passes the section had already reached 50% cracked area of failure. Meanwhile section F did not show anything until 517,000 passes. The cracked area at this level was only 12 percent for Section F which was the best performance among the fatigue cracking sections. Figures 4-10 and 4-11 show the pattern of fatigue cracks for Section E after 500,000 passes and Section F after 517,000 passes, respectively.

Figure 4-9. After Testing Condition of Sections E and F

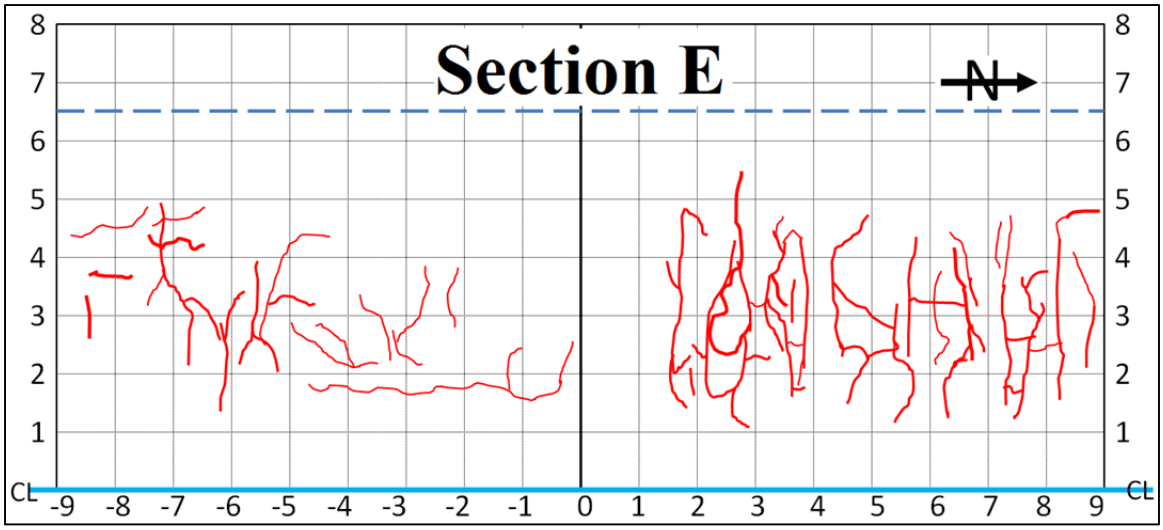


Figure 4-10. Pattern of Fatigue Cracks for Section E after 500,000 Passes

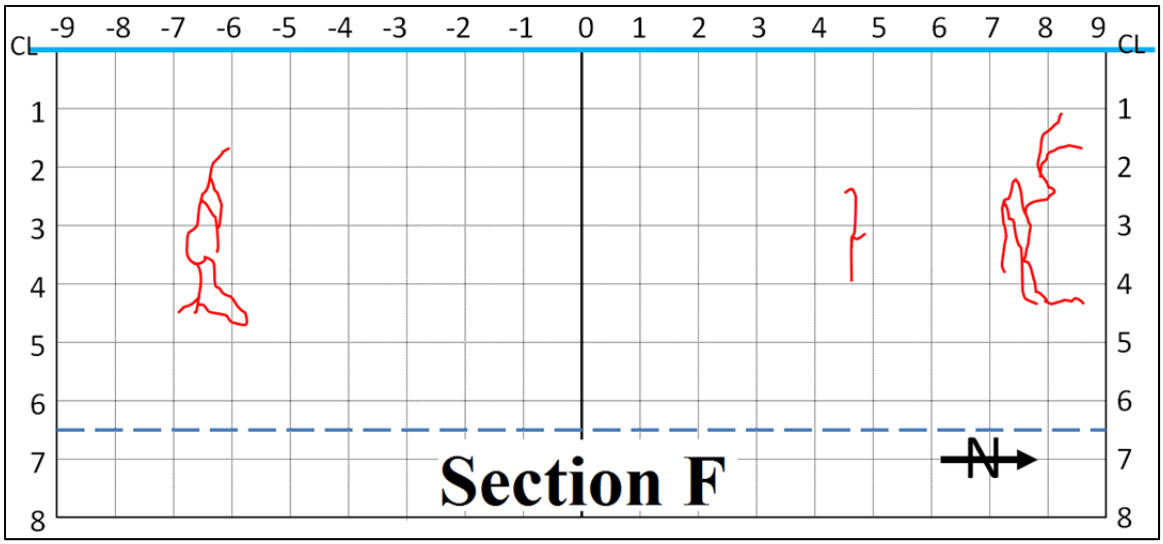


Figure 4-11. Pattern of Fatigue Cracks for Section F after 517,000 Passes

Figure 4-12 shows the condition of all fatigue cracking sections side by side at the end of testing. As it can be seen, Section F has the best resistance to fatigue cracking

while Section G has the worst. Table 4-4 provides the actual percentage of cracked area for all of the sections. The data are plotted in Figure 4-13.

Figure 4-12. After Testing Condition of All Fatigue Cracking Sections

Table 4-4. Comparison of Percent Cracked Area for Fatigue Cracking Sections

No. of Passes (x 1,000)	% Cracked Area			
	Section F, RAP&RAS-WMA	Section E, High RAP	Section L, Type D	Section G, BMD
320	0	0	0	31
400	0	12	-	-
416	-	-	25	51
444	0	37	-	-
470	0	37	-	-
500	0	50	-	-
517	12	-	-	-

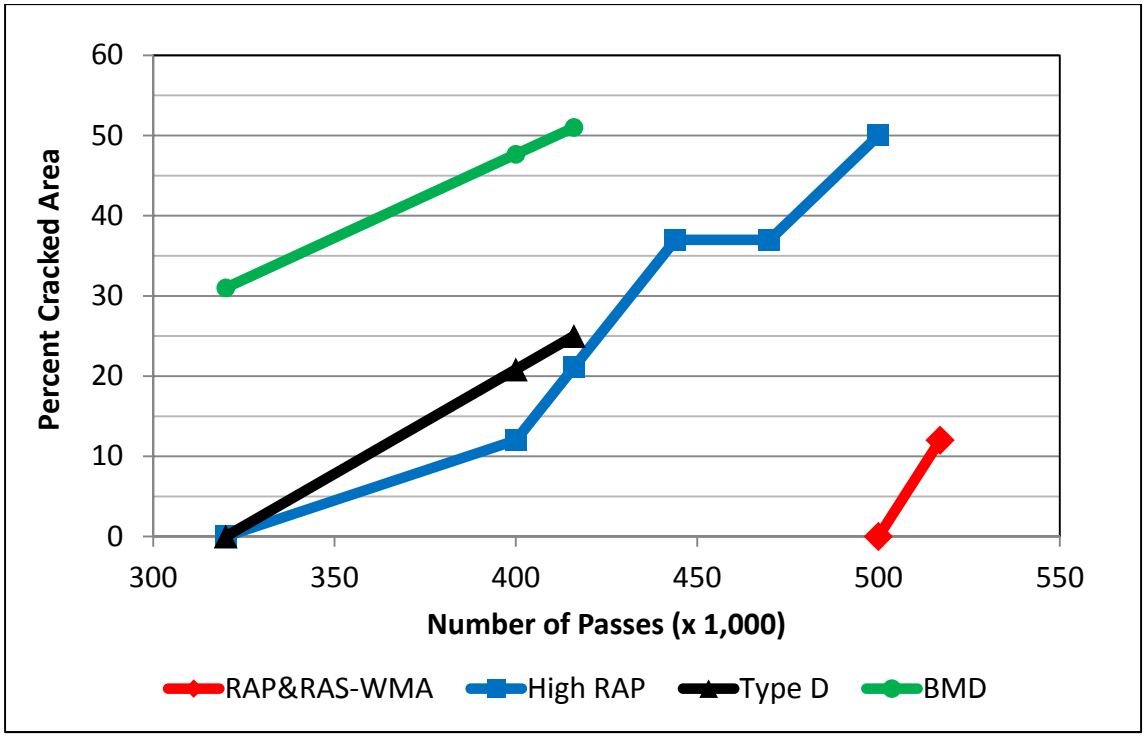


Figure 4-13. Percent Cracked Area for Fatigue Cracking Sections

In addition to measurement of percent cracked area, the transverse profiles of sections have also been recorded. Figure 4-14 shows the calculated average permanent deformation at these sections. The "BMD" mixture suffered large deformations of close to 1.0 inch on average while "Type D" mixture did not have more than 0.5 inch. This caused a big difference in elevations of sections G and L which made further loading of section L impossible as the APT machine would be imbalanced. In the other pair of sections (E and F), the "High RAP" mixture had average permanent deformation of slightly more than 0.3 inch and the "RAP&RAS-WMA" never reached even 0.15 inch. Based on the available information so far, it seems that the "RAP&RAS-WMA" mixture has a better resistance against fatigue cracking.

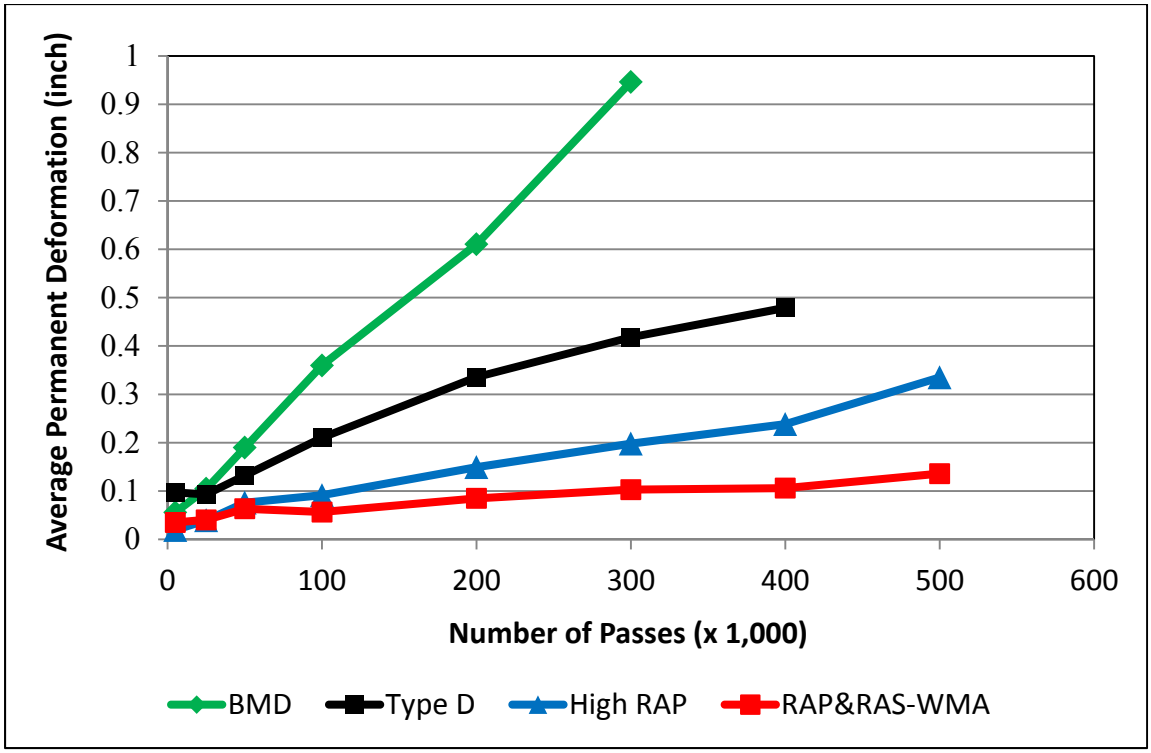


Figure 4-14. Average Permanent Deformation of Fatigue Cracking Sections

4.5.2 Reflection Cracking Performance of Field Sections

All four different mixtures were placed as a 2.0 inch overlay on top of a "Type C" asphalt mixture layer (Table 4-1). This layer had 2.0 inch thickness with three saw cuts each seven feet apart. The evolution of reflection cracks on top of these cuts was monitored periodically to determine the performance of mixtures.

Sections B and C were tested together for nearly 125,000 passes from April to June 2015. Figures 4-15 and 4-16 show the condition and crack pattern of these sections after testing, respectively.

Figure 4-15. After Testing Condition of Sections B and C

At 12,000 passes, both sections showed signs of reflection cracking. These sections performed similarly until 30,000 passes. However, after that Section C (i.e. RAP&RAS-WMA mixture) started to perform slightly better than Section B (i.e. High RAP). At 100,000 passes, the reflection cracks were present over 64.5% of the length of saw cuts of the underlying layer for Section B. The value for Section C was about 53.8%. The loading continued until 125,000 passes, but the extent of cracks did not change. At this stage, it was decided to stop loading and move the APT machine to the next pair of reflection cracking sections.

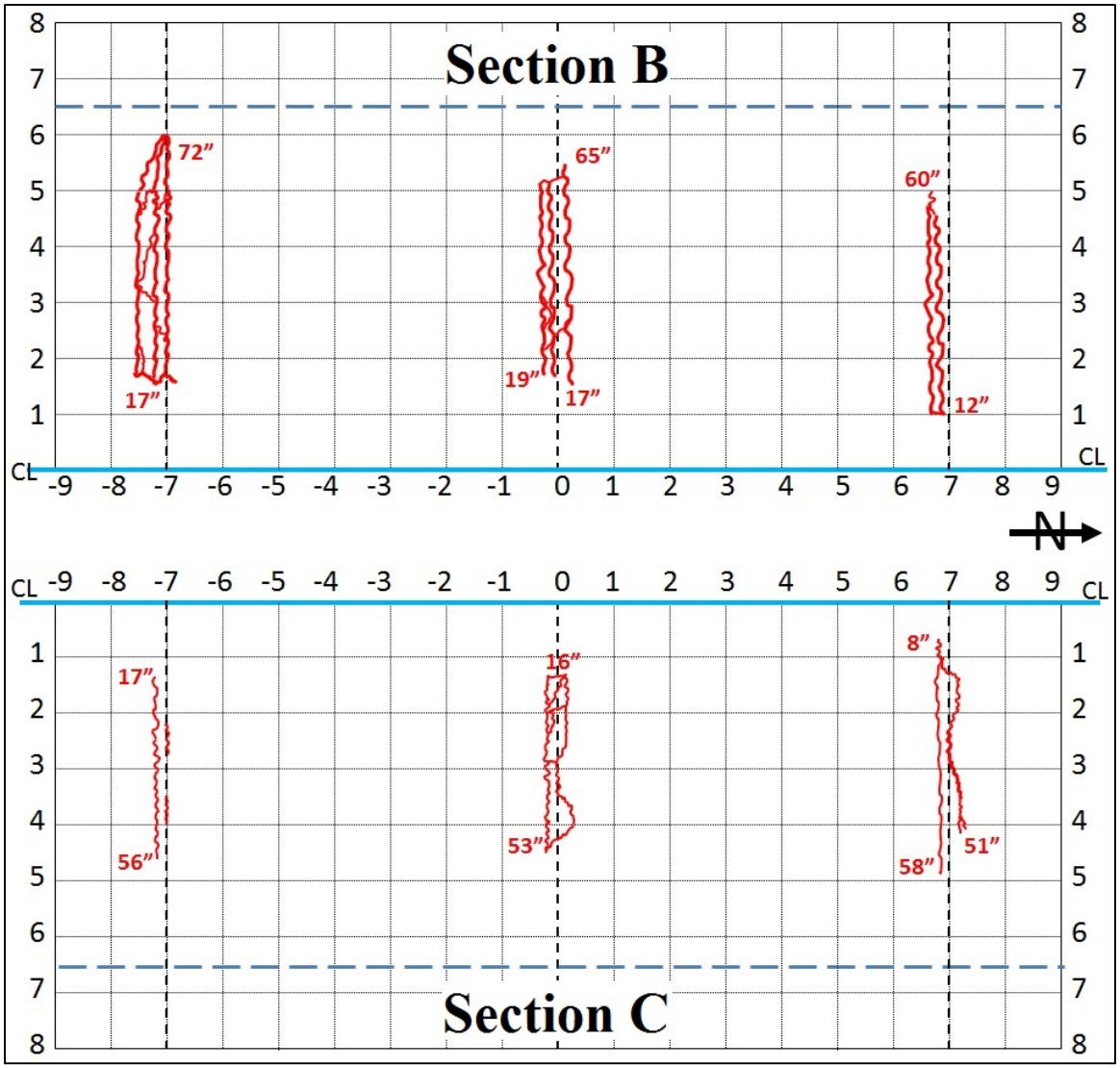


Figure 4-16. Pattern of Reflection Cracks for Sections B and C after 125,000 Passes

Sections A and D were subjected to 145,000 passes between June to July 2015. Figures 4-17 and 4-18 show the condition and cracking pattern of these sections after testing, respectively. First cracks were observed at 41,000 passes, when the reflection cracks were present over 15.0% of the saw cuts for Section A (i.e. Type D mixture) and about 4.7% for Section D (i.e. BMD mixture). After 41,000 passes, the extent of

reflection cracks kept increasing in Section A while for Section D it remained constant until 85,000 passes. The final rate of reflection cracks at the end of loading was 50.4% for Section A and 36.3% for Section D.

Figure 4-17. After Testing Condition of Sections A and D

Figure 4-19 presents the evolution of reflection cracks for all four sections. As the chart shows, the BMD mixture provides the best resistance to reflection cracking. At 125,000 passes, the reflection cracks for mixtures of "BMD", "Type D", "RAP&RAS-WMA" and "High RAP" are 26.7%, 44.0%, 53.8% and 64.5%, respectively.

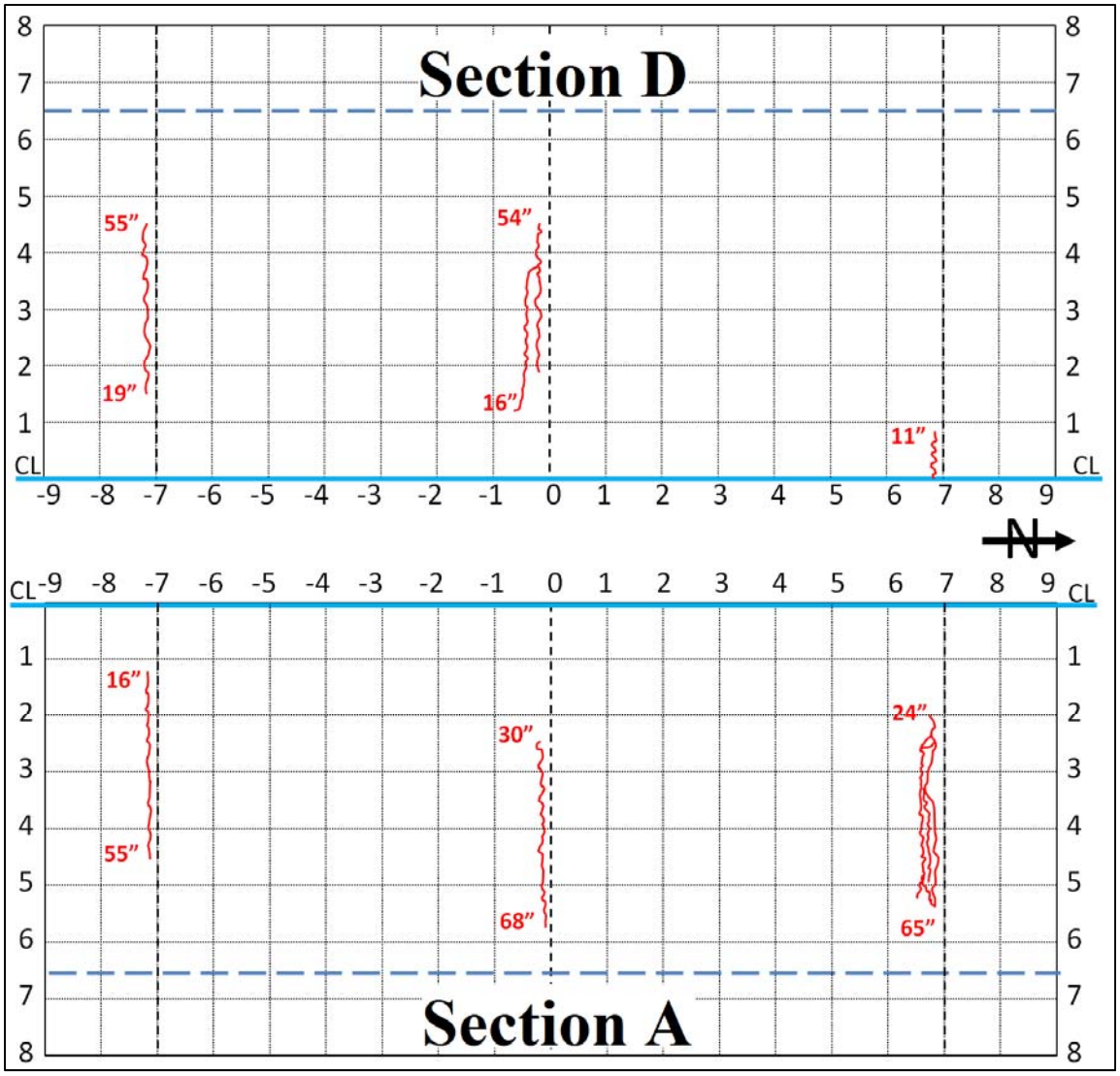


Figure 4-18. Pattern of Reflection Cracks for Sections A and D after 145,000 Passes

Like fatigue cracking sections, the change in transverse profile of surface layer was monitored with the profiler. However, for reflection cracking sections it was done only once at the beginning of testing and once at the end of testing. Figure 4-20 shows the average permanent deformation of these sections.

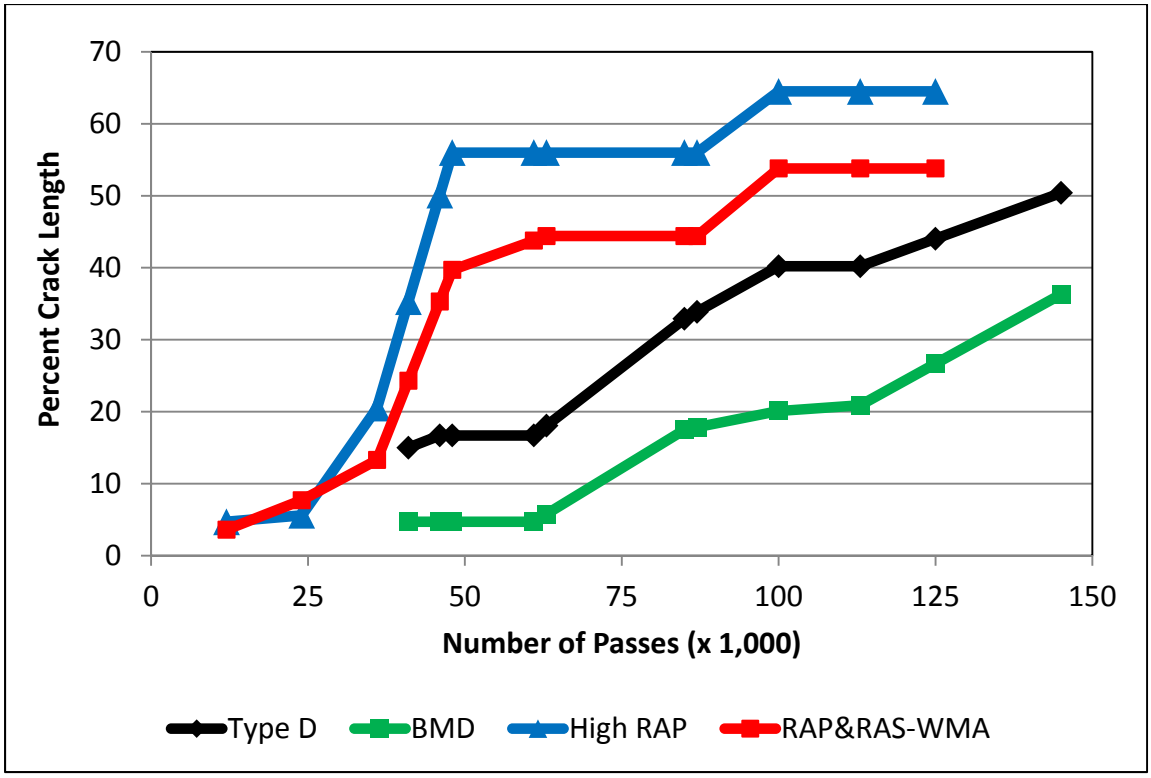


Figure 4-19. Evolution of Cracks for Reflection Cracking Sections

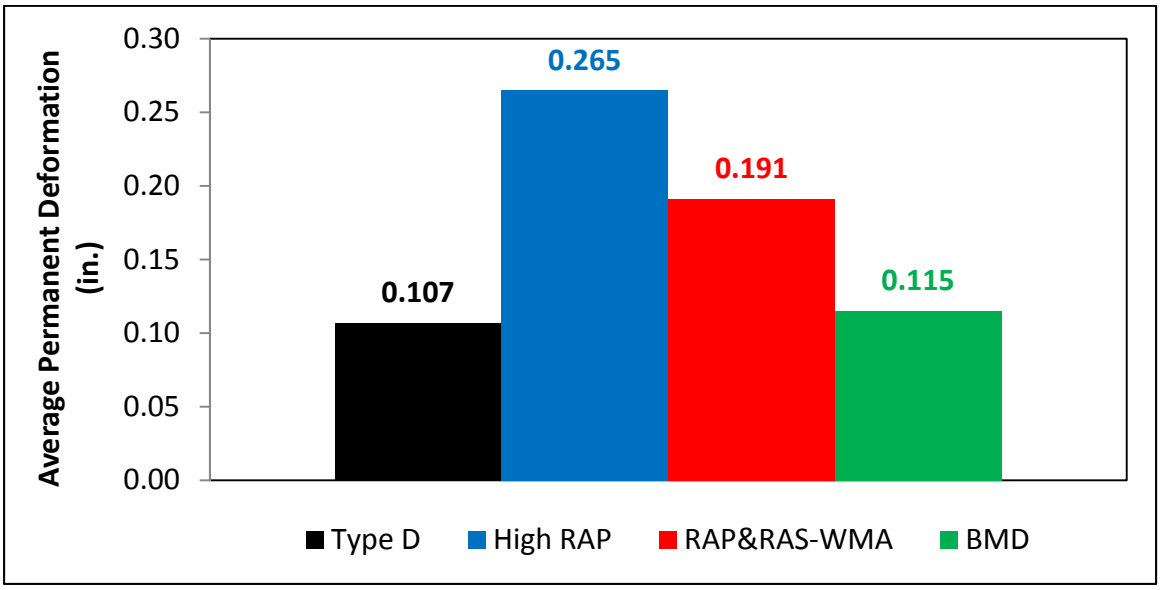


Figure 4-20. Average Permanent Deformation of Reflection Cracking Sections

4.5.3 Rutting Performance of Field Sections

Almost half of the 2,500,000 passes were applied to the rutting sections. Figure 4-21 shows the condition of these sections at the end of testing. In spite of high number of passes, none of them showed any sign of failure. In fact, the maximum measured rutting never exceeded 0.2 inch which is a very small value.

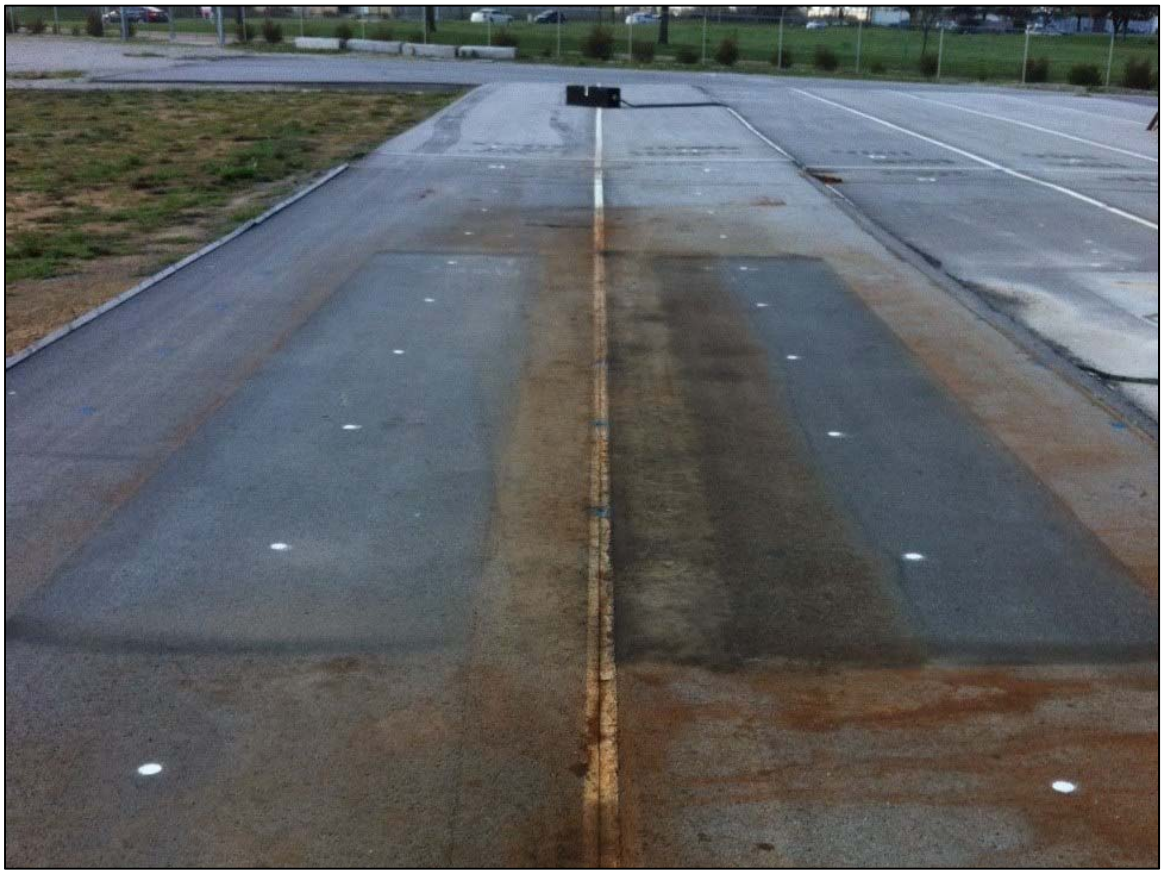


Figure 4-21. Rutting Sections after Testing

Figure 4-22 presents the comparison between the average permanent deformations of the mixtures. As it can be seen, each pair of sections that were tested

together had similar performances. If the as-built thicknesses of the sections are the same, then the sections with recycled materials of both RAP and RAS (i.e. sections of "BMD" and "RAP&RAS-WMA") are expected to have slightly better resistance in rutting. However, despite the installation of load cells on the axle to ensure consistent loading of sections and extra care of staff in measurements, minor inconsistency in loading or error of measurements may shadow this slight difference of the permanent deformations. Therefore, further loading of these sections are needed to reveal the superiority of one mixture to another. In any case, these mixtures have surpassed the 500,000 passes that they were designed for. Thus, it can be concluded that none of these mixtures will have any problem in resisting rutting.

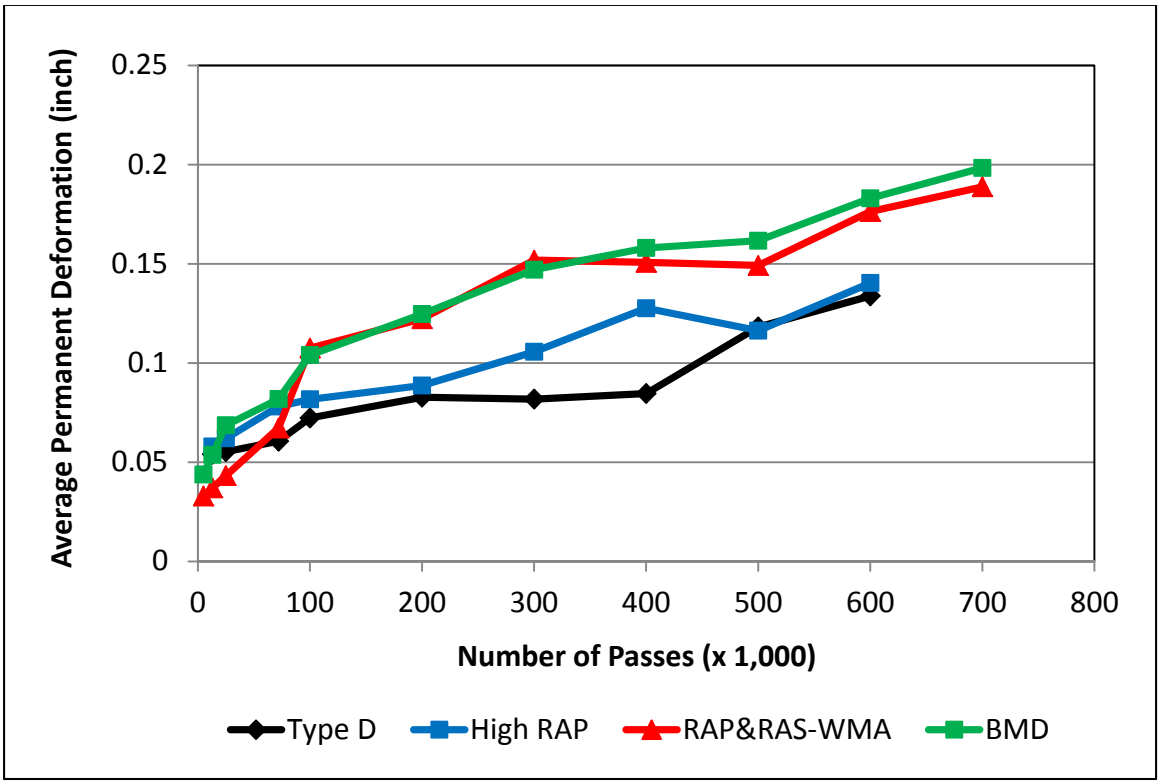


Figure 4-22. Average Permanent Deformation of Rutting Sections

4.6 Post Mortem Information of Field Sections

From practical point of view, constructing different pavement sections with identical thicknesses is impossible. It is clear that the thickness of asphalt layer significantly contributes to its resistance to cracking. Therefore, the performance ranking based solely on cracking and rutting measurements is not valid unless the uniformity of asphalt thicknesses is verified. For this purpose, a transverse trench was cut in each cracking section of the APT site. Figure 4-23 shows these trenches.

Figure 4-23. Post Mortem Photos of Cracking Sections

The thickness of asphalt layers along the trench was measured at 4 inches interval for further processing. Figures 4-24 shows the variation of asphalt layer thicknesses in fatigue cracking sections. It should be reminded that the thickness of asphalt layer in these sections was supposed to be 3 inches.

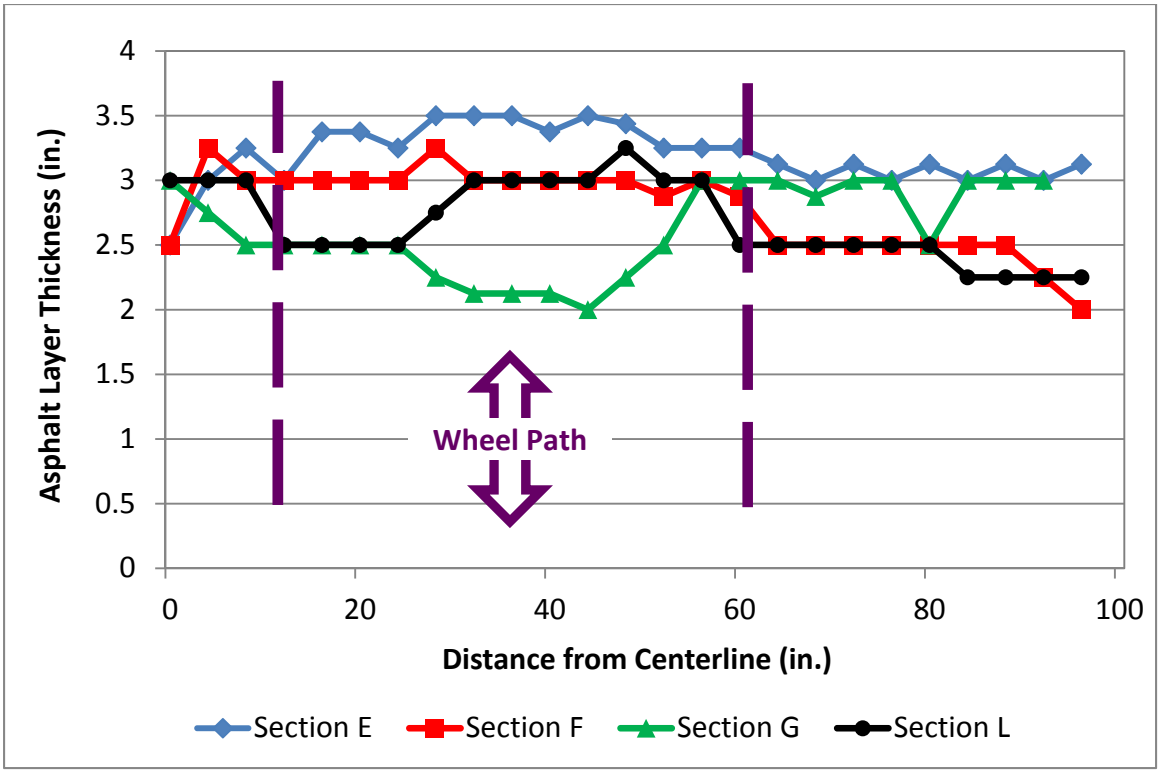


Figure 4-24. Thickness of Asphalt Layer in Fatigue Cracking Sections

The most important segment of each section is the loading zone which is about 50 inches wide at the middle of each lane. In that region, Section E has the highest thickness, Sections F and L are very close to each other but thinner than Section E and Section G

has the lowest thickness. This is probably one of the reasons behind the poor performance of "BMD" mixture in fatigue cracking.

In addition to the cutting of the trenches, coring has also been performed on cracking sections along their loading zone. The coring crew was able to retrieve five cores in fatigue cracking sections. However, in reflection cracking sections only two to three cores have been achieved because of existence of physical obstacles. Figure 4-25 shows the thickness of these cores for fatigue cracking sections. It indicates that the thicknesses of sections G and L are less than for the two other sections.

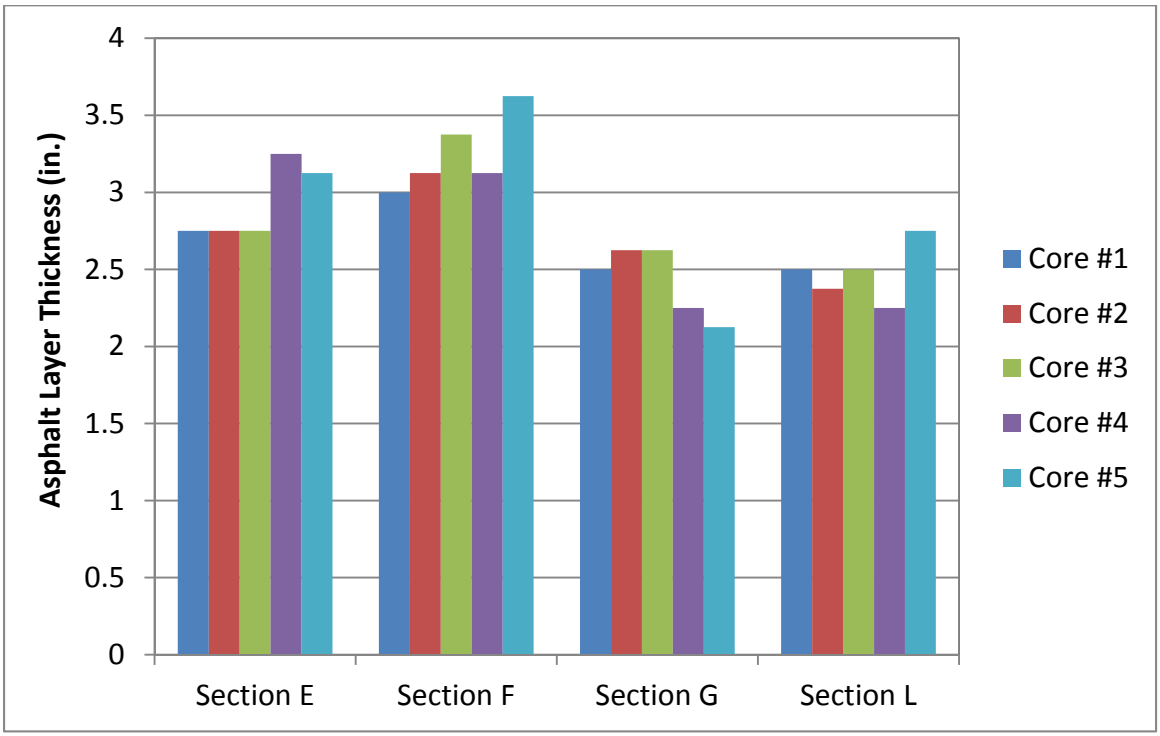


Figure 4-25. Thickness of Retrieved Cores from Fatigue Cracking Sections

Figure 4-26 provides the condition and thickness of two of these cores which were obtained from sections G and E. The fatigue cracks are observed in both cores. It must be mentioned that, due to the ubiquity of fatigue cracks in Section G, the cores of this section had to be taped to stay intact.

Figure 4-26. Retrieved Cores from Sections G and E

Figure 4-27 provides the total thickness of asphalt layers (i.e. surface mixture and underlying "Type C" mixture, 2 inches thick each) for reflection cracking sections. It seems that the construction crew was able to maintain more uniformity within each section. Therefore, no differences are considered for the thickness of surface layers. The heights of obtained cores from reflection cracking sections are compared in Figure 4-28. One of the retrieved cores from Section D is shown in Figure 4-29. The propagation of reflection crack on top of the pre-existing saw cut is visible in this photo.

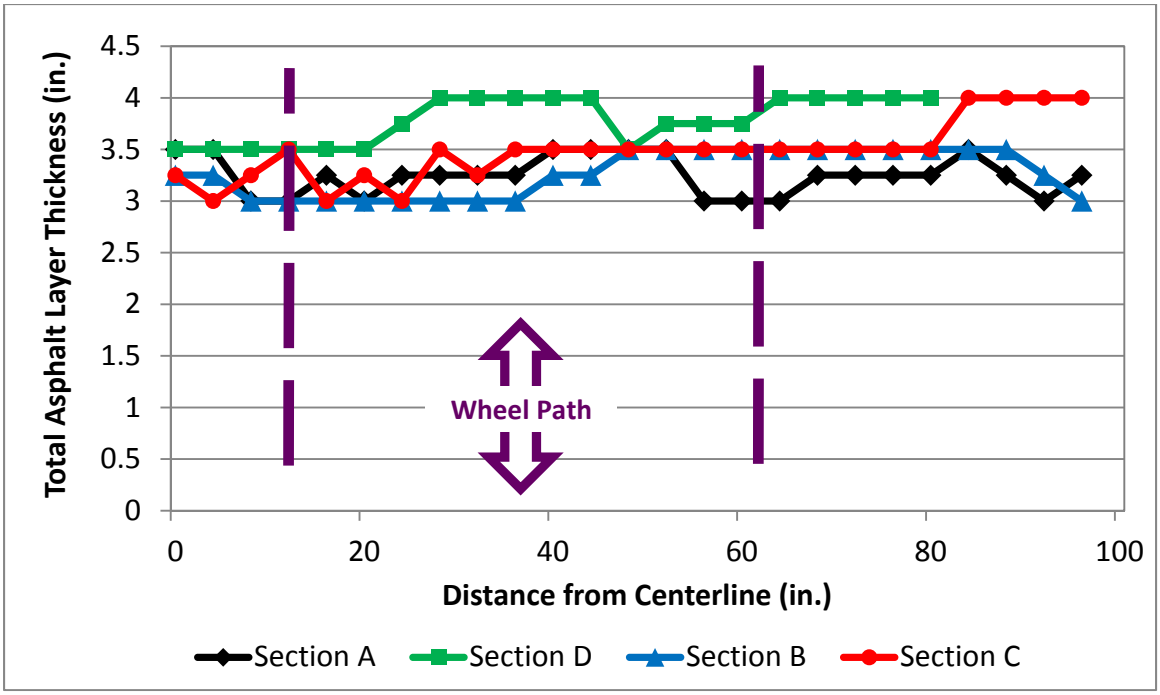


Figure 4-27. Thickness of Asphalt Layers in Reflection Cracking Sections

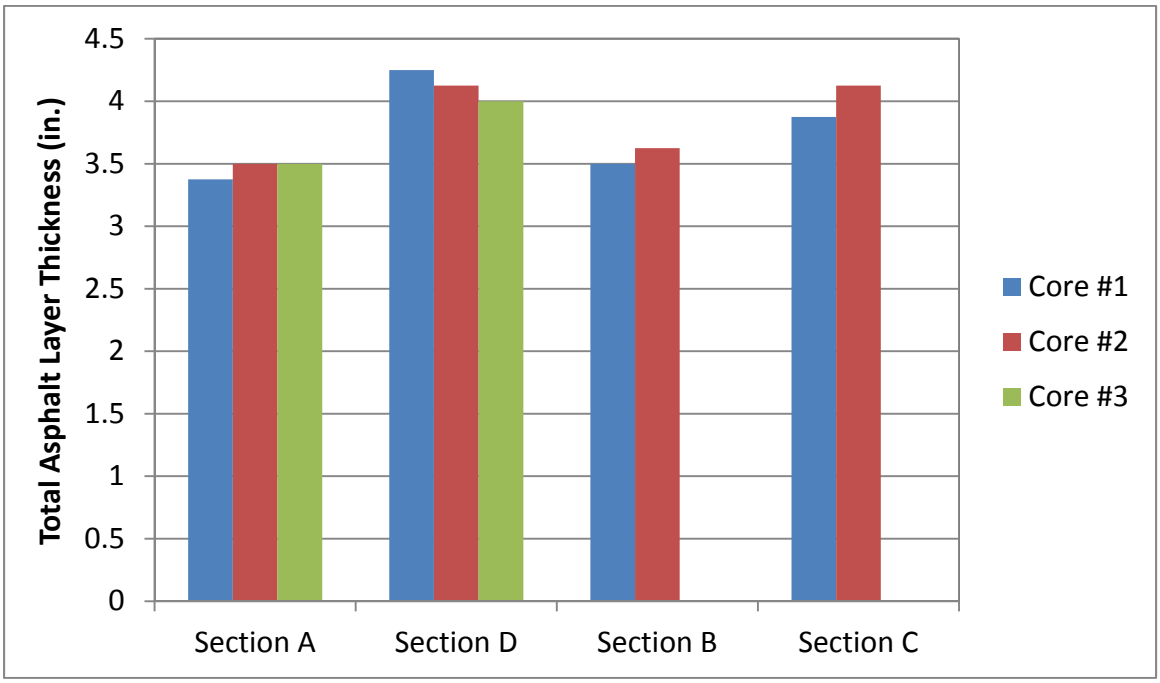


Figure 4-28. Thickness of Retrieved Cores from Reflection Cracking Sections

Figure 4-29. Obtained Core from Section D

4.7 Adjustment of Performance Life Based on As-Built Thicknesses

The post-mortem investigation revealed that the as-built thickness of different sections is not uniform. Therefore, it is necessary to adjust the performance life of each section based on the actual thickness. For this purpose, from the thickness of asphalt layer measured in the trenches and on the retrieved cores, an averaged thickness value for each fatigue cracking section was calculated. These values are shown in Table 4-5.

Table 4-5. As-Built Thickness of Fatigue Cracking Sections

Mixture	Fatigue Cracking	
	Section	Thickness (in.)
High RAP	E	3.0
RAP&RAS-WMA	F	3.2
BMD	G	2.4
Type D	L	2.5

A certain level of cracking was considered as the reference value at which the prospective rehabilitation needs to be applied. This threshold was considered as 25 percent cracked area for fatigue cracking sections and 50 percent cracked length for reflection cracking sections. The required number of passes to increase cracking to this level for every section was extracted from the APT experiment results. This number is associated with the as-built thicknesses of the sections which are not equal. Therefore, to make a basis for further meaningful comparison, the design thickness of 3 inches will be the reference value. This will be the thickness of the asphalt layer at the initial construction stage, for a hypothetical project. It is assumed that the pavement with this structure will be loaded until it reaches the selected threshold of fatigue cracks (i.e. 25 percent cracked area), then will be rehabilitated with an overlay of 2 inches thick. The frequency of placement of that overlay is determined from the performance of each mixture in the reflection cracking sections.

The required number of passes to reach the designated cracking threshold for the actual APT site sections should be corrected for the surface course of 3 inches or the overlay of 2 inches. In order to do that, a hypothetical pavement structure was considered. The surface layer of this pavement is built with each mixture one at a time. All of the underlying layers remain the same as the structure of fatigue cracking sections. The empirical equation of AASHTO 1993 for structural design of flexible pavements (Equation 4-1) was employed to predict the number of passes of a standard axle that the pavement can have during its service life. For every section, the surface layer coefficient was calculated from the number of passes that the section had in the APT experiment with its as-built thickness. Then, the same values were used to find the number of passes for the design thickness of 3 inches.

$$\log_{10}(W_{18}) = Z_R \times S_0 + 9.36 \times \log_{10}(SN+1) - 0.20 + \frac{\log_{10}\left(\frac{\Delta PSI}{4.2-1.5}\right)}{0.40 + \frac{1094}{(SN+1)^{5.19}}} + 2.32 \times \log_{10}(M_R) - 8.07 \qquad (Eq. 4-1)$$

Where,

W_{18} = predicted number of 80 kN (18 kips) ESALs

Z_R = standard normal deviate

S_0 = combined standard error of the traffic prediction and performance prediction

SN = Structural Number (indicative of the total pavement thickness)

ΔPSI = difference between the initial and terminal design serviceability index

M_R = Subgrade Resilient Modulus (in psi)

It should be mentioned that in the equation 4-1, the structural number (SN) of each section is calculated based on the layers thicknesses and moduli of the fatigue cracking sections of APT experiment. These details can be found in Romanoschi and Scullion (2014).

By following the aforementioned procedure, the required number of passes to reach the designated cracking threshold was corrected for the design thickness. Table 4-7 provides these corrected values. In this table, the corrected number of passes in fatigue cracking sections represents the service life of a pavement section with a 3 inches thick layer built with each mixture. For the reflection cracking sections the number of passes in the APT experiment is used which shows the service life of a 2 inches thick overlay that is constructed from the mixtures. Figures 4-30 and 4-31 depict the performance of mixtures side by side.

Table 4-7. Corrected Number of Passes for Design Thickness

Mixture	**Fatigue Cracking (Initial Construction)**			**Reflection Cracking (Overlay)**	
	Number of Passes		**Mixture Ranking**	Number of Passes	**Mixture Ranking**
	APT	**Service Life**		**Service Life**	
High RAP	423,000	Same as APT	**3**	46,000	**4**
RAP&RAS -WMA	536,000	503,600	**1**	94,700	**3**
BMD	292,000	321,600	**4**	173,500	**1**
Type D	416,000	436,700	**2**	145,000	**2**

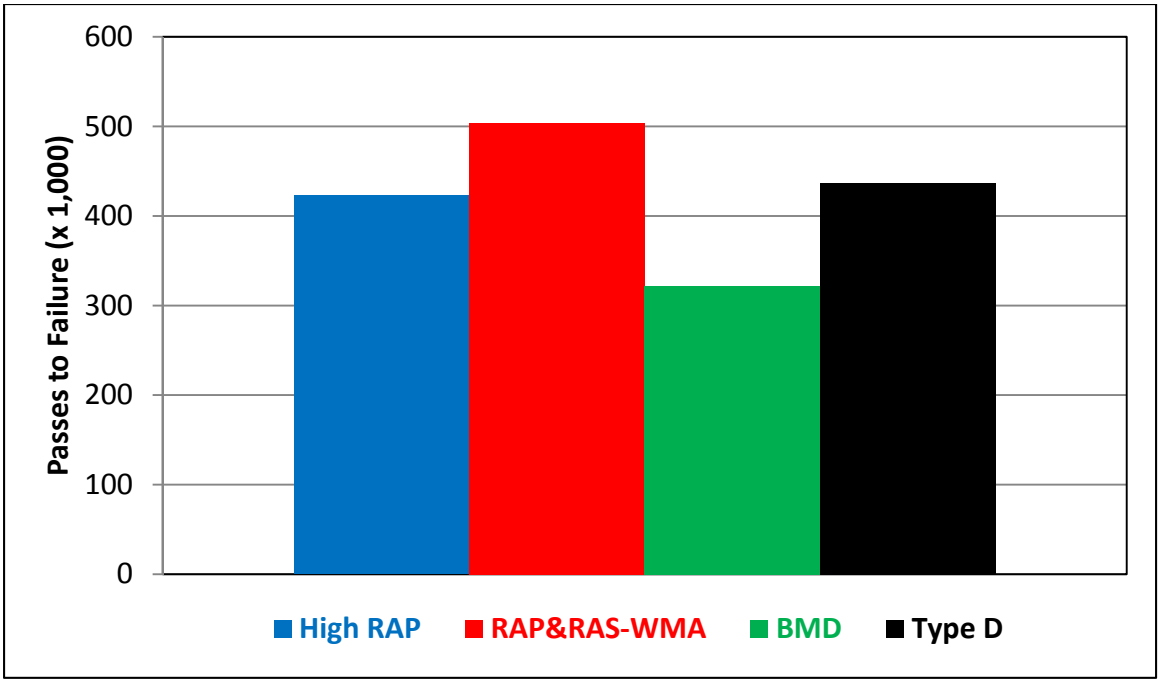


Figure 4-30. Comparison of Resistance of Mixtures to Fatigue Cracking

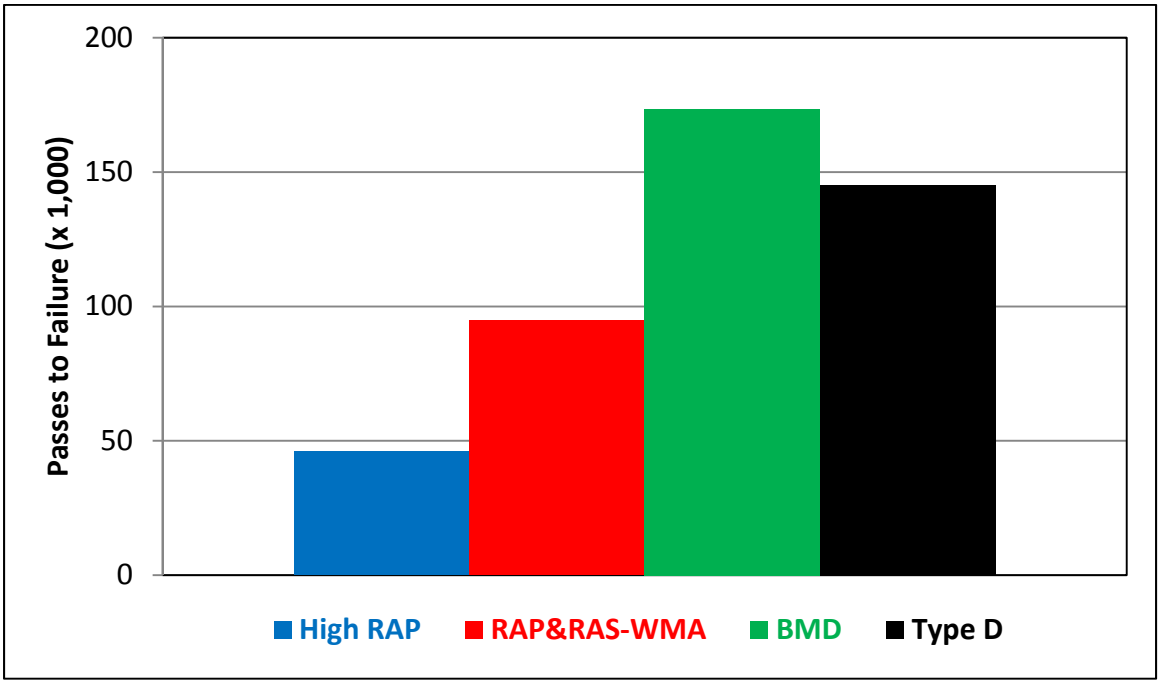


Figure 4-31. Comparison of Resistance of Mixtures to Reflection Cracking

As it can be seen, the “RAP&RAS-WMA” mixture has the best resistance to fatigue cracking and it is the third mixture for resistance to reflection cracking. The “Type D” mixture provides the second best performance against both fatigue cracking and reflection cracking. The “High RAP” is the third against fatigue cracks and the worst against reflection cracks. For the “BMD” mixture, the poorest performance is in fatigue cracking while it has the best against reflection cracks.

At this point, the lab results can be compared with the results of the field sections at the APT facility. The mixtures performance in the reflection cracking sections is comparable with the lab results from the OT. The same order of ranking was observed both in the lab and in the field. This shows that the OT can be used in the lab to predict the performance or ranking of asphalt mixtures with respect to their resistance to reflective cracks. However, it should not be used for prediction of performance against fatigue cracking.

4.8 Summary of Findings from the APT Experiment

The four different mixtures of this study were tested in two pairs for rutting, fatigue cracking and reflection cracking with nearly 2,500,000 passes of the standard axle. The performance of all of the mixtures was excellent in resistance to rutting. The four sections built with these mixtures were subjected to a total number of 1,300,000 passes and the maximum permanent deformation in none of them exceeded 0.2 inch. It seems that rutting is not a concern with these mixtures.

The same mixtures were tested for their resistance to fatigue cracking with more than 900,000 passes in total. The “BMD” mixture showed the poorest performance. The “Type D” mixture performed worse than “High RAP” mixture while the “RAP&RAS-WMA” mixture was the best. However, the post mortem investigations revealed that the section containing the “BMD” mixture had the lowest as-built thickness along the loading path. This adversely affects its resistance to cracking. Moreover, the sections of the “High RAP” and the “RAP&RAS-WMA” mixtures had thicker asphalt layers. This helps them to better resist cracking.

The resistance to reflection cracking was another criterion that was evaluated for these mixtures. For this purpose, a 2.0 inches thick course of “Type C” mixture was placed underneath the surface layer with three saw cuts each 7.0 feet apart. The sections were then tested in pair for the total number of 270,000 passes. The results showed that the “BMD” mixture has the best performance. The mixtures of “Type D”, “RAP&RAS-WMA” and “High RAP” are in subsequent orders. In this case, the post mortem inspection showed that the inconsistency in the thickness of the asphalt layers is negligible.

The post mortem information was then employed to adjust the number of passes yielding the failure of fatigue cracking sections for a uniform thickness. From this inspection, the ranks of the “RAP&RAS-WMA” and the “BMD” mixtures did not change while the “Type D” and the “High RAP” mixtures switched their ranking. Since the thicknesses of the surface layer of the reflection cracking sections were almost the same, it was concluded that no further adjustment is needed.

CHAPTER 5

LIFE CYCLE ASSESSMENT OF ENVIRONMENTAL BURDEN AND COST

5.1 Introduction

The good performance of a mixture in laboratory or field testing cannot be the only factor that secures the achievement of sustainability goals. It may demand very high levels of energy or generate tremendous amount of greenhouse gases that shadows the benefits of its less frequent M&R requirement. On the other hand, a mixture that its production and placement consume lower levels of energy or burden the environment less, may require too many M&R that eventually is not sustainable. Therefore, it is a necessity to look at the entire life cycle to have a proper image of suitability of a mixture. This chapter covers the life cycle analyses of the environmental footprint and cost of the four mixtures of interest. *Roadprint* and *PaLate* programs were employed to assess the environmental burdens. The cost analysis is done through the classic equations of engineering economy with the information from the construction contractor of the sections at the APT facility.

5.2 Determination of Frequency of Rehabilitation for Different Mixtures

The life cycle environmental burden or cost of a pavement section should consider both the initial construction and the maintenance activities. The initial construction is done only once for each section while the number of overlays depends on the performance of the mixtures. The columns of “Service Life” in Table 4-7 were used to determine the

necessity of a subsequent rehabilitation. For example, the pavement section constructed with a 3 inches thick asphalt layer of "Type D" mixture is able to take 436,700 passes of standard axle before it needs maintenance. Then, a 2 inches overlay of the same mixture will last 145,000 passes before the necessity of application of the second overlay. These values were compared with the expected traffic of the analysis period to determine the frequency of rehabilitation activities.

Equation 5-1 (Huang 2004) was used to predict the traffic for the analysis period. The required parameters in this equation were determined from the information recorded at the Cooper Street in the city of Arlington, close to UTA campus. These parameters are shown in Table 5-1.

$$ESAL = (ADT)_0(T)(T_f)(G)(D)(L)(365)(Y) \qquad (Eq. 5-1)$$

Where,

ADT_0 = Average Daily Traffic at the Start of the Design Period

T = Percentage of Trucks in the ADT

T_f = Truck Factor

G = Growth Factor

D = Directional Distribution

L = Lane Distribution

Y = Design Period

Figure 5-1 shows the distribution of vehicles by type for the selected location. The growth of traffic was calculated from the available data of the previous years; Figure 5-2 presents this information. Figure 5-3 shows the predicted traffic over the analysis period.

Table 5-1. Required Parameters for Prediction of Traffic

Analysis Period	Daily Traffic	% of Trucks	Truck Factor	Directional Distribution	Lane Distribution	Growth Rate
50 years	20,121	3.0	0.21	1	0.50	0.02

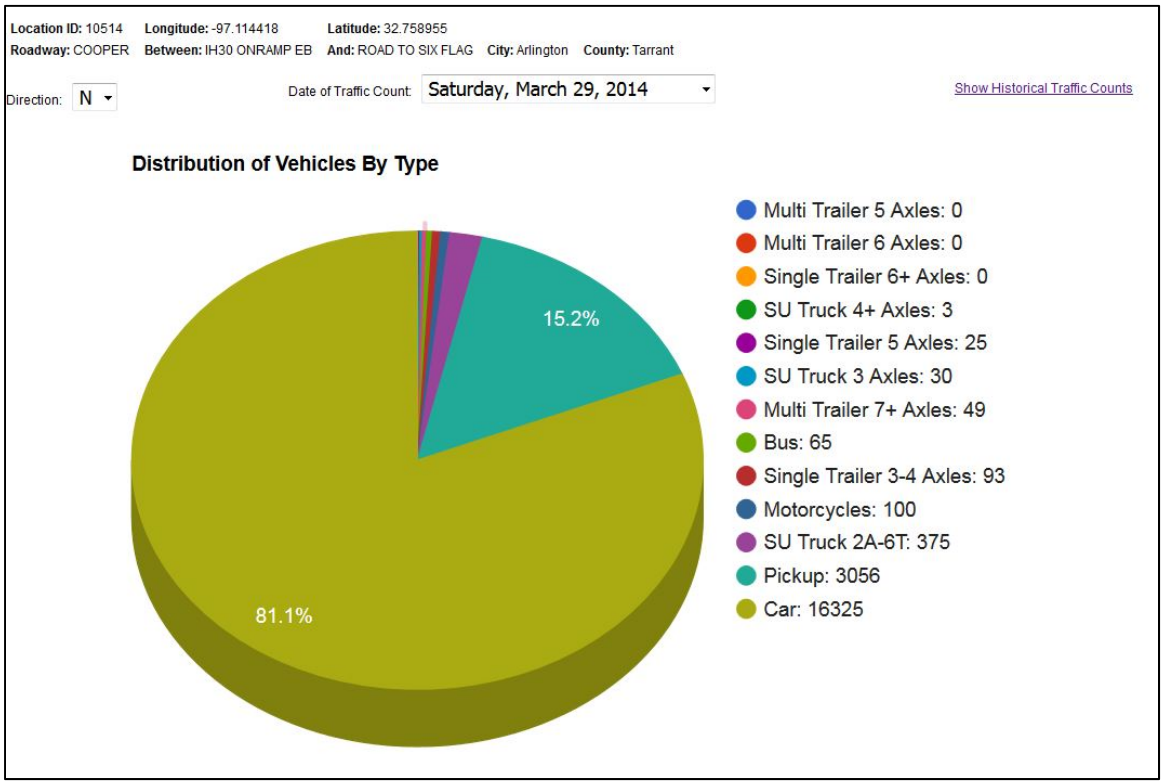


Figure 5-1. Distribution of Traffic by Vehicle Type in Cooper Street (NCTCOG 2015)

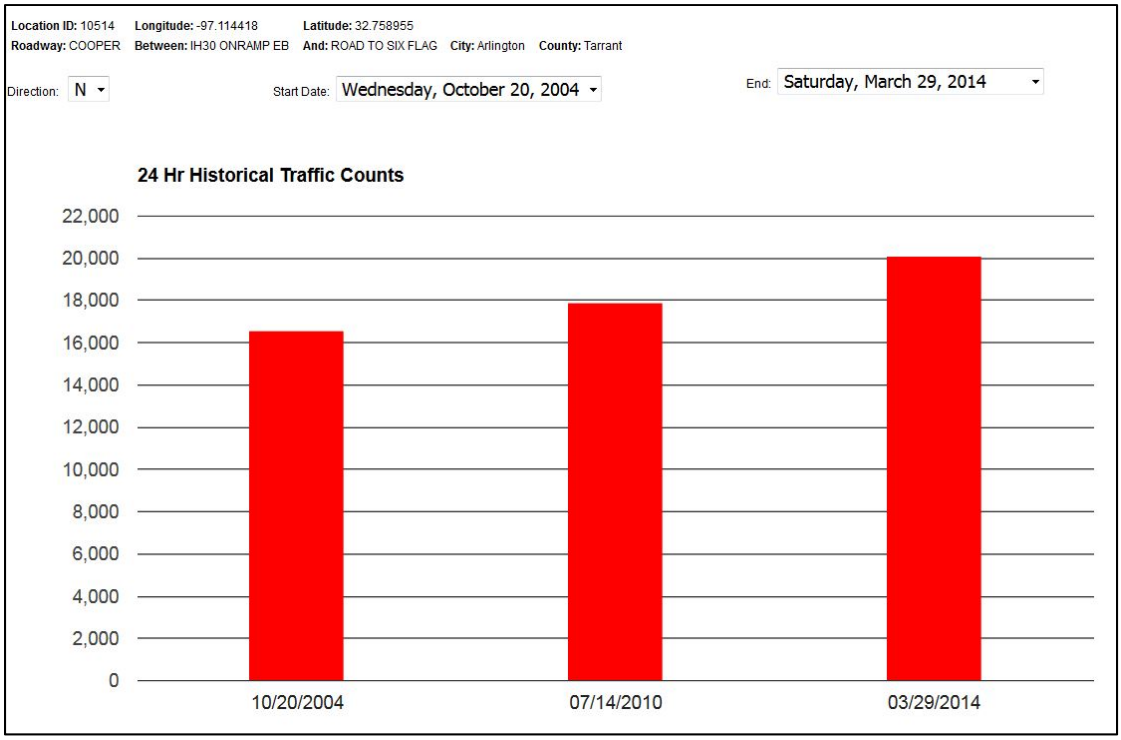


Figure 5-2. Traffic Growth at Cooper Street (NCTCOG 2015)

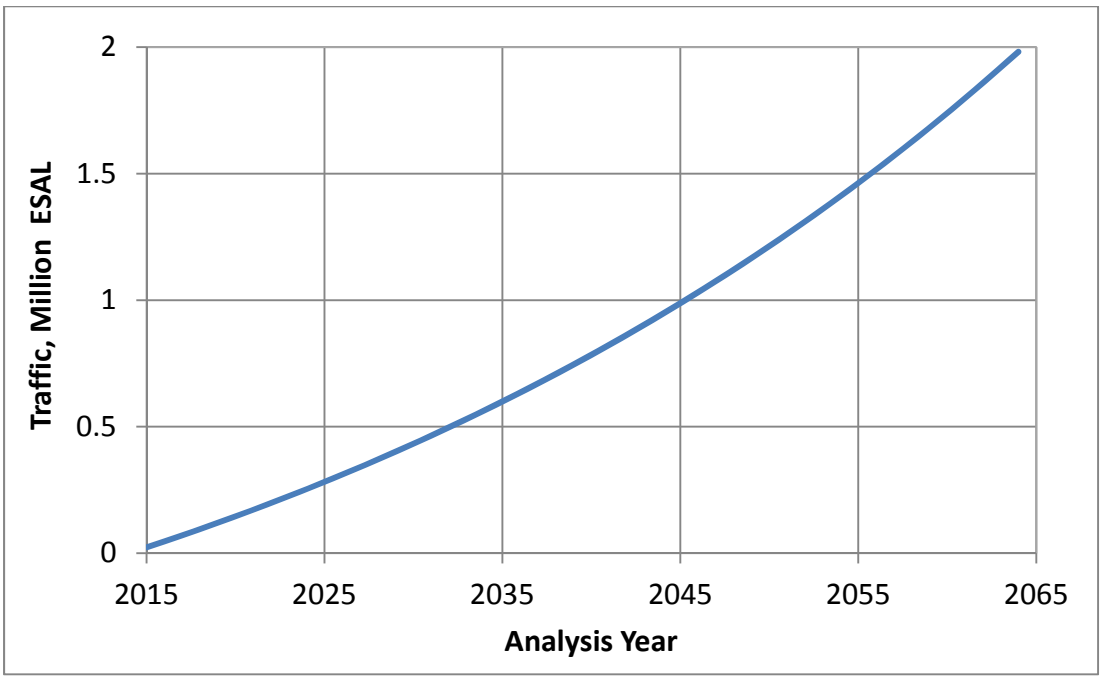


Figure 5-3. Estimation of Traffic in the Analysis Period

Table 5-2 shows the number of required overlays for each mixture as well as the remaining fraction of service life of the last overlay at the end of analysis period. As it can be seen, the poor performance of "High RAP" mixture in resistance to reflection cracking results in higher frequency of overlay placement during the analysis period, almost once a year. However, since its resistance to fatigue cracking was not very bad, the necessity for the first rehabilitation only comes after 16 years of initial construction. For the "BMD" mixture the situation is the opposite. It requires the first overlay after 13 years, but after that the rehabilitation is needed every 3-4 years. The "RAP&RAS-WMA" mixture has performed better than the "High RAP" mixture. Therefore, it almost needs 16 overlays during the analysis period. The "Type D" mixture has performed relatively well both in resistance to fatigue cracking and reflection cracking hence it does not need any overlay for the first 17 years and after that it needs an overlay every 3 years. It should be noted that the obtained results in this section were used to calculate the environmental footprint and cost of the life cycle of each mixture.

Table 5-2. Frequency of Overlay Application for Different Mixtures

Mixture	Year of First Overlay Application	NO. of Overlays	Salvage (% of Overlay)
High RAP	16	34	10.8
RAP&RAS-WMA	19	16	38.8
BMD	13	10	43.0
Type D	17	11	34.3

5.3 Life Cycle Assessment of Environmental Burden

Since the frequency of rehabilitation for different mixtures was determined, the assessment of environmental burden of the entire life cycle is feasible. For this purpose, *PaLate* and *Roadprint* programs were employed to evaluate the environmental burden of the mixtures. After that, a comparison was made between the outputs of these two tools to ensure the accuracy of the results.

5.3.1 Required Information for Environmental Analyses

Since the comparison between different asphalt mixtures is of interest, the effects of underlying layers of base and subbase were not considered in the analyses. The mixtures composition was extracted from Table 4-2. Table 5-3 shows the transport distance to the asphalt plant for each mixture component, along with their mode of transport. It was assumed that the recycled materials of RAP and RAS were collected within the 10 miles radius of the asphalt plant.

Table 5-3. Information on Source and Transport Mode of Mixture Constituents

Quarry of Aggregates / Asphalt Refinery	Distance to Asphalt Plant (miles)	Mode of Transport
Bridgeport Aggregates	60	Truck
Mill Creek Aggregates	110	Train
Tin Top (Field Sand)	50	Truck
Valero (Bitumen)	100	Train

Additionally, the list of the utilized equipment in the placement and compaction of the asphalt layer was acquired from the contractor. Table 5-4 shows their specifications and other related information. These values were introduced into the analysis tools to include the effect of the placement and compaction equipment. It should be also mentioned that the production rate of the asphalt plant was considered as 250 tons per hour.

An important assumption in the course of analyses was considering the influence of WMA technology. In absence of well-documented measurements, it was decided to use the lowest recommended value in literature, i.e. 15 percent (Hassan 2009). Therefore, it was considered that the WMA technology consumes 15 percent less energy and generates 15 percent less GHG when compared to HMA.

Table 5-4. Information on Utilized Equipment in Construction of Asphalt Layer

<table>
<tr><th>Specification</th><th>HMA Paver</th><th>Breakdown Roller</th><th>Intermediate Roller</th><th>Finish Roller</th><th>Shuttle Buggy</th></tr>
<tr><td>Engine HP</td><td>174</td><td>134</td><td>114</td><td>46</td><td>300</td></tr>
<tr><td>Working Time (%)</td><td>100</td><td>100</td><td>100</td><td>75</td><td>100</td></tr>
<tr><td>Efficiency Factor (%)</td><td>85</td><td>85</td><td>85</td><td>85</td><td rowspan="8">N/A</td></tr>
<tr><td>Production Rate (ft/min)</td><td>35</td><td rowspan="3">N/A</td><td rowspan="3">N/A</td><td rowspan="3">N/A</td></tr>
<tr><td>No. of Lifts</td><td>2</td></tr>
<tr><td>Paving width (ft)</td><td rowspan="6">N/A</td></tr>
<tr><td>Roller Speed (ft/min)</td><td>300</td><td>300</td><td>300</td></tr>
<tr><td>Drum Width (ft)</td><td>6.5</td><td>6</td><td>4.5</td></tr>
<tr><td>Drum Overlap (inch)</td><td>6</td><td>6</td><td>6</td></tr>
<tr><td>No. of Passes</td><td>4</td><td>20</td><td>1*</td></tr>
</table>

* RAP&RAS-WMA mixture needed 2 passes of the finish roller.

5.3.2 Results of Environmental Burden Analysis with PaLate

The *PaLate* program was explained in details in chapter three. This program provides the outputs in three distinct phases of 'Materials Production", "Materials Transportation" and "Processes or Equipment". Figures 5-4 to 5-8 compare the environmental footprint of different mixtures for these phases for five factors of energy consumption and emissions of CO_2, PM_{10}, CO and SO_2, respectively. Results of the other factors are presented in Appendix B.

The energy consumption for the "High RAP" mixture is the highest, due to the higher number of overlays. After this mixture, the "RAP&RAS-WMA", the "Type D" and the "BMD" mixtures are in decreasing orders of energy consumption. Moreover, major consumption of energy happens in the "Materials Production" phase while the other two phases have a negligible share.

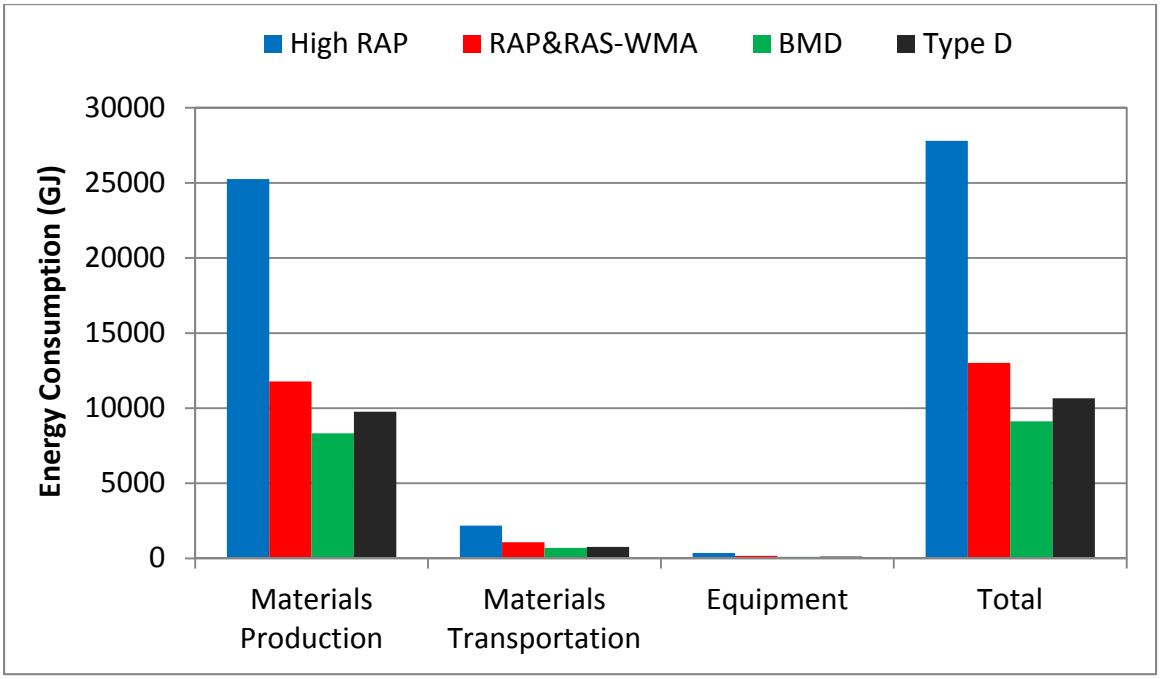


Figure 5-4. Comparison of Energy Consumption of Asphalt Mixtures in *PaLate*

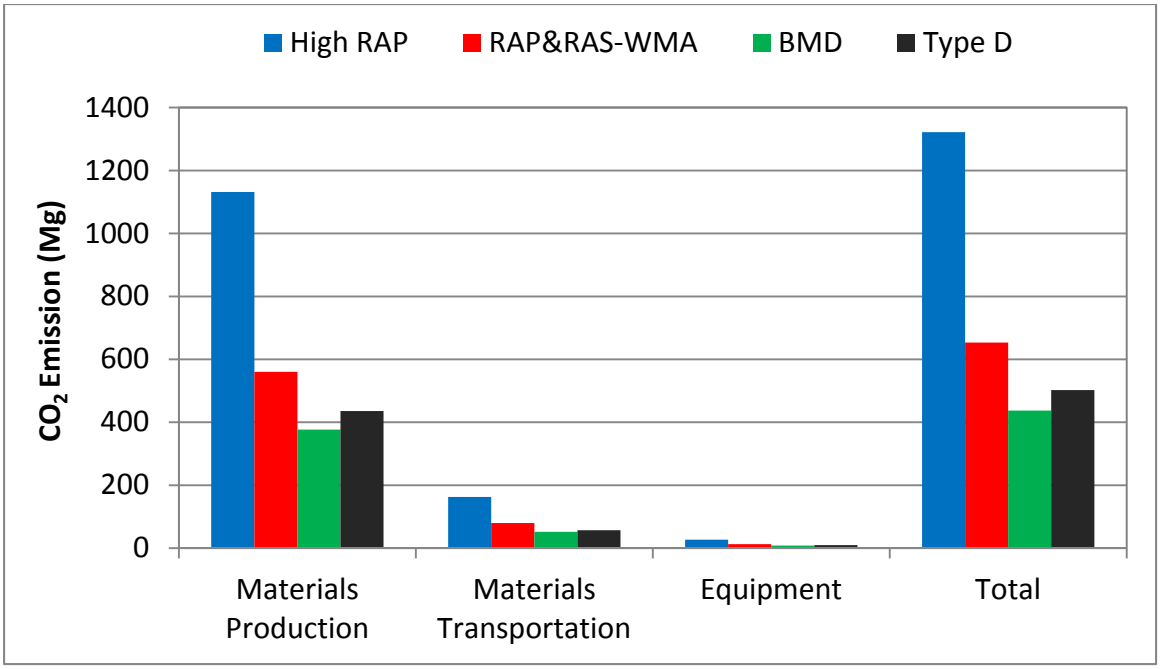


Figure 5-5. Comparison of CO_2 Emission of Asphalt Mixtures in *PaLate*

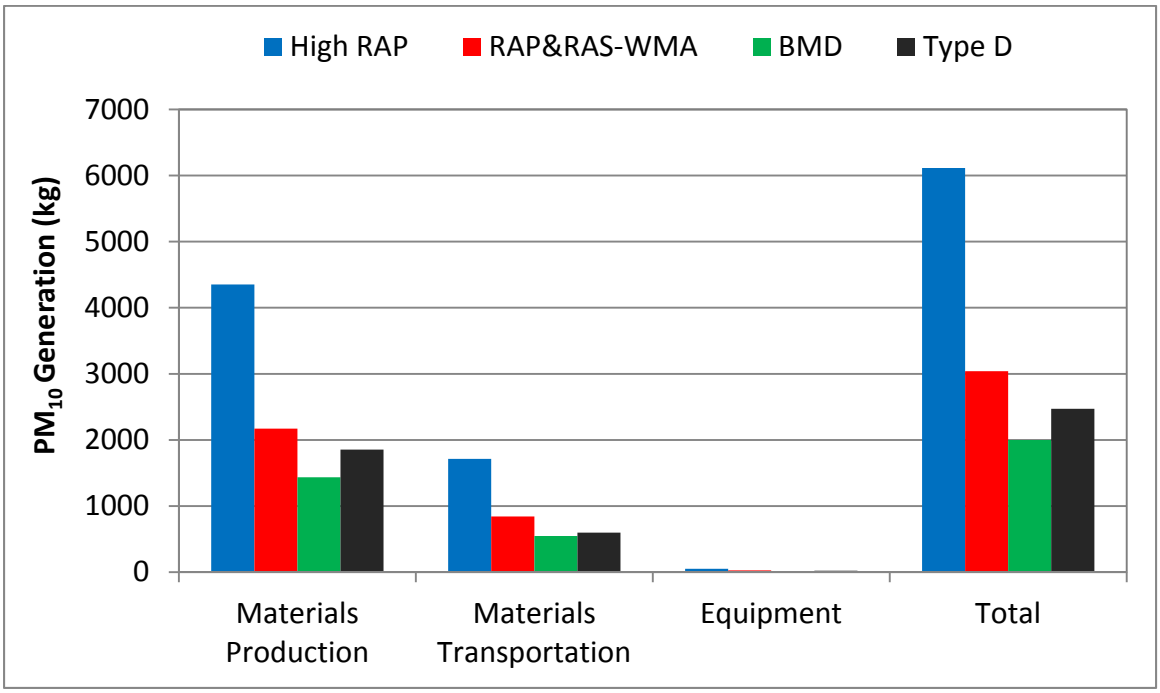


Figure 5-6. Comparison of PM_{10} Emission of Asphalt Mixtures in *PaLate*

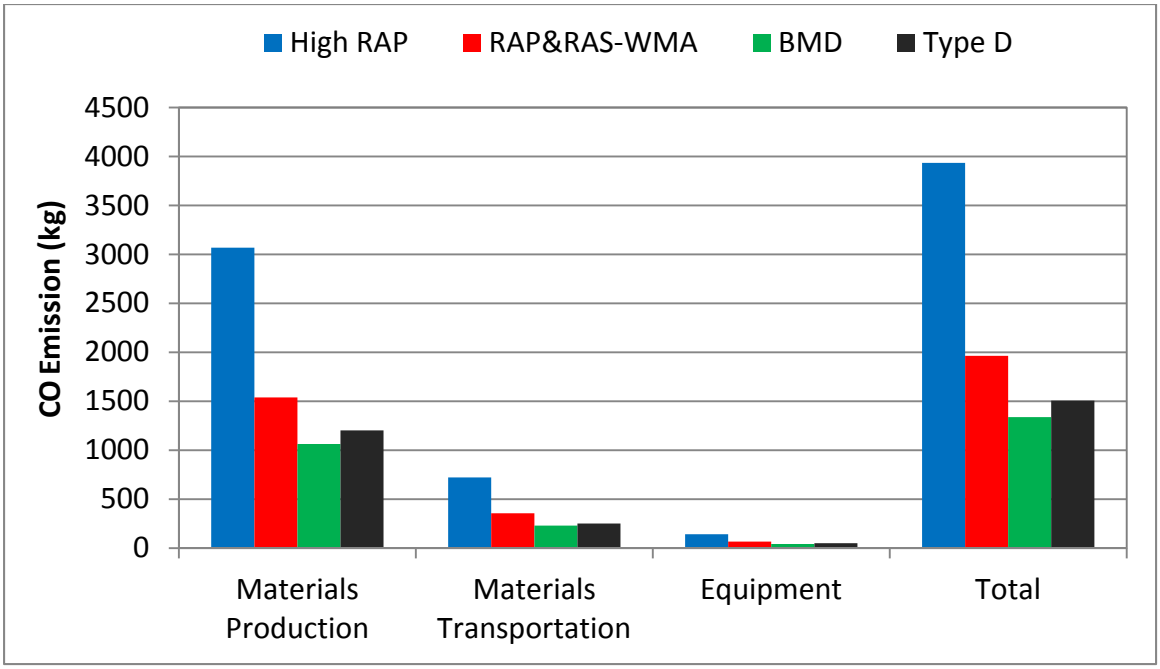


Figure 5-7. Comparison of CO Emission of Asphalt Mixtures in *PaLate*

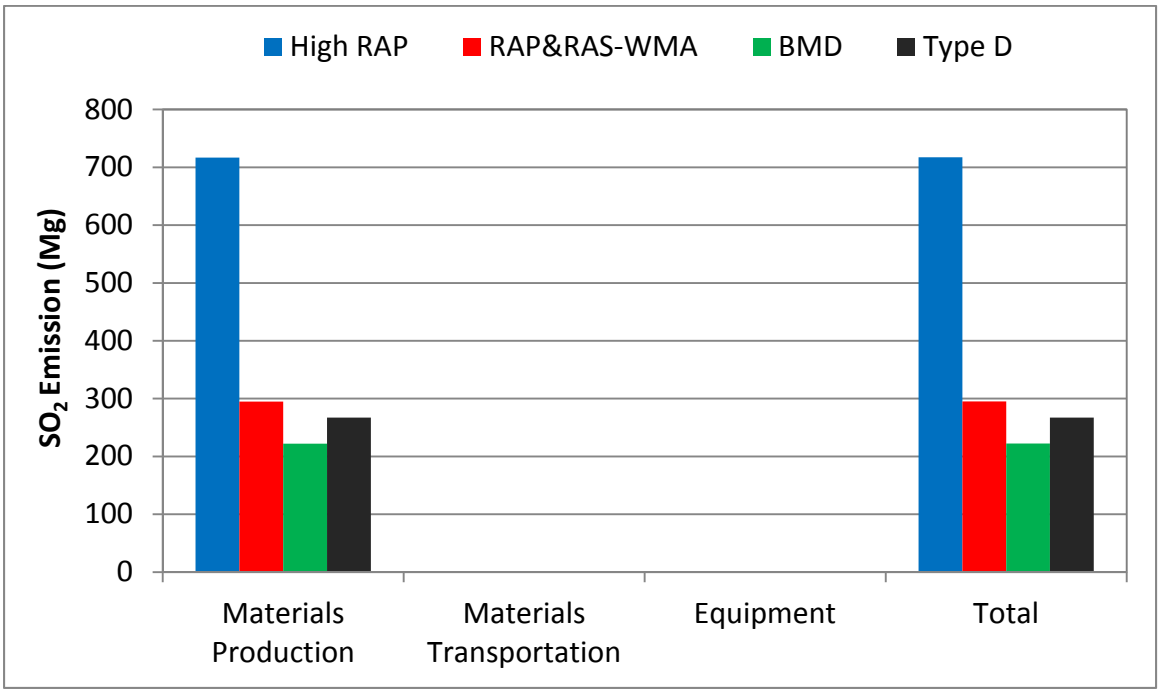


Figure 5-8. Comparison of SO_2 Emission of Asphalt Mixtures in *PaLate*

Same ranking of mixtures can be seen in the other presented factors. Similar to energy consumption, the share of "Materials Production" phase is significant in all of the other factors. The contribution of this phase is even more distinguishable in the emission of SO_2. For this factor, the emission of the "Materials Production" phase is almost 1000 times of the emission of the two other phases. Thus, this phase should be the focus of further investigations to reduce the environmental problems.

The equipment usually does not incur much pressure to the environment. The only factor in which its role comes into attention is the CO emission. Even for this factor, its share never exceeds 3 percent of the total emission. Therefore, this phase seems not to raise much environmental concern.

The "Materials Transportation" phase plays more important role than the "Equipment" phase. Its contribution is the most when the generation of PM_{10} is evaluated. In this factor, almost 25 percent of the total emission comes from the "Materials Transportation" phase. This phase also needs attention if lowering the environmental burden of asphalt pavements is intended.

The total values of the five aforementioned factors are normalized by the values for the "Type D" mixture. Figure 5-9 presents these normalized factors. It is seen that the least difference between the mixtures is in the "PM_{10} Generation" factor. It means that the generation of dust between different mixtures is relatively closer to each other, compared with other factors. However, the differences are not much. In any case, the ranking of the mixtures does not change from one factor to another. From the results of the *PaLate* program, it can be concluded that the "BMD" mixture influences the

environment the least and the "High RAP" mixture the most. The "Type D" and "RAP&RAS-WMA" mixtures are in the middle with the "Type D" being environmental friendlier.

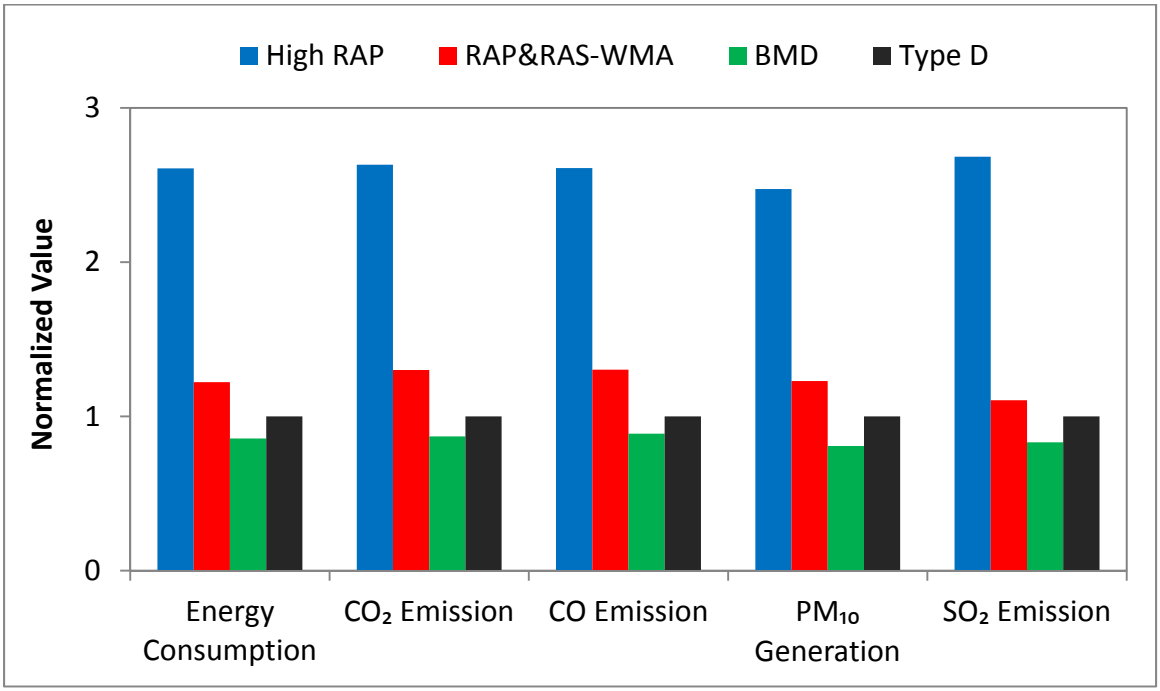


Figure 5-9. Comparison of Normalized Factors for Asphalt Mixtures in *PaLate*

5.3.3 Results of Environmental Burden Analysis with Roadprint

Roadprint program was also used to evaluate the environmental burden. Similar to *PaLate*, this program provides the results in three phases of "Materials Production", "Materials Transportation" and "Construction Equipment". Figures 5-10 to 5-14 provide the results for the same factors of interest that were presented for *PaLate* program. The other *Roadprint* outputs are presented in the Appendix B.

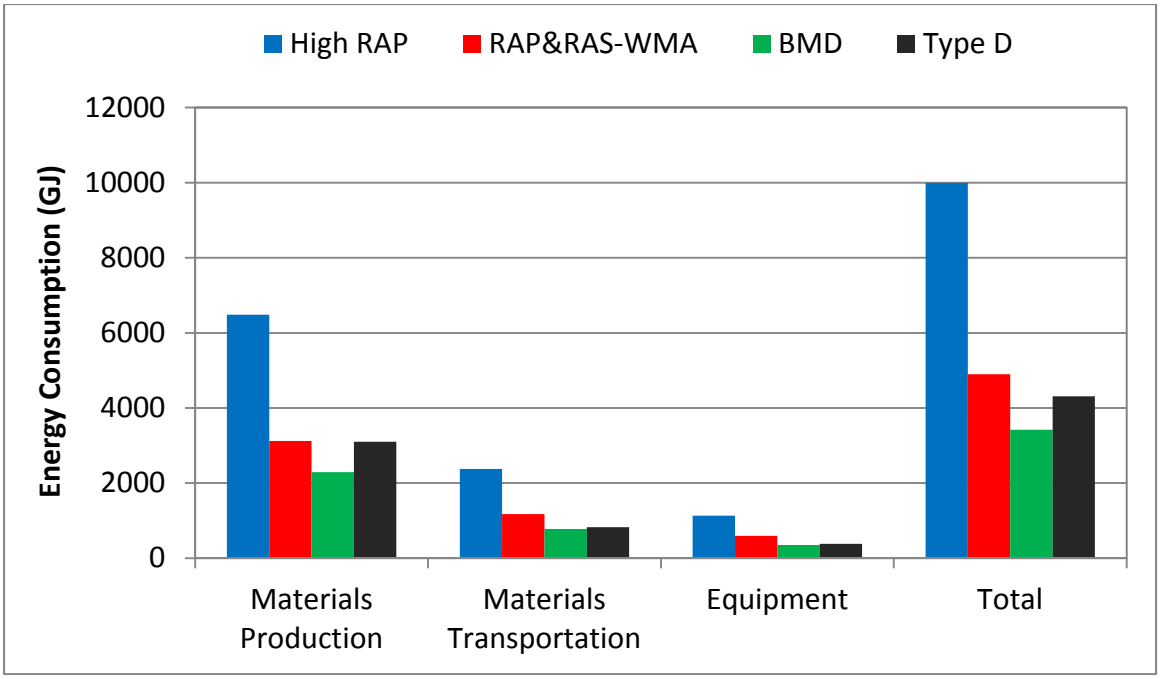


Figure 5-10. Comparison of Energy Consumption of Asphalt Mixtures in *Roadprint*

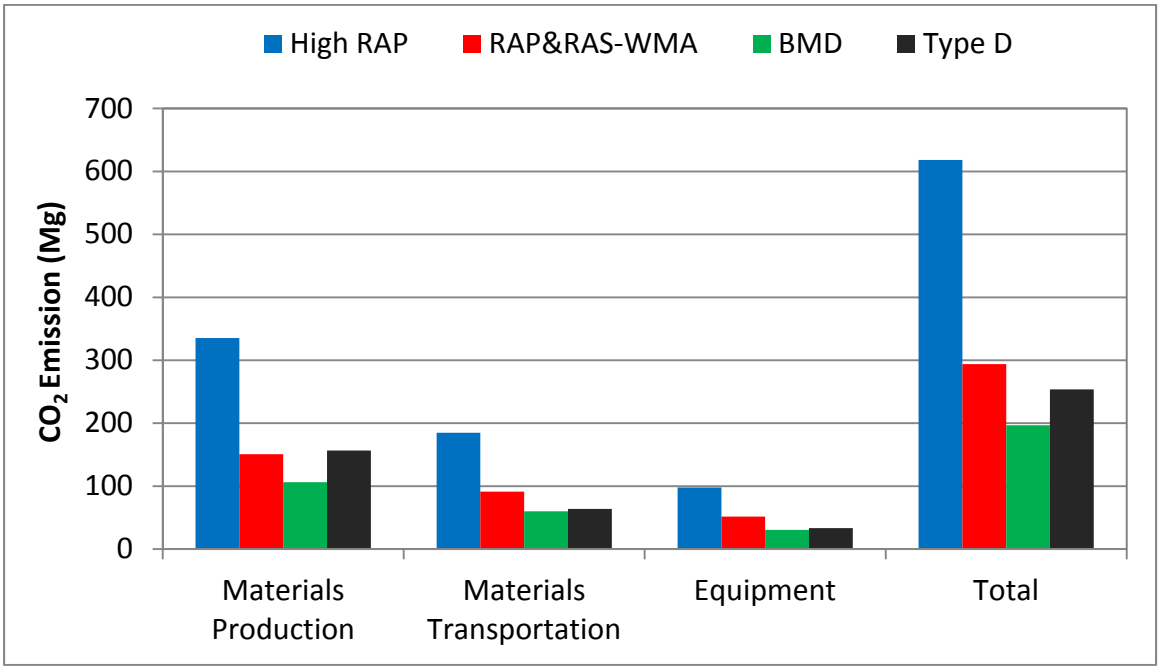


Figure 5-11. Comparison of CO_2 Emission of Asphalt Mixtures in *Roadprint*

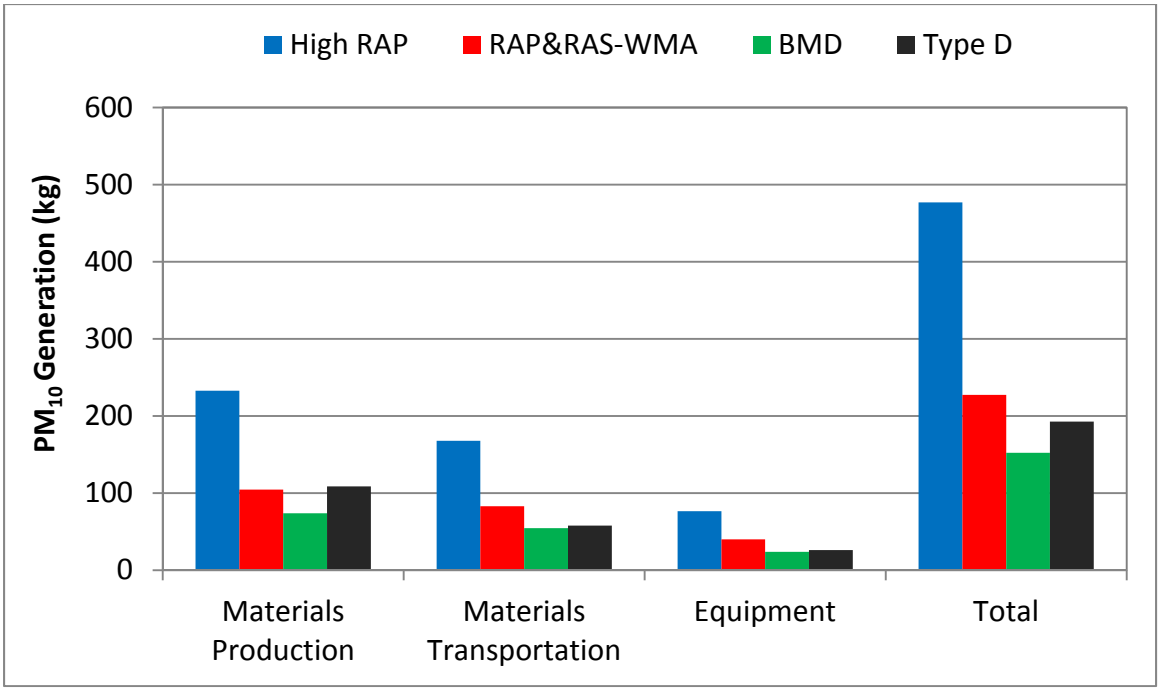


Figure 5-12. Comparison of PM_{10} Emission of Asphalt Mixtures in *Roadprint*

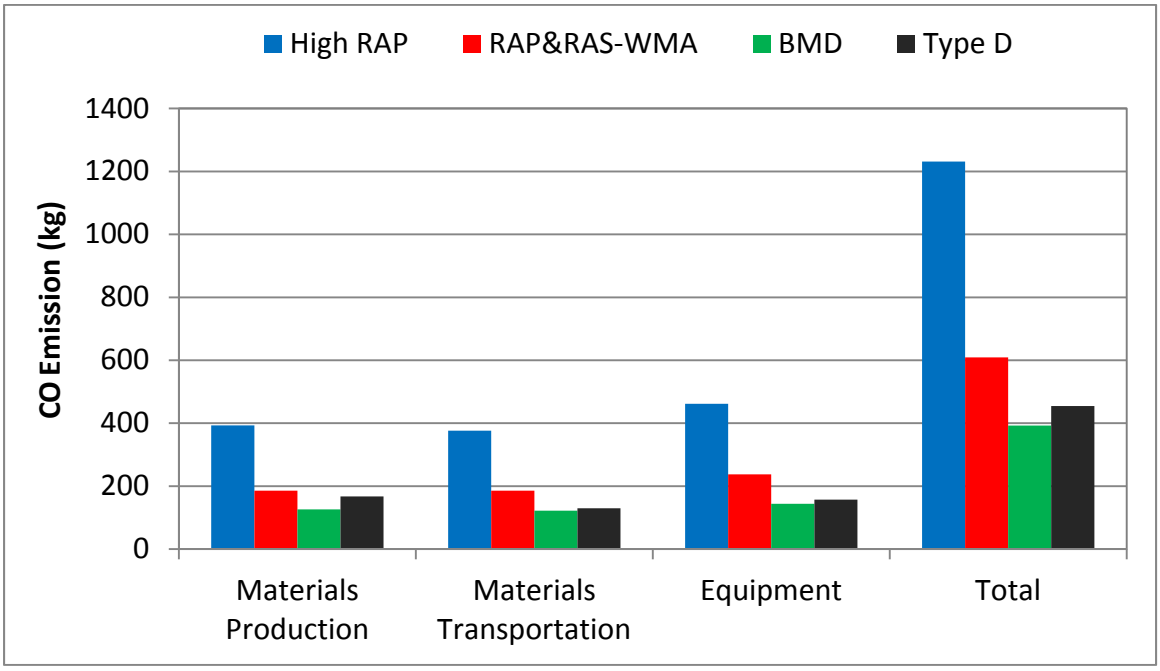


Figure 5-13. Comparison of CO Emission of Asphalt Mixtures in *Roadprint*

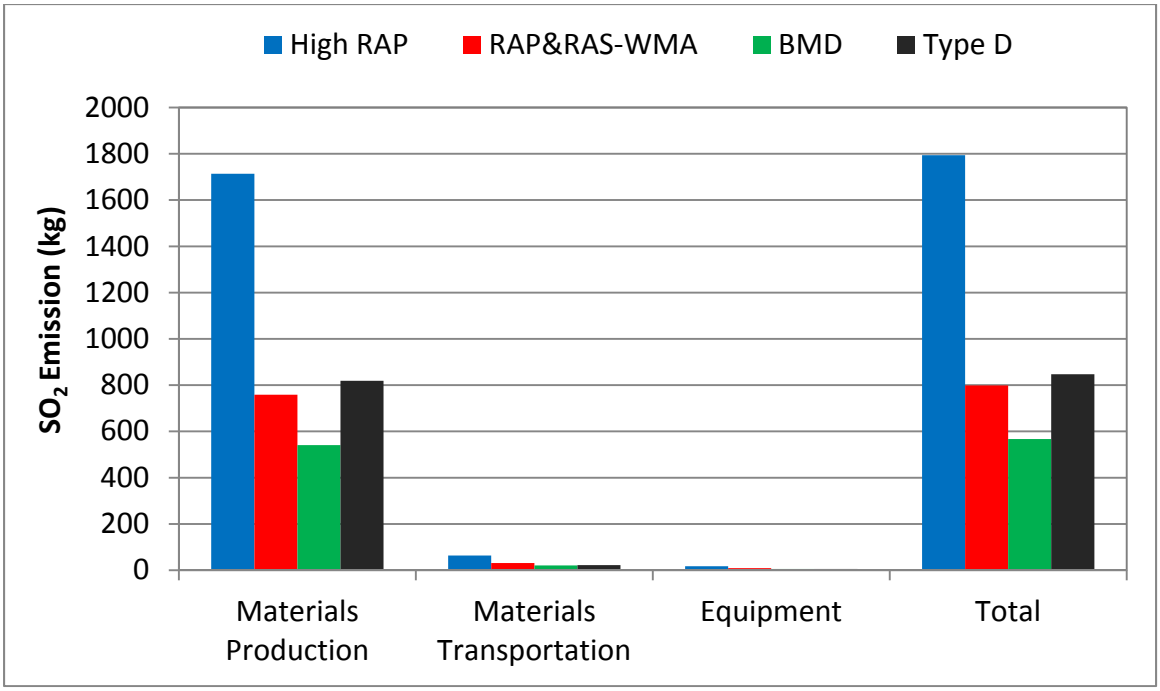


Figure 5-14. Comparison of SO_2 Emission of Asphalt Mixtures in *Roadprint*

From the *Roadprint* results, it can be seen among different phases that the "Materials Production" usually has the highest influence on the environment. However, this difference is much less than what the *PaLate* program suggests. For CO emission, all the phases have relatively the same influence. The role of "Equipment" phase is slightly more than the other two phases. After inspecting the charts of other factors (in Appendix B), it is seen that the construction equipment may have noticeable impact on the environment from the standpoint of some of these factors. It is clear that the use of equipment is a function of the number of rehabilitation projects. Therefore, decreasing the required overlays can significantly serve the environment.

Figure 5-15 shows the normalized factors in the program of *Roadprint*. In all of the factors, the "BMD" mixture is the most environmental friendly one while the "High

RAP" mixture is the least. In fact, the environmental burden of the "High RAP" mixture is almost three times of that of the "BMD" mixture. Moreover, the "Type D" mixture in most of the factors is better than the "RAP&RAS-WMA". However, when the SO_2 emission is inspected, the "Type D" pressures the environment more than the "RAP&RAS-WMA" mixture.

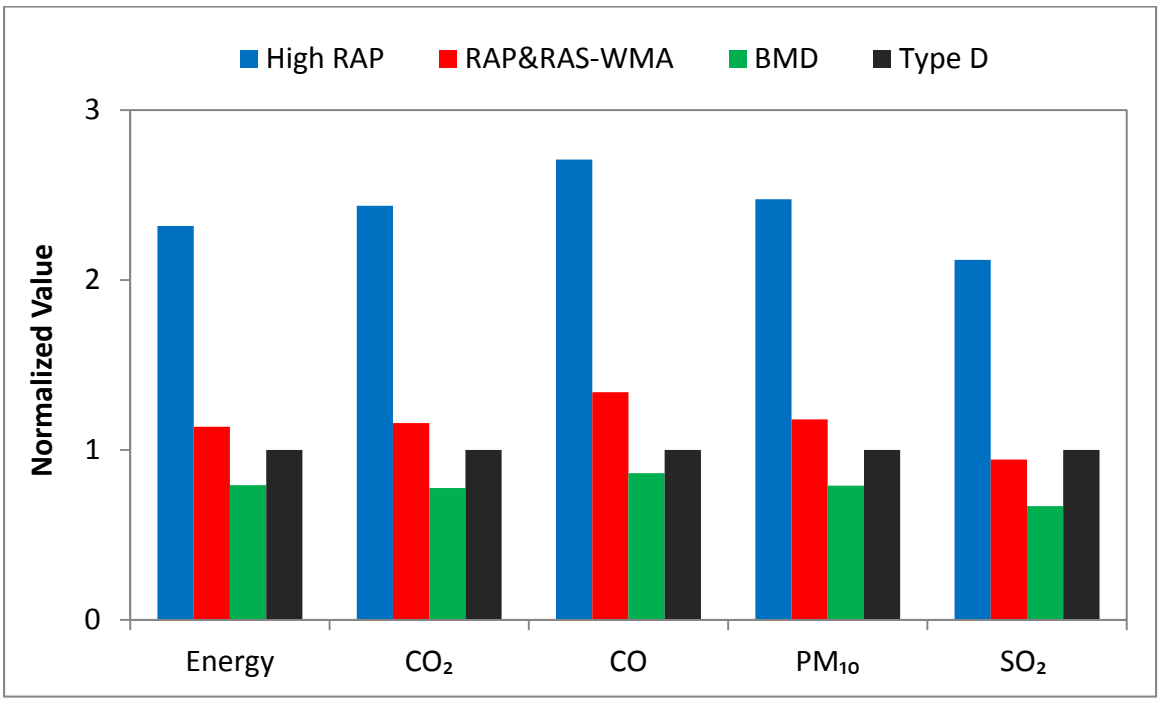


Figure 5-15. Comparison of Normalized Factors for Asphalt Mixtures in *Roadprint*

The environmental burden break down of the "Materials Production" phase is presented in Figures 5-16 to 5-18. These figures include the energy consumption, CO_2 emission and CO emission for the production of the components of the asphalt mixtures, i.e. bitumen, aggregates and recycled materials.

As it can be seen in Figure 5-16, the majority of energy consumption occurs in the production of bitumen, regardless of the mixture type. Chiu et al. (2008) also obtained similar results. Also, the production of aggregates is more energy consuming than the recycled materials. The same order exists in the emission of CO_2, presented in Figure 5-17. This time, the share of recycled materials is very small and can be neglected. When it comes to inspecting the emission of CO, the contribution of bitumen is still high, but it is no longer the highest. At this factor, the production of aggregates has the highest share. Although the recycled materials have the lowest values, their contribution is more noticeable now. This should be related to the use of equipment in reclaiming the old pavement. It shows again the importance of "Equipment" phase in the environmental analysis which should not be neglected.

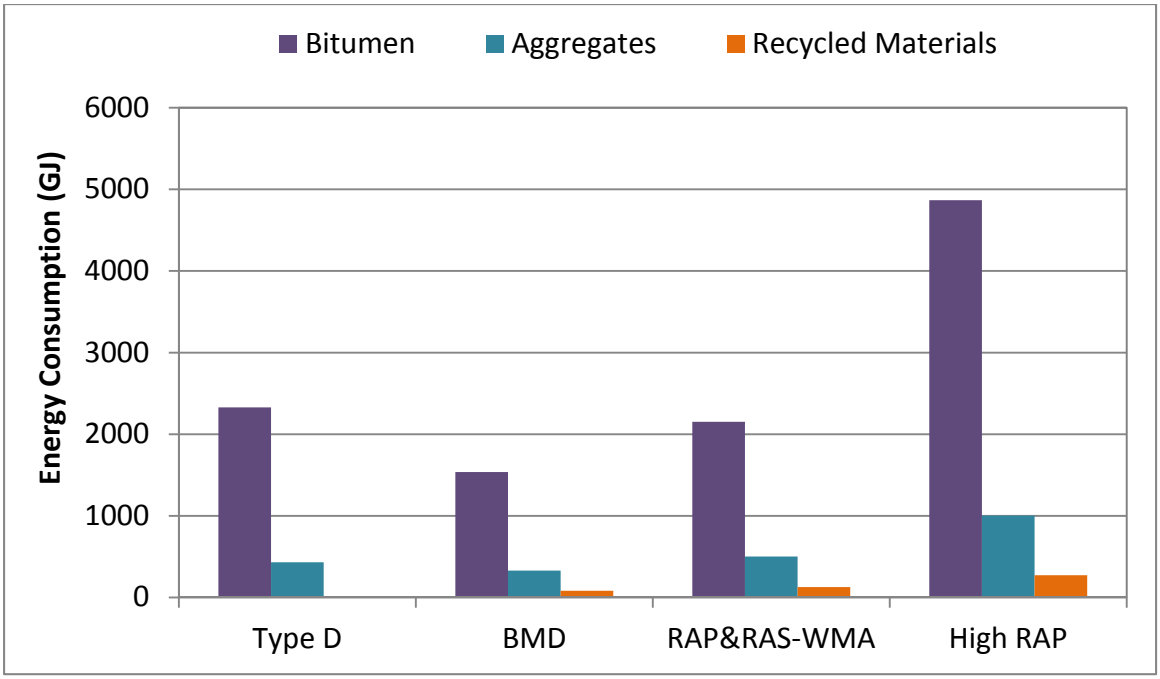


Figure 5-16. Energy Consumption of Different Components of Mixtures

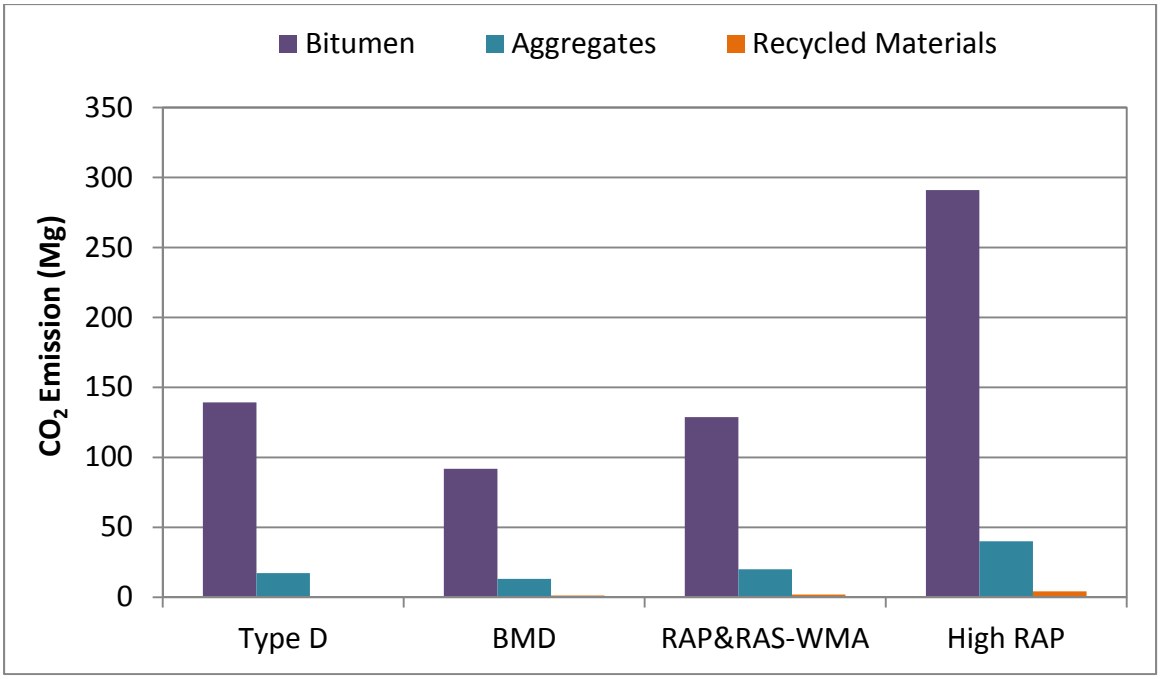


Figure 5-17. CO_2 Emission of Different Components of Mixtures

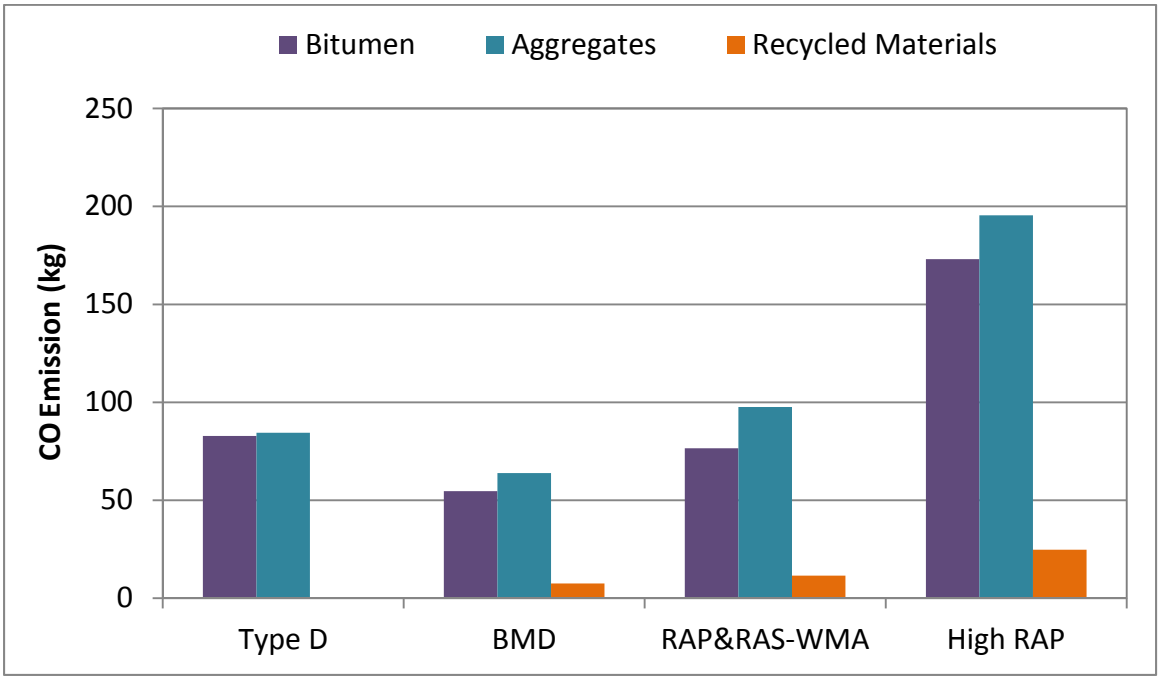


Figure 5-18. CO Emission of Different Components of Mixtures

The results can also be presented based on the share of initial construction versus overlay placements. Figure 5-19 shows this comparison for energy consumption and Figure 5-20 shows it for normalized CO_2 emissions. Relatively the same trend was observed for the other factors. This figure clearly demonstrates the role of subsequent overlays in the energy consumption of different mixtures. The production of "BMD" and "Type D" mixtures consume more energy than of the other mixtures. This is in accordance with the findings of many other researchers for the virgin mixtures. However, the good performance of these mixtures reduces the number of required overlays which eventually makes them more environmental friendly. This fact has been neglected in many former studies on sustainability of asphalt mixtures.

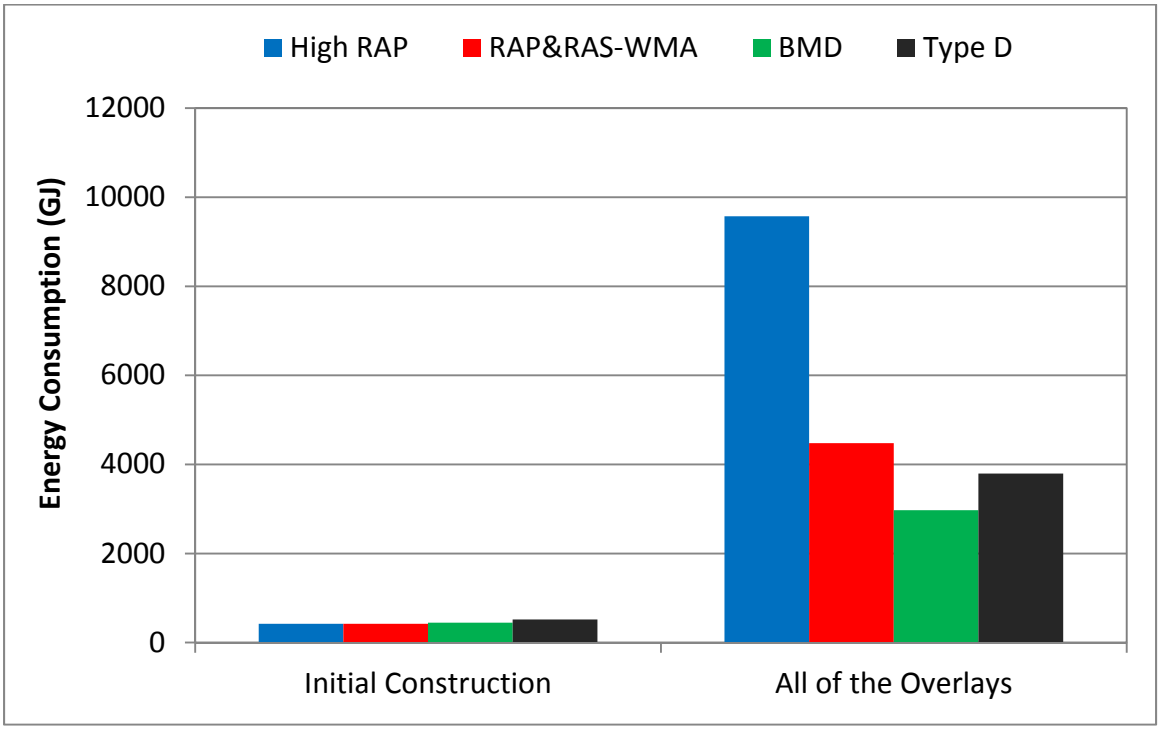


Figure 5-19. Energy Consumption in Different Construction Stages

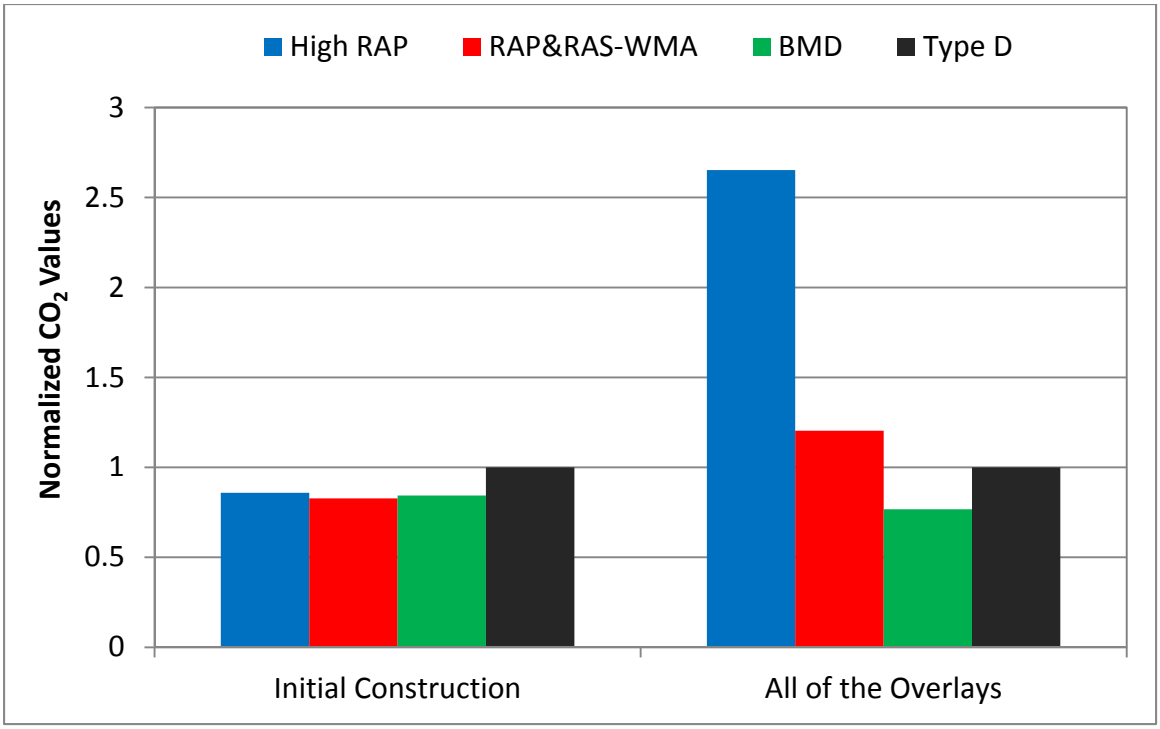


Figure 5-19. Normalized CO_2 Emission in Different Construction Stages

5.3.4 Comparison of the Results of Roadprint and PaLate

The purpose of utilizing two separate environmental analysis tools is to assure the accuracy of the mixtures ranking. Among the factors that *Roadprint* and *PaLate* programs provide, five of them are identical. These factors are energy consumption and emissions of CO_2, CO, PM_{10} and SO_2 which were presented in former sections. Table 5-5 presents the comparison of results for these factors. It should be mentioned that the values of each factor for different mixtures were normalized by the value of that factor for the "Type D" mixture. Figure 5-21 shows this comparison for energy consumption

factor. Since the values of the other factors have similar relationship, only the results of energy consumption are plotted for brevity.

Table 5-5. Comparison of the Results of *Roadprint* and *PaLate*

Mixture	Energy		CO_2		CO		PM_{10}		SO_2	
	P*	***R****	***P***	***R***	***P***	***R***	***P***	***R***	***P***	***R***
Type D	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
BMD	**0.9**	**0.8**	**0.9**	**0.8**	**0.9**	**0.9**	**0.8**	**0.8**	**0.67**	**0.8**
RAP&RAS-WMA	**1.2**	**1.1**	**1.3**	**1.2**	**1.3**	**1.3**	**1.2**	**1.2**	**0.94**	**1.1**
High RAP	**2.6**	**2.3**	**2.6**	**2.4**	**2.6**	**2.7**	**2.5**	**2.5**	**2.12**	**2.7**
**** P: PaLate***						**** R: Roadprint***				

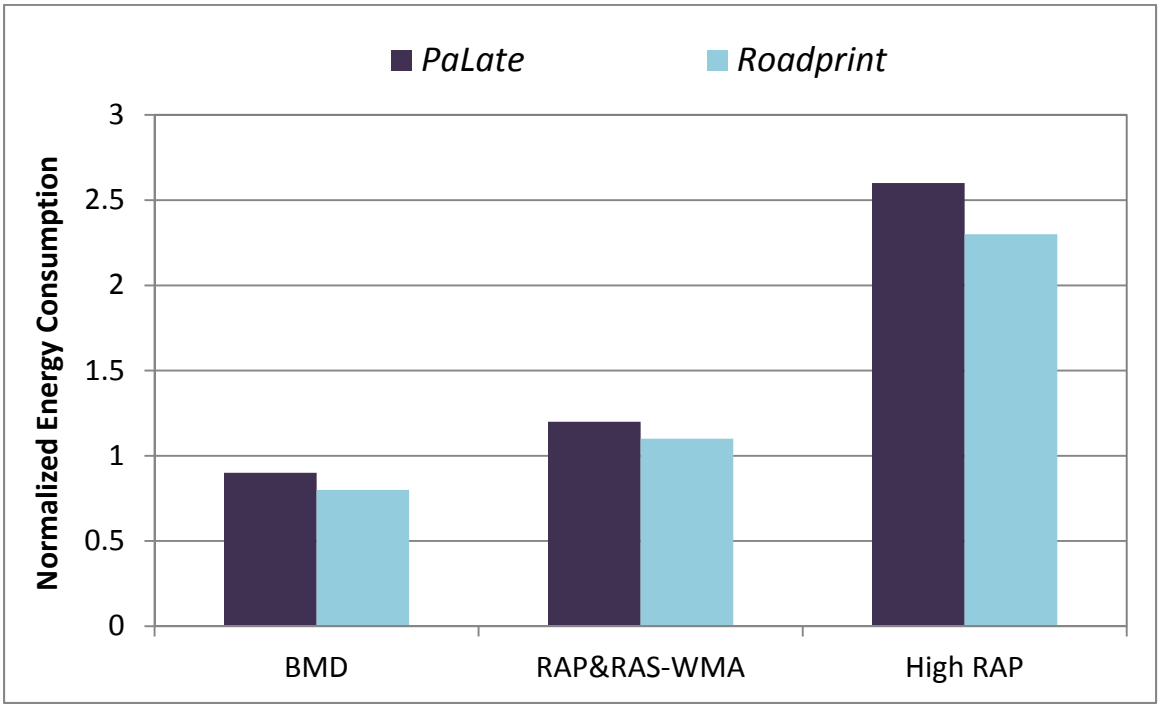


Figure 5-20. Comparison of *PaLate* and *Roadprint* Results, Energy Consumption

It is clear that the *PaLate* program estimated higher levels of environmental burden for the mixtures than *Roadprint* did. This variation is normal as the two programs have different data inventories. The important point of this comparison is that the two programs rank the mixtures in a similar order. Based on their results, the "BMD" mixture is the most environmental friendly mixture and the "Type D", "RAP&RAS-WMA" and "High RAP" mixtures are in subsequent decreasing order.

5.4 Life Cycle Cost Analysis, LCCA

As the last step in the sustainability assessment of recycled asphalt mixtures, the life cycle cost of the studied mixtures is analyzed. The cost of initial construction and any subsequent required rehabilitation is considered for the analysis period.

5.4.1 Required Information for Life Cycle Cost Analysis

The information regarding the construction of the APT facility field sections was acquired from the contractor. This information was then used to calculate the cost of the same hypothetical pavements that were introduced in section 4.6. In addition to that, some assumptions have been made. Table 5-6 provides the production cost of each mixture along with the cost of equipment and the crew. Table 5-7 shows the geometrical dimensions of the pavement at different stages of construction.

Table 5-6. Asphalt Mixtures Construction Costs

Mixture	Unit Price ($/ton)	Equipment Move ($/project)	Lay-Down Operations ($/day)
High RAP	58.00	5,000	7,600
RAP&RAS-WMA	57.20		
BMD	68.75		
Type D	66.00		

Table 5-7. Construction Information of the Pavement

	Length (mile)	Width (ft.)	Thickness (in.)	Mixture Density (pcf)	Total Weight (ton)	Lay-Down Period (day)
Initial Construction	1	12	3	145	1,148	1
Overlay			2		766	

The calculation of the initial construction cost of the mixtures can be easily done with this information. However, for overlays which will be applied in future, the value of money should be included in the analysis if the current information is used. For this purpose, a growth rate should be considered for increase in the cost of rehabilitation in subsequent years. Since the most expensive component of the asphalt mixtures is the bitumen, it was assumed that the price of mixtures increases at the same rate as that of the

bitumen. The bitumen price is also a function of world oil prices. Figure 5-22 shows the prediction of World Bank for crude oil prices for the next decade. This trend gives us a growth rate of 5.4% which is then used to adjust the cost of overlays in corresponding years.

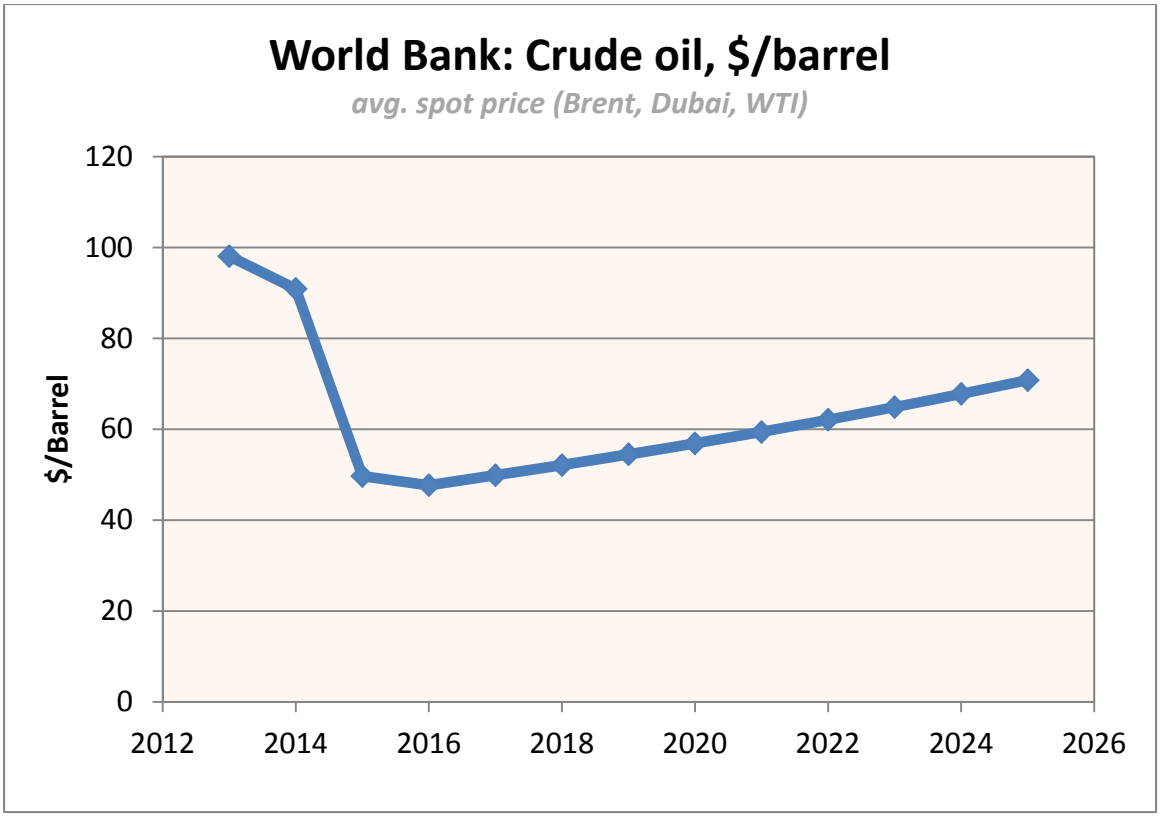


Figure 5-21. Prediction of Crude Oil Prices in Subsequent Years (World Bank 2015)

Another influential component in the calculation of cost for different mixtures is the recycled materials. The unit price of each mixture includes the production cost of these materials. However, the fact that these materials are not needed to be dumped at the landfill is not considered. This is an advantage of recycled asphalt mixtures over virgin

mixtures. In this analysis, the total weight of recycled materials which are used in the production of each mixture is calculated. This value is then multiplied by the current landfill tipping fee in Texas which is $28.95 (Clean Energy Projects Inc. 2015). For simplification, it is assumed that the growth rate of this fee is the same as for the rehabilitation costs. In addition to this, at the time of each overlay application, the amount of removed asphalt layer is considered to be dumped at the landfill. Therefore, landfilling charges are also included in the LCCA.

Classic engineering economy equations are employed to include the time value of construction costs. Figure 5-23 presents a schematic illustration of the concept. Equations 5-2 and 5-3 are used to calculate NPV and EUAC.

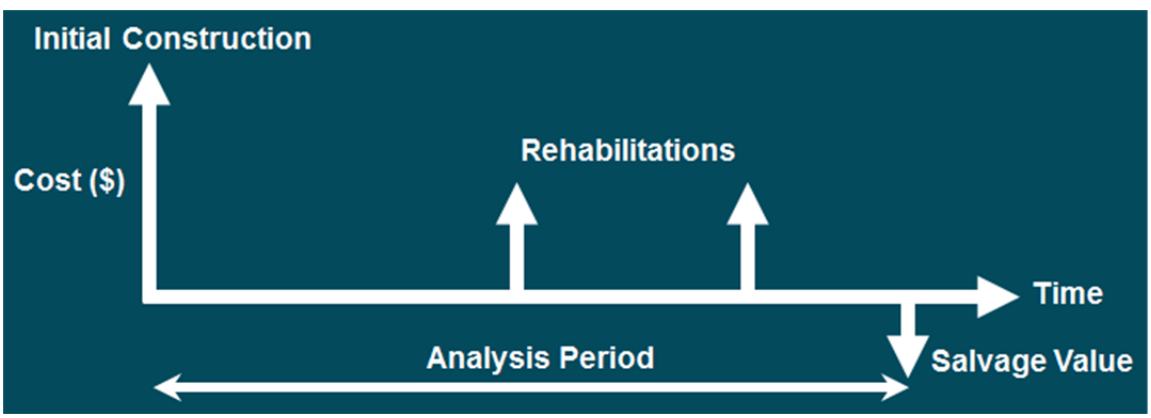


Figure 5-22. Schematic Illustration of Economic Calculations

$$NPV = InitialCost + \sum_{k=1}^{N} RehabCost_k \left[\frac{1}{(1+i)^{n_k}}\right] - SalvageValue \left[\frac{1}{(1+i)^{n}}\right]$$

$$(Eq. 5-2)$$

$$EUAC = NPV\left[\frac{i(1+i)^n}{(1+i)^n - 1}\right] \qquad (Eq. 5-3)$$

Where,

i = Discount Factor

n_k = Year at which the overlay is placed

n = Analysis Period

5.4.2 Results of Life Cycle Cost Analysis

The basic information was used to calculate the construction costs at current time. Tables 5-8 and 5-9 show the results for initial construction and overlay placement, respectively. The data are also plotted in Figure 5-24. As it can be seen, the cost of both initial construction and overlay placement for the "Type D" mixture is the highest. The "BMD", "High RAP" and "RAP&RAS-WMA" mixtures are in subsequent decreasing order.

Table 5-8. Initial Construction Costs

Mixture	Material ($)	Placement and Compaction ($)	Landfill ($)	Total ($)
High RAP	66,607	12,600	(6,018)	73,189
RAP&RAS-WMA	65,688		(5,718)	72,570
BMD	78,953		(5,652)	85,901
Type D	75,794		-	88,394

Table 5-9. Present Cost of Each Overlay Placement

Mixture	Material ($)	Placement and Compaction ($)	Landfill ($)	Total ($)
High RAP	44,405	12,600	18,152	75,157
RAP&RAS-WMA	43,792		18,352	74,744
BMD	52,635		18,396	83,631
Type D	50,530		22,164	85,294

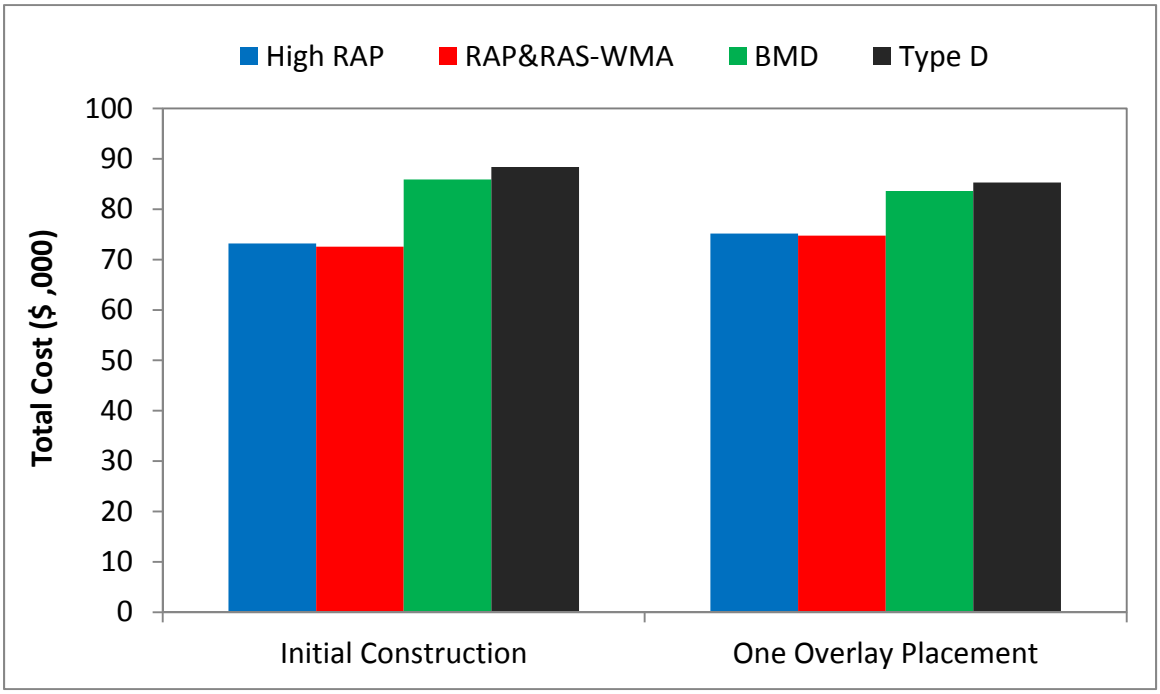


Figure 5-23. Comparison of Raw Construction Costs for Different Mixtures

In order to have a picture of the entire life cycle costs of mixtures, the recurrence of required overlay placement should be taken into account. The growth rate of 5.4% generates the increase in the cost of rehabilitation over the years. The calculations of

NPV and the EUAC are done through considering two discount rates. One is 4% which is smaller than the growth rate, and the other one is 7% which is greater than the growth rate. Figure 5-25 provides the comparison between the normalized life cycle costs of the mixtures. Similar to the environmental burden analyses, the values for "Type D" is considered as the basis for normalization. These values are presented in Table 5-10 which include the cost of each stage of construction and rehabilitation of the "Type D" mixture for the two discount rates.

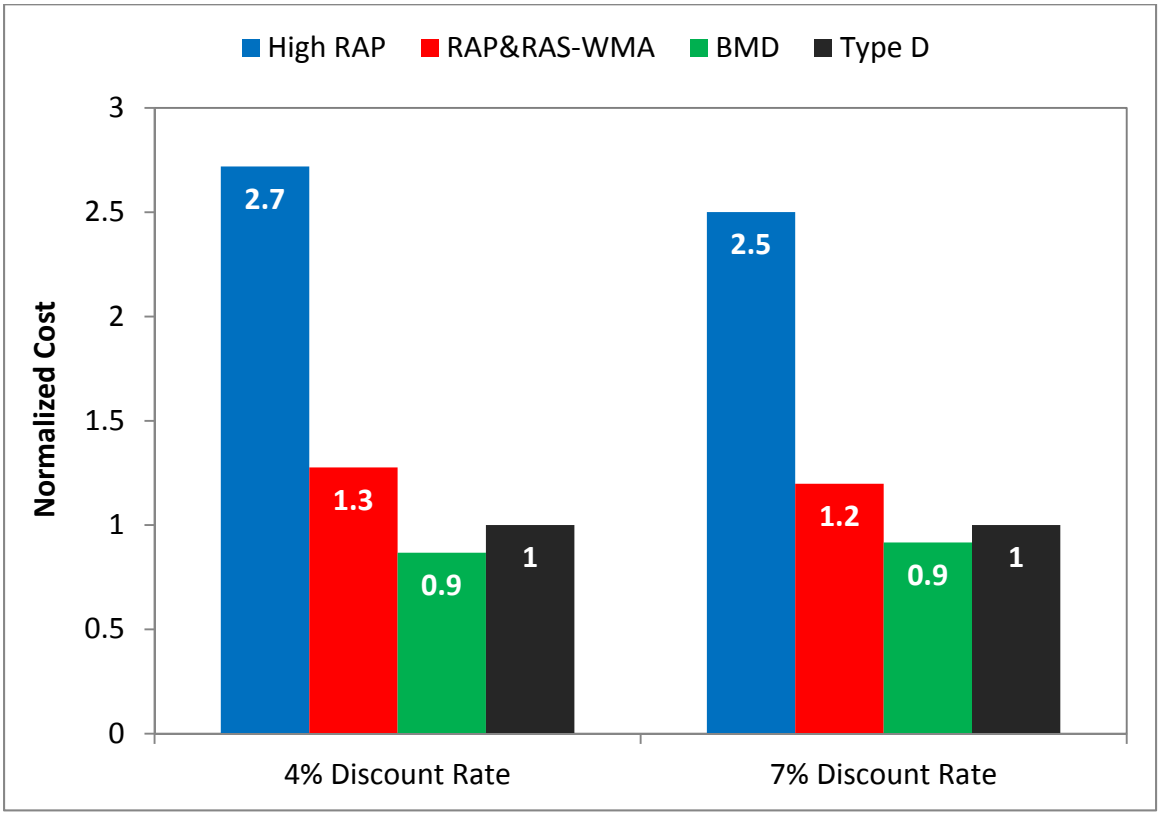


Figure 5-24. Normalized Life Cycle Cost of Mixtures

Table 5-10. Construction Cost of Virgin Mixture for Two Discount Rates

Discount Rate		**4%**	**7%**
	Year	PV ($)	PV ($)
Construction	0	88,394	88,394
Overlay 1	16	105,642	67,024
Overlay 2	20	111,446	63,104
Overlay 3	24	117,569	59,413
Overlay 4	28	124,029	55,938
Overlay 5	31	129,105	53,466
Overlay 6	34	134,390	51,104
Overlay 7	37	139,890	48,845
Overlay 8	40	145,616	46,687
Overlay 9	43	151,576	44,623
Overlay 10	46	157,781	42,651
Overlay 11	48	162,057	41,385
Salvage	50	(164,740)	(111,409)
NPV ($)		**1,510,480**	**648,880**
EUAC ($)		**70,313**	**47,018**
* PV : Present Value			

Although the cost of initial construction or the cost of each overlay placement for the "Type D" mixture was more than the other mixtures, its entire life cycle cost (LCC) is not the highest. In fact, regardless of the value of discount rate, the "Type D" is the second most economical mixture. In this ranking, the "BMD" is the best while the "RAP&RAS-WMA" is the third and the "High RAP" is the least economical. The LCC of the "High RAP" mixture is 2.7 and 2.5 times of the "Type D" mixture at discount rates of 4% and 7%, respectively. These values are 1.3 and 1.2 for the "RAP&RAS-WMA" mixture and the "BMD" mixture costs almost 10% less than the virgin mixture.

5.5 Summary of Findings from Life Cycle Analyses

A mixture that has higher environmental burden or cost at the initial construction stage, may have less environmental impact or cost less during its service life because of its superior performance and less need of rehabilitation. Therefore, it is essential to analyze the entire life cycle of the mixtures to assess their sustainability.

In this chapter, the traffic of the analysis period was estimated through the collection of local information for a street close to the UTA campus. Then, the frequency of required overlays was determined from the performance of each mixture at the field sections. *Roadprint* and *PaLate* programs were employed to calculate the environmental footprint of each mixture. It was found that the "Materials Production" phase usually has a higher environmental impact than "Materials Transportation" and "Equipment" phases. This is in agreement with Lin (2012). Within this phase, the production of bitumen had

the highest consumption of energy and the highest emission for most of the greenhouse gases. Although *PaLate* estimated a higher environmental burden of all of the mixtures more than *Roadprint* did, both tools ranked the mixtures in the same order. It was concluded that in the entire life cycle, the "BMD" is the most environmental friendly mixture and the "Type D", the "RAP&RAS-WMA" and the "High RAP" mixtures are in subsequent order.

The LCCA was also performed using the collected data from the contractor of the field sections. A growth rate was considered for the increase in the cost of overlays placement and the calculations were done with two discount rates, 4% and 7%. In both cases, the ranking of the mixtures was the same as for the environmental burden, i.e. the "BMD" was the most economical mixture while the "High RAP" was the least. The difference in the LCC of the mixtures decreased as the discount rate increased. Although the ranking of mixtures seems to remain unchanged, the LCC of mixtures get closer to each other if higher discount rates are used, due to the fact that the initial construction cost for the mixtures of "Type D" and "BMD" is more than for the other two mixtures.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

The scarcity of resources has made the asphalt practitioners to utilize more recycled materials with the intent to both lower the cost and save the environment. Many research projects have characterized the recycled materials and evaluated the performance of recycled mixtures in lab and field. The general understanding is that the use of recycled materials reduces the cost and environmental impacts of pavement projects; the majority of available studies in the literature support it. However, these studies usually include only the initial construction stage, or at most, also consider some hypothetical rehabilitation scenarios which may not reflect the reality. A mixture with lower construction cost or less environmental burden may not have a satisfactory performance, which requires more subsequent rehabilitation of the pavement. This way, it may lead to higher costs and environmental impacts when its entire life cycle is evaluated.

The purpose of this study was to assess the sustainability of three recycled asphalt mixtures in comparison with a mixture of all virgin materials. The virgin mixture was "Type D" which is a common dense-graded surface mixture in Texas. The recycled mixtures were labeled as "High RAP", "RAP&RAS-WMA" and "BMD". The "High RAP" mixture had 19 percent fractionated RAP. The "RAP&RAS-WMA" had 15 percent RAP and 3 percent RAS while the production technology was WMA. The "BMD" mixture had 15 percent RAP, 3 percent RAS and slightly higher binder content. The field performance of these mixtures was tested in the UTA APT Facility. The criteria were the

resistance to rutting, the resistance to fatigue cracking and the resistance to reflection cracking. The life of the sections after initial construction was estimated from the fatigue cracking sections while the life of subsequent overlays were predicted from the reflection cracking sections. *PaLate* and *Roadprint* programs were employed to calculate the environmental footprint of the mixtures during their life cycle. Also, classic engineering economy equations were used to estimate their life cycle cost.

6.1 Conclusions of Study

The conclusions of this study can be summarized as:

- The field performance of APT sections showed that rutting cannot be a concern in any of the mixtures. Each section was loaded with at least 600,000 passes of the standard axle and the permanent deformation never exceeded 0.2 inch.
- The performance of sections in fatigue cracking was adjusted based on the as-built thickness of the asphalt layer. It was found that the "RAP&RAS-WMA" mixture had the best performance while the "Type D", "High RAP" and "BMD" mixtures were in decreasing order of fatigue cracking performance.
- Post mortem inspection was also done for the reflection cracking sections. It was observed that the thicknesses of asphalt layer of sections are similar to each other. Therefore, no adjustment was needed. Based on the APT experiment results, the "BMD" mixture had the best performance in resistance to reflection cracking. The "Type D"

mixture had the second best performance and the "RAP&RAS-WMA" and the "High RAP" were the third and fourth, respectively.

❖ When the results of test sections were compared with TTI lab testing results, it was suggested that the OT machine of TTI is capable of predicting the mixtures performance for resistance to reflection cracking. It ranked the mixtures in a similar order as the APT experiment.

❖ After investigating the environmental impacts of mixtures, it was found that the "BMD" is the most environmental friendly mixture, followed by the "Type D", the "RAP&RAS-WMA" and the "High RAP" mixtures. The same ranking order was observed both in *Roadprint* and *PaLate* programs. While the "High RAP" mixture is noticeably worse than the others, the difference between the other three mixtures is not very significant. Specifically the difference of "Type D" and "BMD" is very small.

❖ Among the different phases of construction, the "Materials Production" phase was found to be most responsible for the energy consumption and for several other key factors. However, the "Equipment" phase had also a very high share in some of the factors. This means that the better field performance of mixtures results in fewer overlay placements which can significantly reduce the environmental impact as the equipment will be utilized less frequent. Moreover, depending on the factor of concern, further investment on a specific phase can decrease the environmental pressure more effectively.

❖ The deconstruction of "Materials Production" phase showed that the production of bitumen consumes energy and emits CO_2 noticeably more than the production of aggregates or the material recycling. However, the aggregates production emits higher

levels of CO than the bitumen production. For this factor, the material recycling is no longer negligible. This can be related to the utilization of recycling equipment.

❖ The cost analysis showed that the construction of one layer of a pavement section with the "High RAP" and the "RAP&RAS-WMA" mixtures are less expensive than that for the "Type D" and the "BMD" mixtures. However, the "BMD" and "Type D" mixtures cost less than two other mixtures when their entire life cycle is considered, regardless of the discount rate. This difference is much more significant when the comparison is made with the LCC of "High RAP" mixture.

In order to summarize the results, it can be mentioned that in spite of larger environmental footprint and higher construction costs at the initial stage, the superiority of the "BMD" and the "Type D" over other mixtures is evident. The less frequent required rehabilitation improved their environmental friendliness and cost effectiveness. The difference of these two mixtures is about 10% with the "BMD" be better than the "Type D". The "RAP&RAS-WMA" is almost 20% worse than the "Type D" while the environmental pressure and cost of the "High RAP" mixture is more than 2.5 times of those of the control mixture.

6.2 Recommendations for Future Studies

- The results of this study showed that when the entire life cycle is evaluated, the use of recycled materials of RAP and RAS may not be always the most economic or environmental friendly solution. This finding cannot be accepted unless extensive testing

of recycled asphalt mixtures is performed. This study included only four different mixtures. Further testing of recycled mixtures seems to be urgent and it is strongly recommended. The APT machine is capable of producing results in a rather short period of time. This will help the asphalt practitioners and decision makers to determine if the use of recycled materials is efficient in the entire life cycle of a pavement project or it just generates more RAP in long term.

- It is recommended to test recycled mixtures with higher OAC to compensate for the stiffness of mixtures. The higher binder content of the "BMD" mixture should be responsible for its superior performance over the "RAP&RAS-WMA" in spite of the fact that this latter is produced with the WMA technology which makes softer mixtures. Other than that, the percentages of RAP and RAS in both mixtures were the same.
- The environmental burden analysis tool should have been prepared for the region of the project that is being assessed. The development of a program with data inventory that includes more information of manufacturers and operation practices in Texas is also recommended.
- Further parallel field testing and lab testing with the OT machine of TTI is recommended. The results of this study showed that the OT is able to properly rank the asphalt mixtures for their resistance to reflection cracking, but not necessarily for their resistance to fatigue cracking.

APPENDIX A

Example of Life Cycle Assessment Calculations

This appendix provides the procedure of performing a life cycle analysis, from definition of scope and inventory analysis to impact assessment. The details of this example are brought from Lin (2012).

- *Definition of Goal and Scope*

The amount of required energy and resources for production of 1kg of HMA is of interest. Thus, "one kg of HMA" is the functional unit. The boundary of the system is defined as follows:

- Material inputs are aggregate and bitumen.
- Electricity is the only source of energy. Its production is not included.
- Carbon dioxide (CO_2) emission is the only output.

Based on this information, the LCA procedure is itemized as illustrated in Figure A-1.

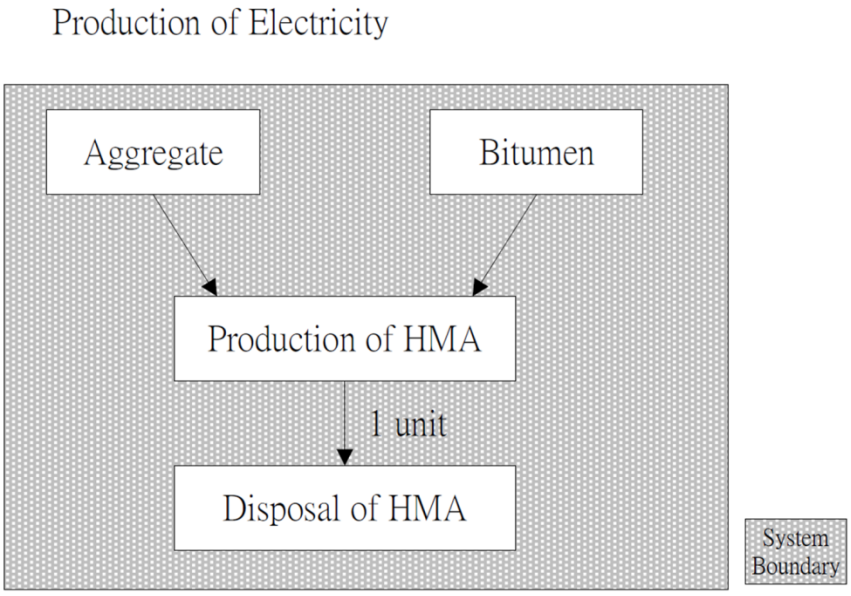


Figure A-1. LCA Process Flow of HMA (Lin 2012)

- *Inventory Analysis*

Figure A-2 provides the details of the collected data which are used for further performing of inventory analysis.

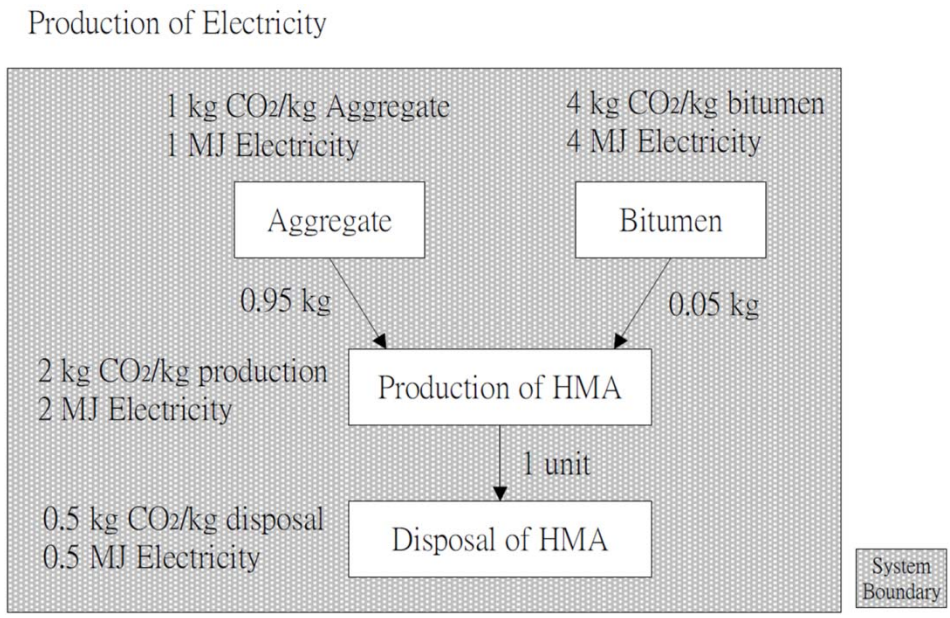


Figure A-2. Data Collection for Processes of LCA (Lin 2012)

$$\left(\frac{1\ kg\ CO_2}{kg\ agg.} \times 0.95\ kg\ agg.\right) + \left(\frac{4\ kg\ CO_2}{kg\ bitumen} \times 0.05\ kg\ bitumen\right)$$

$$+ \left(\frac{2\ kg\ CO_2}{kg\ HMA\ prod.} \times 1\ kg\ HMA\right) + \left(\frac{0.5\ kg\ CO_2}{kg\ HMA\ diposed} \times 1\ kg\ HMA\right)$$

$$= 3.65\ kg\ CO_2$$

$$\left(\frac{1\ MJ\ elec.}{kg\ agg.} \times 0.95\ kg\ agg.\right) + \left(\frac{4\ MJ\ elec.}{kg\ bitumen} \times 0.05\ kg\ bitumen\right)$$

$$+ \left(\frac{2\ MJ\ elec.}{kg\ HMA\ prod.} \times 1\ kg\ HMA\right) + \left(\frac{0.5\ MJ\ elec.}{kg\ HMA\ diposed} \times 1\ kg\ HMA\right)$$

$$= 3.65\ MJ\ elec.$$

These calculations for all the processes are done through forming a large matrix (C), subdivided into two matrices (A and B). Each column in matrix C represents one of the steps of LCA in Figure A-2. For example, the first column represents the aggregate production and its associated burden.

$$C = \begin{pmatrix} kg\ of\ agg. \\ kg\ of\ bitumen \\ kg\ of\ HMA \\ HMA\ disposal \\ MJ\ of\ elec. \\ kg\ of\ CO_2 \end{pmatrix} = \begin{bmatrix} 1 & 0 & -0.95 & 0 \\ 0 & 1 & -0.05 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 1 & 4 & 2 & 0.5 \\ 1 & 4 & 2 & 0.5 \end{bmatrix}$$

Matrix "A" represents economic inflows and outflows. Matrix "B" represents environmental effects and resource usage.

$$A = \begin{bmatrix} 1 & 0 & -0.95 & 0 \\ 0 & 1 & -0.05 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad B = \begin{bmatrix} 1 & 4 & 2 & 0.5 \\ 1 & 4 & 2 & 0.5 \end{bmatrix}$$

The desired vector is defined as "F". Production of 1kg HMA is the target of analysis in this example.

$$F = \begin{pmatrix} kg\ of\ aggregate \\ kg\ of\ bitumen \\ kg\ of\ HMA \\ HMA\ Disposal \end{pmatrix} = \begin{bmatrix} 0 \\ 0 \\ 1 \\ 0 \end{bmatrix}$$

In next step, the scaling vector "S" is found by inversion as follows.

$$S = A^{-1}f = \begin{bmatrix} 1 & 0 & -0.95 & 0 \\ 0 & 1 & -0.05 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 1 \\ 0 \end{bmatrix} = \begin{bmatrix} 0.95 \\ 0.05 \\ 1 \\ 1 \end{bmatrix}$$

Finally, by multiplying the environmental matrix "B" by the scaling vector "S", the total environmental burden and energy consumption (matrix "G") for production of desired output (vector "F") is determined.

$$G = B.S = B.A^{-1}.F = \begin{bmatrix} 1 & 4 & 2 & 0.5 \\ 1 & 4 & 2 & 0.5 \end{bmatrix} \begin{bmatrix} 0.95 \\ 0.05 \\ 1 \\ 1 \end{bmatrix} = \begin{pmatrix} 3.65\ kg & CO_2 \\ 3.65\ MJ & Elec. \end{pmatrix}$$

- *Impact Assessment*

Since the "one kg HMA" is the functional unit (i.e. what is of interest), the impact assessment will be the same as inventory analysis in this instance.

- *Interpretation*

This step overviews the outcomes of the assessment. The critical processes, i.e. the most energy intensive and/or high emitting processes, are identified to be the subject of further efficiency improvement studies. For example, if utilization of new technologies can lower energy consumption of bitumen production from 4 MJ/kg to 3 MJ/kg, how much saving can be made? Does that saving justify investing more for the new technology?

APPENDIX B

Outputs of Life Cycle Assessment Tools for Environmental Burden

B-1 Results of Environmental Assessment of Asphalt Mixtures by *PaLate*

The outputs of the *PaLate* program include the factors of Energy and Water Consumption, generation of CO_2, NO_x, PM_{10}, SO_2, CO, Hg, Pb, Resource Conservation and Recovery Act (RCRA) Hazardous Waste, and Human Toxicity Potential (Cancer and Non-cancer). Figures B-1 through B-7 show the results for the factors that are not included in chapter 5.

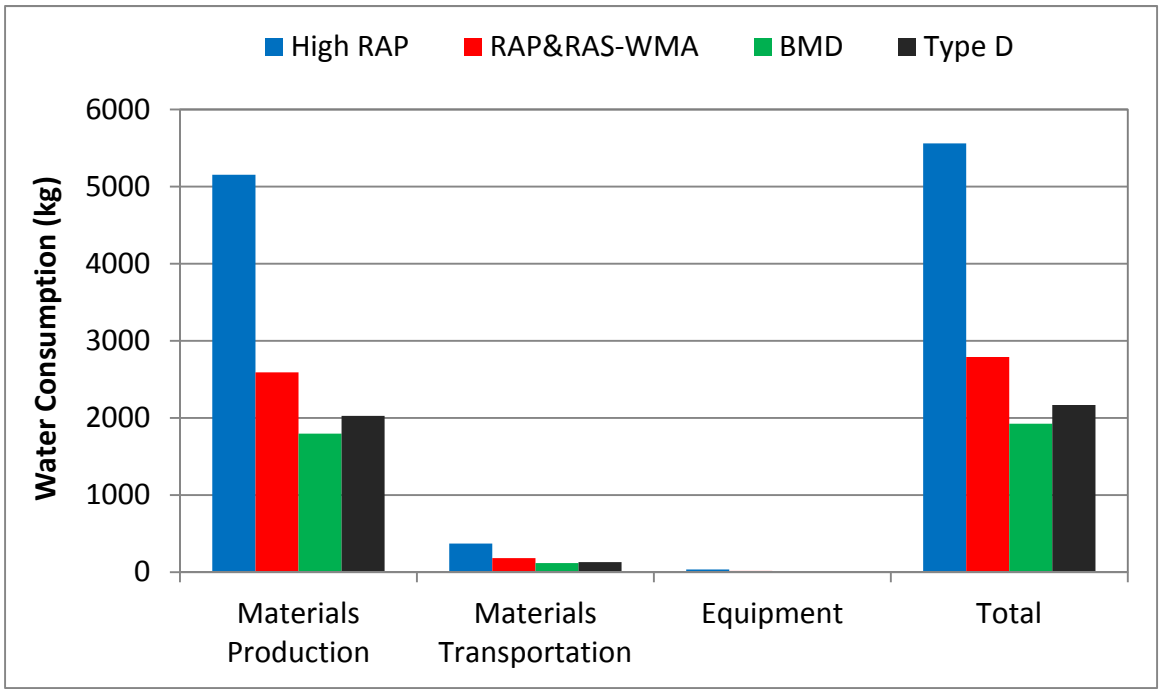


Figure B-1. Water Consumption of Asphalt Mixtures in *PaLate*

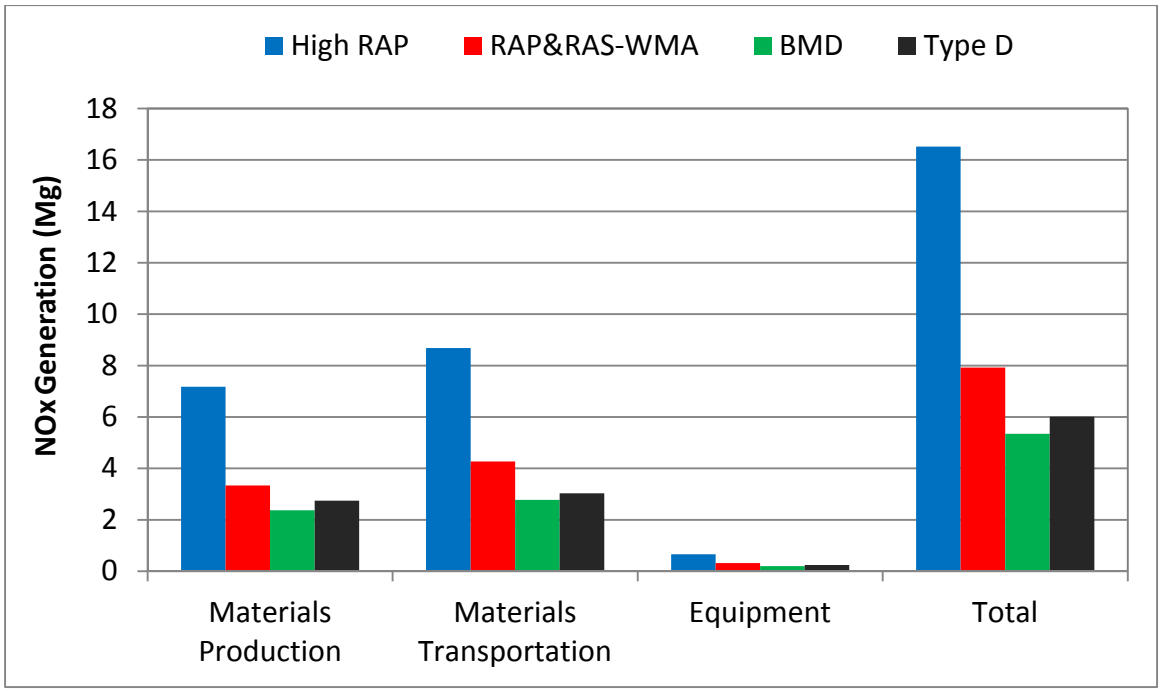


Figure B-2. Generation of NO_X of Asphalt Mixtures in *PaLate*

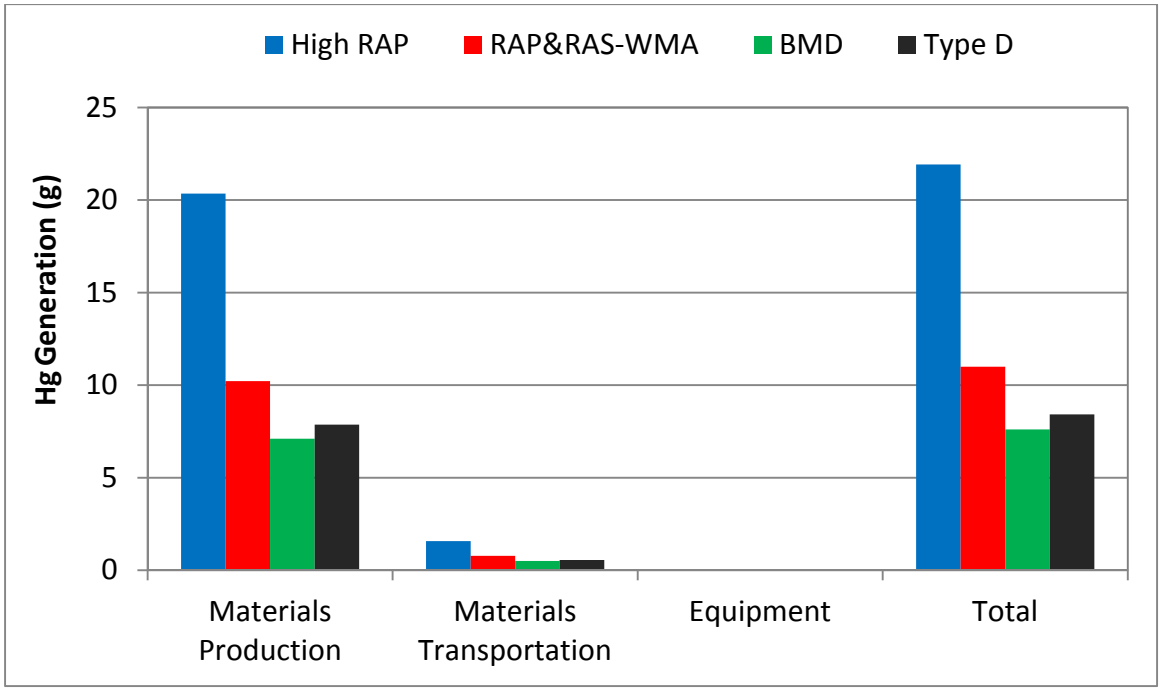


Figure B-3. Generation of Mercury of Asphalt Mixtures in *PaLate*

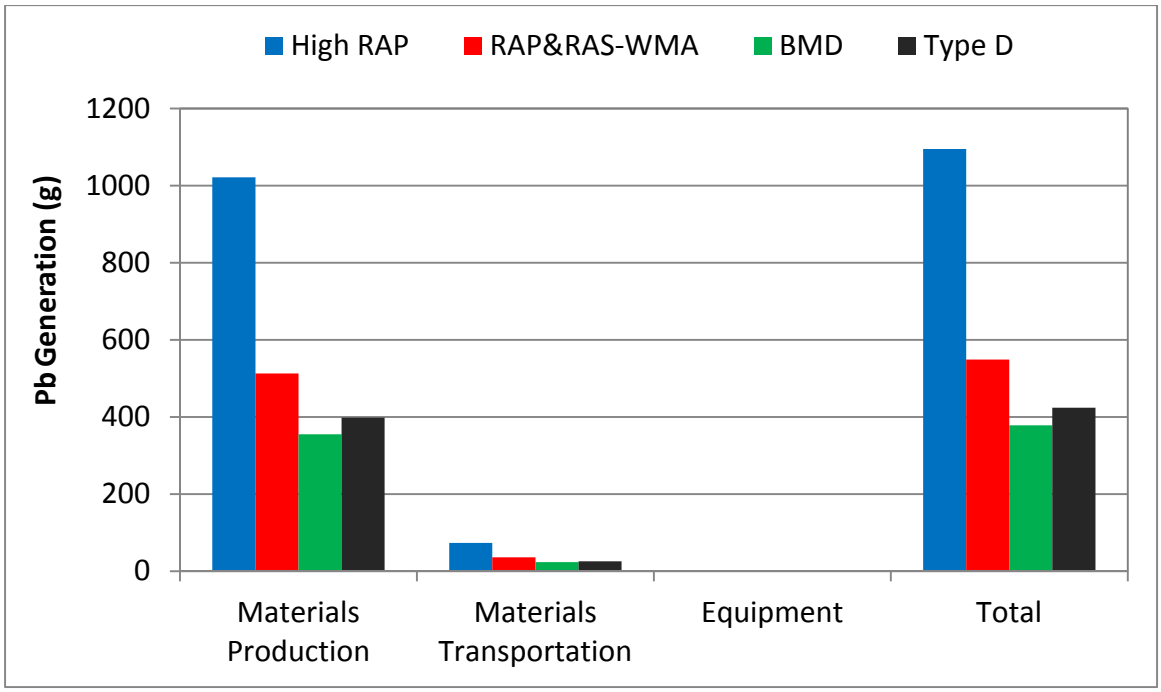


Figure B-4. Generation of Lead of Asphalt Mixtures in *PaLate*

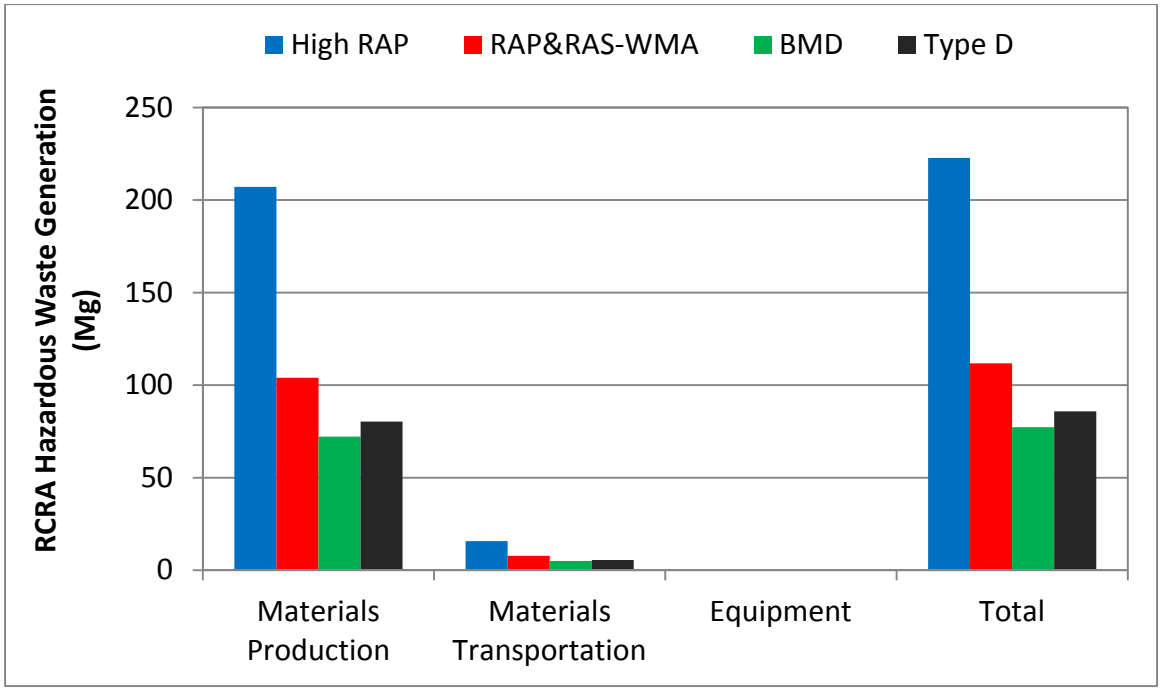


Figure B-5. Generation of RCRA Hazardous Waste of Asphalt Mixtures in *PaLate*

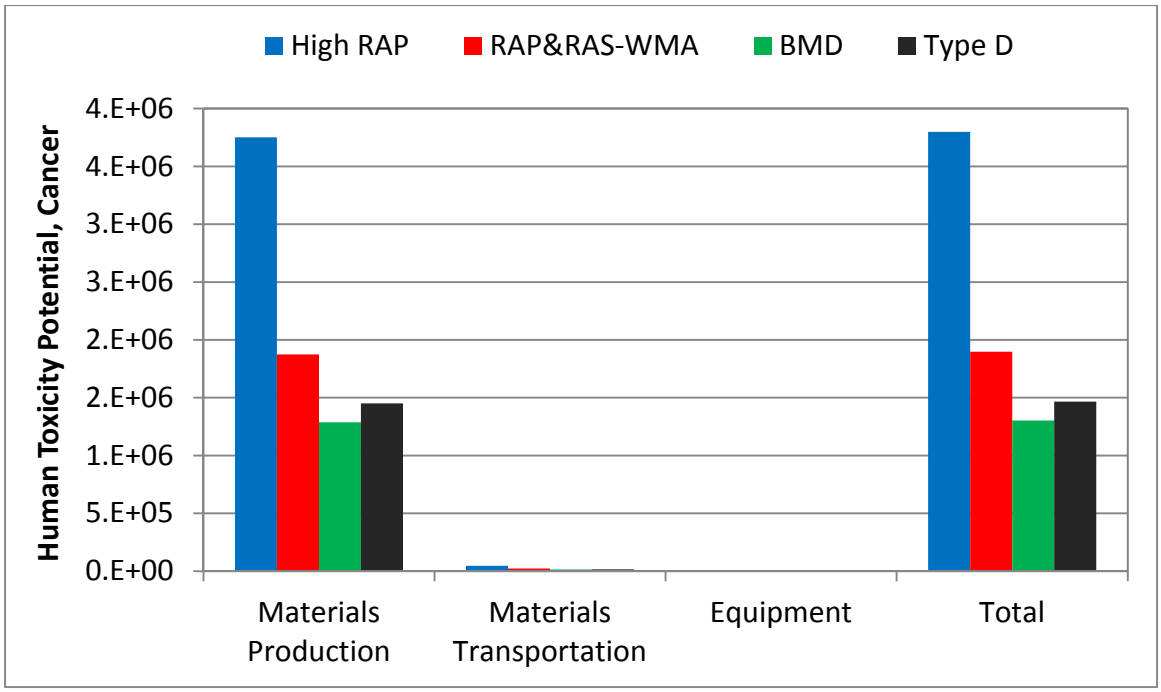


Figure B-6. Human Toxicity Potential (Cancer) of Asphalt Mixtures in *PaLate*

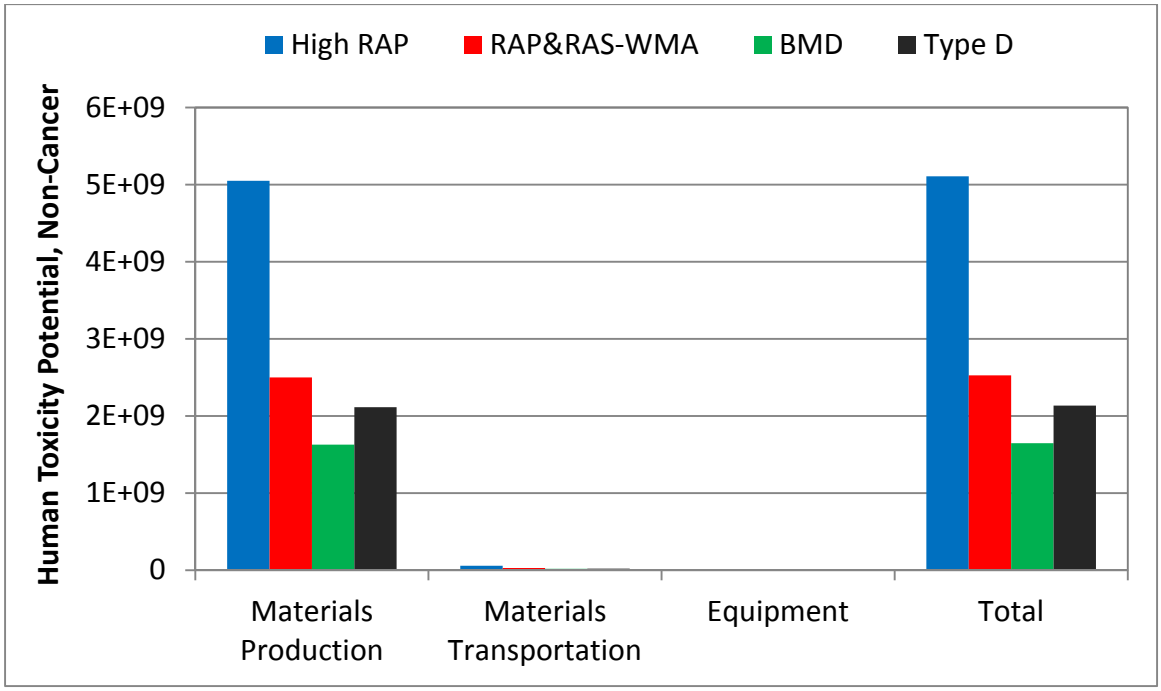


Figure B-7. Human Toxicity Potential (Non-Cancer) of Asphalt Mixtures in *PaLate*

B-2 Results of Environmental Assessment of Asphalt Mixtures by *Roadprint*

The *Roadprint* program provided the factors of Energy Consumption, CH_4, CO, CO_2, SO_2, PM_{10}, $PM_{2.5}$, Volatile Organic Compounds (VOC), Acidification, Photochemical Smog, Human Health Criteria, and Eutrophication. Out of these factors, the ones that are not presented in the main manuscript are shown in Figures B-8 through B-14.

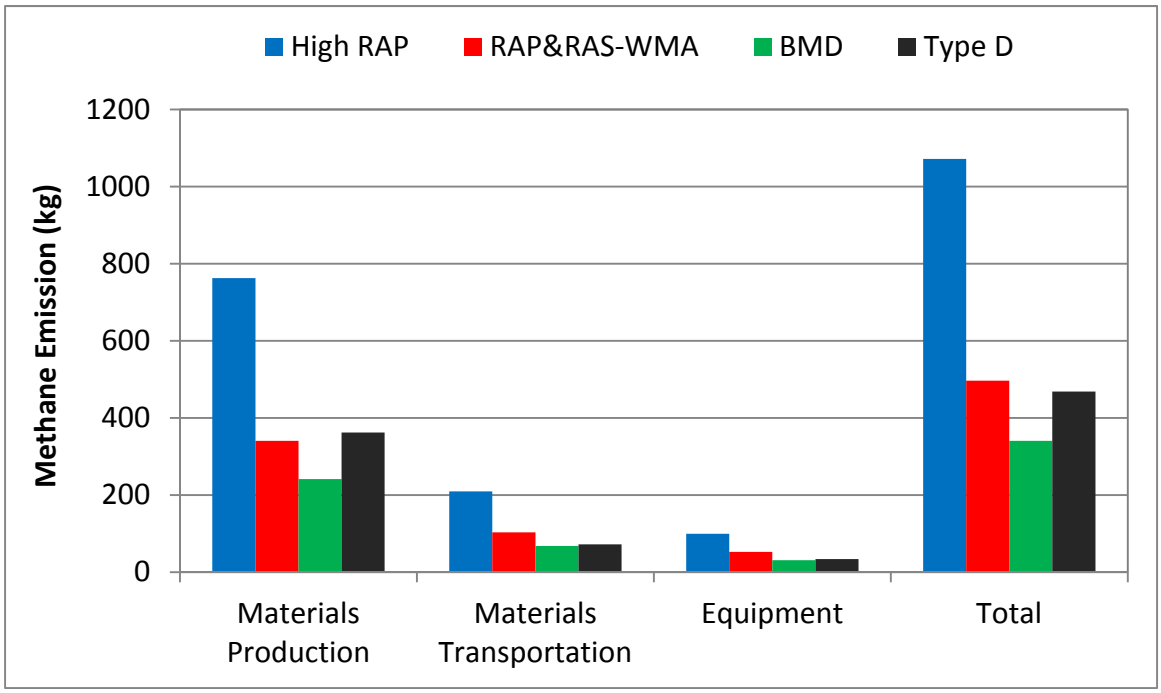


Figure B-8. Methane Emission of Asphalt Mixtures in *Roadprint*

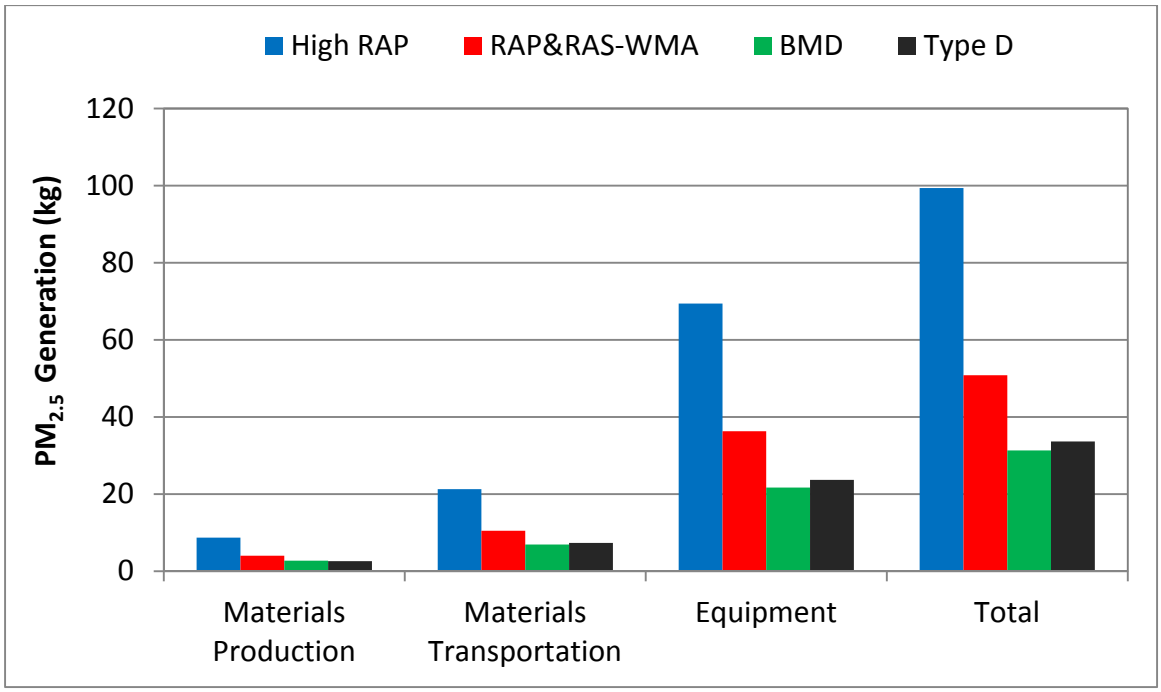


Figure B-9. Generation of $PM_{2.5}$ of Asphalt Mixtures in *Roadprint*

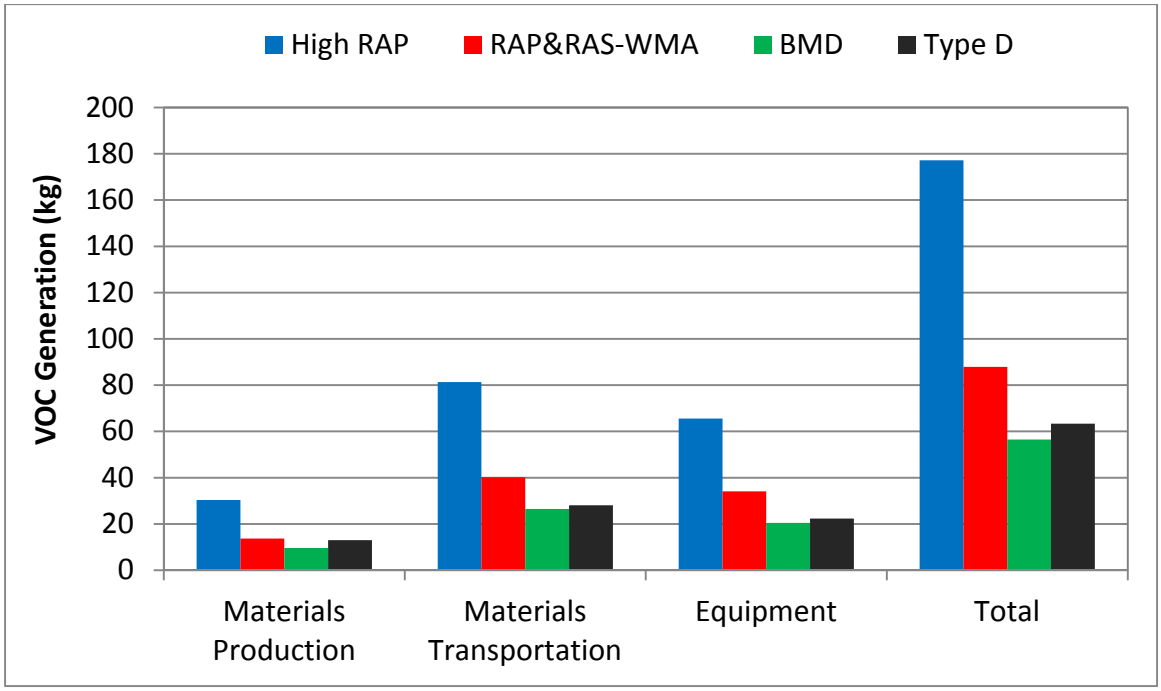


Figure B-10. Generation of VOC of Asphalt Mixtures in *Roadprint*

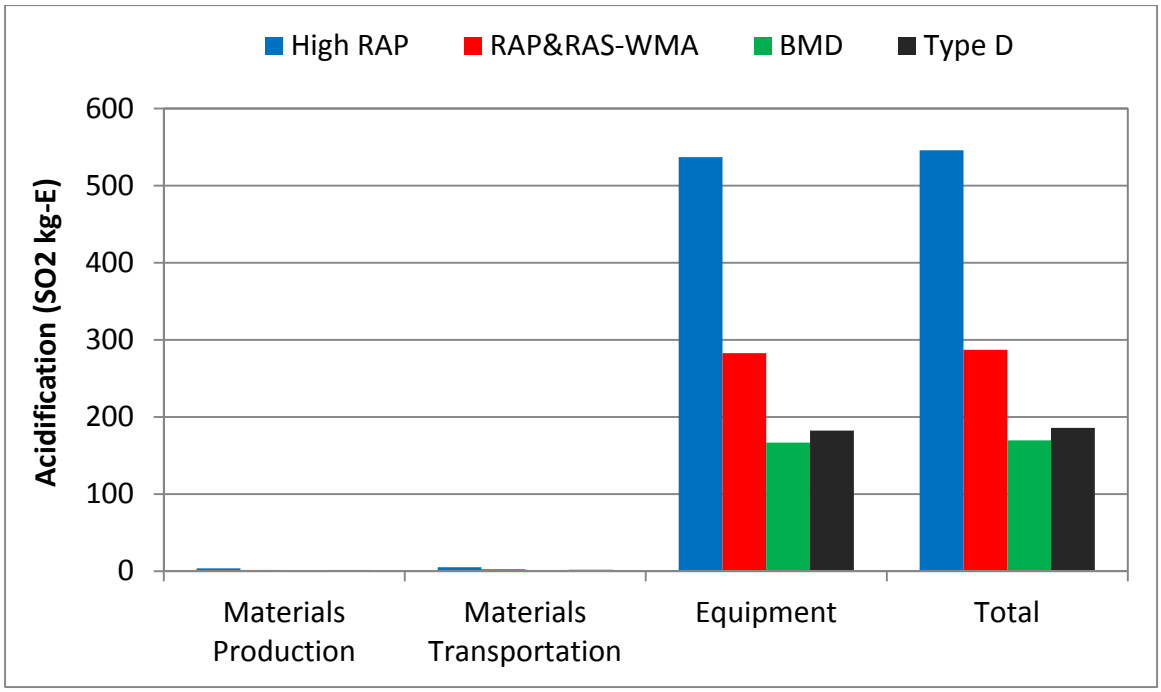


Figure B-11. Acidification of Asphalt Mixtures in *Roadprint*

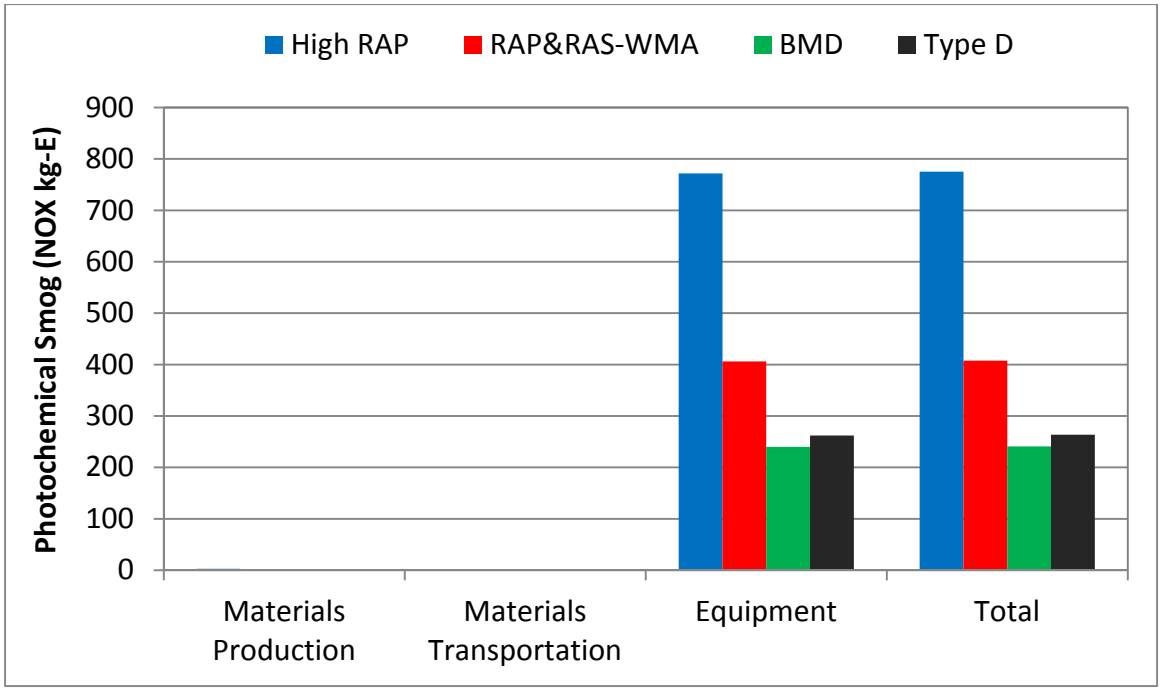


Figure B-12. Photochemical Smog of Asphalt Mixtures in *Roadprint*

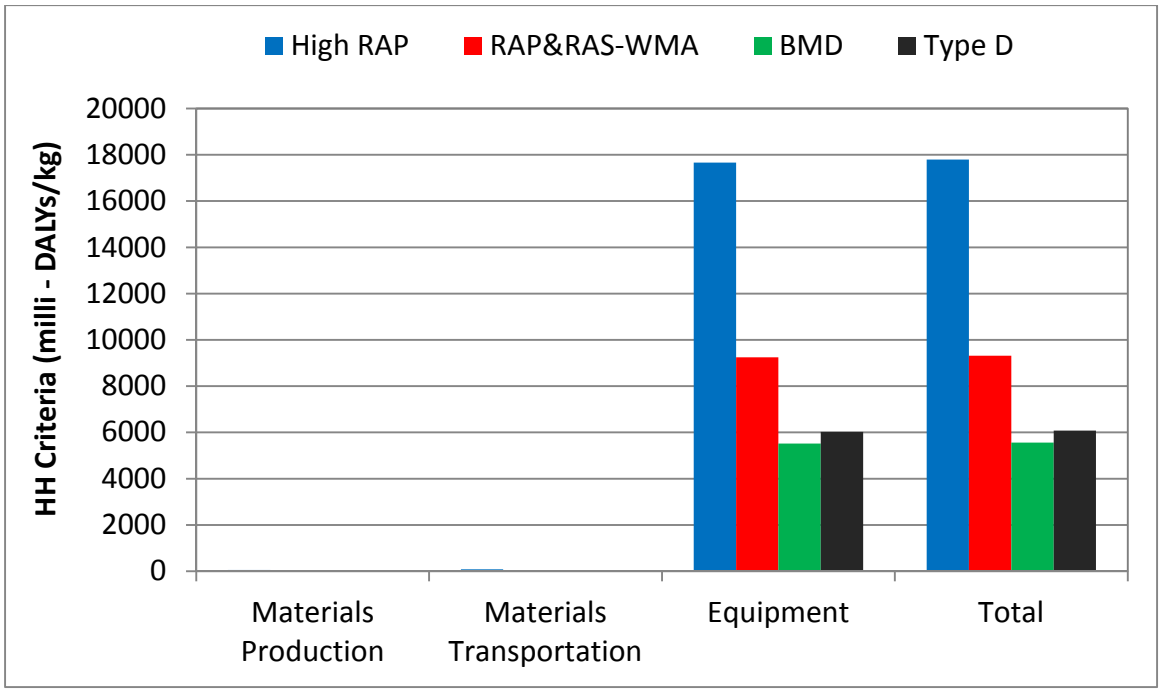


Figure B-13. Human Health Criteria of Asphalt Mixtures in *Roadprint*

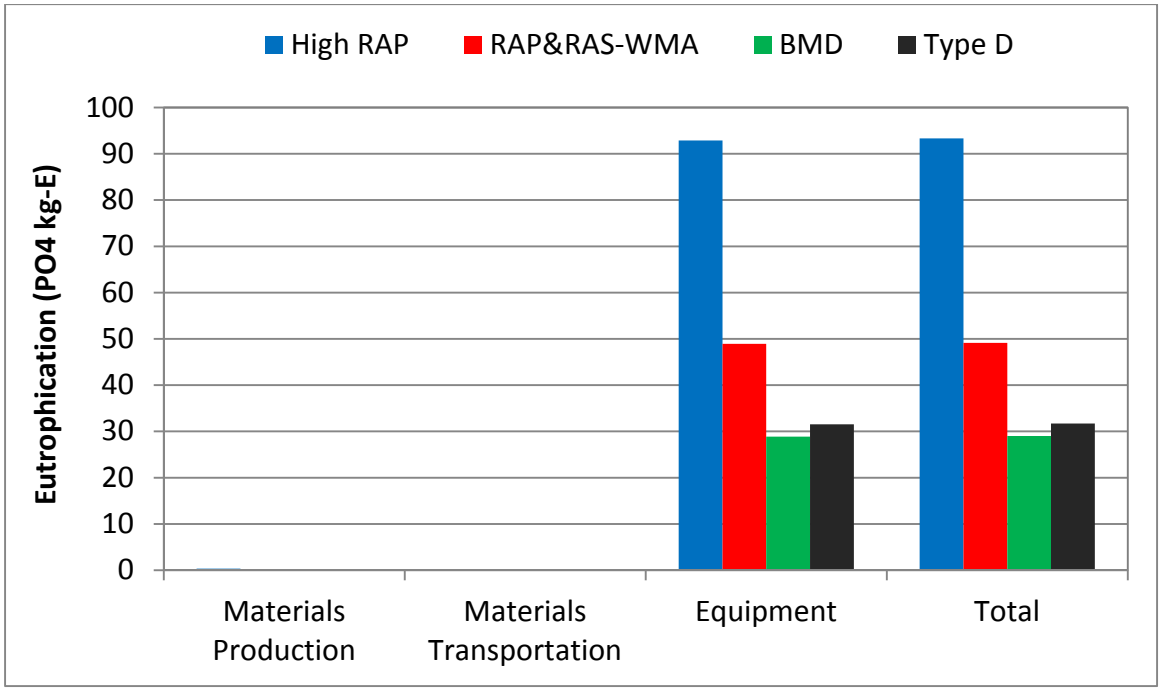


Figure B-14. Eutrophication of Asphalt Mixtures in *Roadprint*

REFERENCES

Al-Qadi I.L., M. A. Elseifi, and S. H. Carpenter (2007). "Reclaimed asphalt pavement: a literature review", Springfield: Illinois Center for Transportation, Report Number FHWA-ICT-07-001.

AASHTO (1993). "AASHTO Guide for Design of Pavement Structures", American Association of State Highway and Transportation Officials. Washington, D.C

AASHTO (2010). "AASHTO M323: Standard Specification for Superpave Volumetric Mix Design", American Association of State Highway and Transportation Officials, Standard Specifications for Transportation Materials and Methods of Sampling and Testing, 30th Ed., AASHTO, Washington, D.C.

Apeagyei A. K., B. K. Diefenderfer, and S. D. Diefenderfer (2011). "Rutting Resistance of Asphalt Concrete Mixtures Containing Recycled Asphalt Pavement", Transportation Research Record 2208, Transportation Research Board, Washington, D.C.

Apul D.S. (2007). "Development of a Beneficial Reuse Tool for Managing Industrial Byproducts: BenReMod-LCA and BenReMod-MCDA Web Based Tools", Final report submitted to USEPA's Office of Solid Waste and Emergency Response (OSWER).

Asphalt Institute (1995). "Superpave performance graded asphalt binder specification and testing", Lexington, KY: Asphalt Institute.

Astec Inc. (2015). "Warm Mix Systems for Continuous Mix and Batch Plants", Astec Inc. Website, Retrieved on June 2015 from http://www.astecinc.com/products/liquid-additives/warm-mix-systems.html

Athena Institute (2013). "Impact Estimator for Highways: User Guide", Athena Sustainable Materials Institute, Retrieved January 2015 from http://www.athenasmi.org/wp-content/uploads/2012/01/ImpactEstimatorForHighways_UserGuide.pdf

Aurangzeb Q., I. L. Al-Qadi, I. M. Abuawad, W. J. Pine, and J. S. Trepanier (2012) "Achieving Desired Volumetrics and Performance for Mixtures with High

Percentage of Reclaimed Asphalt Pavement", Transportation Research Record, Journal of the Transportation Research Board, No. 2294, pp. 34–42.

Aurangzeb Q. and I. L. Al-Qadi. (2014). "Asphalt Pavements with High Reclaimed Asphalt Pavement Content, Economic and Environmental Perspectives", Transportation Research Record: Journal of the Transportation Research Board, No. 2456, pp. 161–169.

Birgisdóttir H. (2005). "Life cycle assessment model for road construction and use of residues from waste incineration", Ph.D. Dissertation in the Institute of Environment and Resources, Technical University of Denmark.

Bonaquist R. (2007). "Can I Run More RAP?", Hot Mix Asphalt Technology, pp. 11–13, National Asphalt Pavement Association, Landham, MD.

Brandt H. C. A. and P. C. De Groot (2001). "Aqueous Leaching of Polycyclic Aromatic Hydrocarbons from Bitumen and Asphalt", Journal of Water Research. Vol. 35, No. 17, pp. 4200-4207.

Button J.W., C.K.Estakhri, and A.J. Wimsatt (2007). "A Synthesis of Warm Mix Asphalt", Texas Transportation Institute, Texas A&M University, College Station.

Carpenter S. H., and J. R. Wolosick (1980). "Modifier Influence in the Characterization of Hot-Mix Recycled Material", Transportation Research Record 777, Washington, D.C., 1980, pp. 15-22.

Chen D., and J. Daleiden (2005). "Roadway Pavement Preservation", Circular No. E-C078, Transportation Research Board, Washington, DC.

Chiu C., T. Hsu, and W. Yang (2008). "Life Cycle Assessment on Using Recycled Materials for Rehabilitating Asphalt Pavements", Journal of Resources, Conservation and Recycling Vol. 52, pp. 545–556.

Clean Energy Projects Inc. (2015). "Landfill Tipping Fees in USA", Retrieved on December 2015 from http://www.cleanenergyprojects.com/Landfill-Tipping-Fees-in-USA-2013.html

Cochran K. (2006). “Construction and Demolition Debris Recycling: Methods, Markets, and Policy”, Ph.D. Dissertation, University of Florida, Gainesville.

Copland A., R. Dongre, and J. D' Angelo (2010a). “Evaluation of RAP Binder Blending II”, presented at RAP ETG, Oklahoma City, OK, October 27.

Copeland A., J. D' Angelo, R. Dongre, S. Belagutti, G. Sholar (2010b). “Field Evaluation of High Reclaimed Asphalt Pavement–Warm-Mix Asphalt Project in Florida: Case Study”, Transportation Research Record: Journal of the Transportation Research Board, 2179, pp 93-101

Copeland A. (2011). “Reclaimed Asphalt Pavement in Asphalt Mixtures: State of the Practice”, Final Report, No. FHWA-HRT-11-021, Office of Infrastructure Research and Development Federal Highway Administration.

Curran M.A., and S. Young (1996). "Report from the EPA Conference on Streamlining LCA", International Journal of Life Cycle Assessment, Vol. 1, No. 1, pp. 57-60.

D' Angleo J., R. Dongre, and A. Copeland (2011). “Evaluation of the Extent of Asphalt Blending in RAP Mixes”, Proceedings of the Fifty-Sixth Annual Conference of the Canadian Technical Asphalt Association (CTAA) - Quebec City, Quebec, pp.289-308.

DeDene C., S. W. Goh, M. R. M. Hasan, and Z. You (2015). “Laboratory Performance Based Cost Assessment of Warm-Mix Asphalt Concrete Technologies”, International Journal of Pavement Research and Technology Vol. 8, No. 1, pp.38-46

EIA (2015). Energy Information Administration Website, Retrieved March 1st, 2015, from http://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=pet&s=f000000__3&f=a

EPA (1993). “Life Cycle Assessment: Inventory Guidelines and Principles”, Environmental Protection Agency, EPA/600/R-92/245. Office of Research and Development. Cincinnati, Ohio, USA.

EPA (2006). "Life Cycle Assessment: Principles and Practice", Environmental Protection Agency, EPA/600/R-06/060, Office of Research and Development. Cincinnati, Ohio, USA.

EPA (2013). "Analysis of Recycling of Asphalt Shingles in Pavement Mixes from a Life Cycle Perspective", Environmental Protection Agency Final Report, Office of Research and Development. Cincinnati, Ohio, USA.

EPA (2015). "Asphalt Roofing", Environmental Protection Agency Website, Accessed June 2015 at http://www.epa.gov/ttnchie1/ap42/ch11/final/c11s02.pdf

Estakhri C., J. Button, and A. E. Alvarez (2010). "Field and Laboratory Investigation of Warm Mix Asphalt in Texas", Texas Transportation Institute, Report 0-5597-2

Forfylow, R.W. and B. Middleton (2008). "Experiences with Warm Mix Asphalt – A Contractor's Perspective", Proceedings of 53rd Annual Conference, Canadian Technical Asphalt Association, Vol. LIII, Saskatoon, Saskatchewan, Canada, pp. 410-432

FHWA (2015a). "Transportation Air Quality Facts and Figures", Federal Highway Administration Website, Accessed June 2015 at http://www.fhwa.dot.gov/environment/air_quality/publications/fact_book/page04.cfm).

FWHA (2015b). "Warm Mix Asphalt Technologies and Research", Federal Highway Administration Website, Accessed June 2015 at (http://www.fhwa.dot.gov/pavement/asphalt/wma.cfm)

Grefe R.P. (2007). "Wisconsin Regulatory Experience with Asphalt Shingle Recycling," Representing Bureau of Waste & Materials Management, Wisconsin Department of Natural Resources, Chicago, Illinois.

Hajj E. Y., P. E. Sebaaly, and R. Shrestha (2007) "A laboratory Evaluation on the Use of Recycled Asphalt Pavements in HMA Mixtures", Regional Transportation Commission, Reno, Nevada.

Hampton T. (2015). "U.S. Studies 'Warm Mix' Asphalt Methods," Engineering News Record, McGraw-Hill Construction, Accessed June 2015 at (http://www.enr.construction.com/products/newproducts/archives/030428.asp).

Hansen K. (2009). "Guidelines for the Use of Reclaimed Asphalt Shingles in Asphalt Pavements," Information Series 136, National Asphalt Pavement Association, Lanham, Maryland.

Hansen K. R. and A. Copeland (2014). "Annual Asphalt Pavement Industry Survey on Recycled Materials and Warm-Mix Asphalt Usage: 2009–2013 Appendix B", National Asphalt Pavement Association, NAPA, 4th Annual Asphalt Pavement Industry Survey, October 2014

Hansen K.R. and D. E. Newcomb (2011). "Asphalt pavement mix production survey on reclaimed asphalt pavement, reclaimed asphalt shingles, and warm-mix asphalt usage", National Asphalt Pavement Association, NAPA, Nov. Grant No.: DTFH-61-1–P-00084 Lanham, MD.

Hassan M. M. (2009). "Life-Cycle Assessment of Warm-Mix Asphalt: An Environmental and Economic Perspective", Transportation Research Record: 88th Annual Meeting of Transportation Research Board, p. 17.

Heijungs R., and S. Suh (2002). "The Computational Structure of Life cycle Assessment," Kluwer Academic Publishers (ISBN 1-4020-0672-1), Dordrecht, p. 241

Hellriegel E.J. (1980). "Bituminous concrete pavement recycling", Interim Report Number FHWA/NJ-81/002 Arlington, VA: New Jersey Department of Transportation.

Hong F., D.H. Chen, and M. Mikhail (2010). "Long-Term Performance Evaluation of Recycled Asphalt Pavement Results from Texas: Pavement Studies Category 5 Sections from the Long-Term Pavement Performance Program", Transportation Research Record 2180, Transportation Research Board, Washington, D.C.

Horvath A. (2004). “A life-cycle analysis model and decision-support tool for selecting recycled versus virgin materials for highway applications,” Final Report for RMRC Research Project No. 23, University of New Hampshire

Huang B., Z. Zhang, and W. Kinger (2004). “Fatigue Crack Characteristics of HMA Mixtures Containing RAP,” Proceedings, 5th International RILEM Conference on Cracking in Pavements, Limoges, France.

Huang Y. H. (2004). “Pavement Analysis and Design”, Second Edition, Prentice Hall, ISBN 0-13-142473- 4

Huang Y., R. Bird, and O. Heidrich (2009). “Development of a life cycle assessment tool for construction and maintenance of asphalt pavements,” Journal of Cleaner Production, Vol. 17, pp. 283-296.

Im S. and F. Zhou (2014). “Field Performance of RAS Test Sections and Laboratory Investigation of Impact of Rejuvenators on Engineering Properties of RAP/RAS Mixes”, FHWA/TX-14/0-6614-3, Texas Transportation Institute, College Station, Texas.

ISO (2006). “Environmental Management — Life Cycle Assessment - Requirements and Guidelines”, International Organization for Standardization, ISO 14044:2006, p. 46

Jensen A.A., and A. Remmen (2004). “Background Report for a UNEP Guide to Life Cycle Management - A Bridge to Sustainable Products”, Final draft 30 December 2004. UNEP/SETAC Life Cycle Initiative.

Kandhal P. S., S. S. Rao, D. E. Watson, and B. Young (1995). “Performance of Recycled Hot-Mix Asphalt Mixtures in the State of Georgia”, National Center for Asphalt Technology, NCAT Report 95-01.

Kang S., R. Yang, H. Ozer, and I. L. Al-Qadi (2014). “Life-Cycle Greenhouse Gases and Energy Consumption for Material and Construction Phases of Pavement with Traffic Delay”, Transportation Research Record, Journal of the Transportation Research Board, No. 2428, pp. 27–34.

Kiehl J.T., and K. E. Trenberth (1997). "Earth's annual global mean energy budget", Bulletin of the American Meteorological Society Vol. 78, No. 2, pp. 197–208.

Kriech A.J., J. T. Kurek, L. V. Osborn, H. L. Wissel, and B. J. Sweeney (2002). "Determination of Polycyclic Aromatic Compounds in Asphalt and Corresponding Leachate Water," Polycyclic Aromatic Compounds, Vol. 22, No. 3-4, pp. 517-536.

Kristjansdottir O., L. Michael, S.T. Muench, and G. Burke (2007). "Assessing the Potential for Warm Mix Asphalt Technology Adoption", Proceedings (CD), 86th Annual Meeting of the Transportation Research Board, National Academy of Sciences, Washington, D.C., 2007.

Lin Y. Y. (2012). "Eco-decision Making for Pavement Construction Projects", Ph.D. Dissertation, University of Washington, Seattle.

Lippert D. L., H. Ozer, I. L. Al-Qadi, A. K. El-Khatib, R. Yang, A. Z. Dahhan, J. W. Vespa, J. S. Trepanier (2014). "Illinois Highway Materials Sustainability Efforts of 2013", Illinois Center for Transportation, Report No. FHWA-ICT-14-015.

Mallick R., K. Kandhal, and R. Bradbury (2008). "Using Warm Mix Asphalt Technology to Incorporate High Percentage of Reclaimed Asphalt Pavement (RAP) Material in Asphalt Mixtures", Transportation Research Record, Journal of the Transportation Research Board, No. 2051, Transportation Research Board of the National Academies, Washington, D.C., pp. 71-79.

Matthews H. S., C. T. Hendrickson, and D. H. Matthews. (2015). "Life Cycle Assessment: Quantitative Approaches for Decisions That Matter", Retrieved July 2015 from https://cmu.app.box.com/s/5mnzyq1y3gcyjrveubf4/1/2746878222

Maupin G.W. (2008). "Use of Manufactured Waste Shingles in a Hot-Mix Asphalt field Project in Virginia", Report Number VTRC 08-R11, Virginia Transportation Research Council and the Virginia Department of Transportation, March 2008.

Maupin G. W., S. D. Diefenderfer, and J. S. Gillespie (2008). "Evaluation of Using Higher Percentages of Recycled Asphalt Pavement in Asphalt Mixes in Virginia",

Publication VTRC 08-R22. Virginia Transportation Research Council, Charlottesville.

McDaniel R. S., and A. Shah (2003). "Use of Reclaimed Asphalt Pavement (RAP) Under SuperPave Specifications," Journal of the Association of Asphalt Paving Technologists, Vol. 72, pp. 226-252.

McDaniel R.S, H. Soleymani, R. M. Anderson, P. Turner, R. Peterson (2000). "Recommended use of reclaimed asphalt pavement in the Superpave mix design method", West Lafayette, IN: North Central Superpave Center, NCHRP Project D9-12, Contractor Final Report.

McGraw J., E. Johnson, G. Johnson, S. Dai, D. Linell, and M. Watson (2010). "Incorporation of Recycled Asphalt Shingles in Hot-Mixed Asphalt Pavement Mixtures", Report No. MN/RC 2010-08, Minnesota Department of Transportation, February 2010.

McMillan C., and D. Palsat (1985). "Alberta's Experience in Asphalt Recycling", Proceedings of the Canadian Technical Asphalt Association, Vol. 30, pp. 148-167.

MeadWestvaco (2015a). "Getting Started with Evotherm", MeadWestvaco Innovations Brochure, Retrieved on June 2015 from (http://www.mwv.com/en-us/asphalt-innovations/products/easset_upload_file906_15242_e.pdf)

MeadWestvaco (2015b). "Evotherm 3G Warm Mix Asphalt", MeadWestvaco Innovations Brochure, Retrieved on June 2015 from (http://www.mwv.com/en-us/asphalt-innovations/products/easset_upload_file99_15242_e.pdf)

MnDOT (2015). "Pavement Design: Life Cycle Cost Analysis", Minnesota Department of Transportation, Retrieved January 2015 from http://www.dot.state.mn.us/materials/pvmtdesign/lcca.html

Mirzadeh I., A. A. Butt, S. Toller, and B. Birgisson (2013). "Life Cycle Cost Analysis Based on the Fundamental Cost Contributors for Asphalt Pavements", Journal of Structure and Infrastructure, Vol. 10, No. 12, pp. 1638-1647.

Mukherjee A. (2012). "The Project Emissions Estimator (PE-2): A Tool to Aid Contractors and Agencies Benchmark Carbon Emissions for Highway Construction Projects", ICSDEC 2012: pp. 144-154.

Musselman J. (2009). "High RAP Performance in Florida", HMA Recycling Expert Task Group, Department of Transportation, Washington, DC. Retrieved on March 2014 from http://www.morerap.us/files/meetings/12-09/musselman-high-rap-performance-florida.pdf

Nathman R., S. McNeil, and T. J. VanDam (2009). "Integrating Environmental Perspectives into Pavement Management: Adding PaLATE to the Decision-Making Toolbox", Presented at the Transportation Research Board 88th Annual Meeting. Washington, D.C.

NAHB. (1998). "From Roofs to Roads – Recycling Asphalt Roofing Shingles into Paving Materials", National Association of Home Builders, Retrieved February 2015 from http://www.epa.gov/epawaste/conserve/imr/cdm/pubs/roof_br.pdf

NCAT (2009). "LTPP Data Shows RAP Mixes Perform as Well as Virgin Mixes," National Center for Asphalt Technology, Asphalt Technology News, Vol. 21, No. 2.

NCTCOG (2015). "Historical Traffic Counts", North Central Texas Council of Governments Retrieved August 2015, from http://www.nctcog.org/trans/data/trafficcounts/indexcdp.asp

Paul H.R. (1996). "Evaluation of Recycled Projects for Performance", Association of Asphalt Paving Technologists, No. 65, Lino Lakes, MN.

Rand D.E. (2011). "High Priced Asphalt in Texas – Going the Way of the Cave Man?" Hot Mix Asphalt Technology, National Asphalt Pavement Association, Lanham, Maryland, Vol. 16, No. 2, pp. 24-26.

Rangaraju P.R., S. Amirkhanian, and Z. Guven (2008). "Life Cycle Cost Analysis for Pavement Type Selection", South Carolina Department of Transportation. FHWA-SC-08-01.

Read J. and D. Whiteoak (2003). "The shell bitumen handbook", 5th ed. London: Thomas Telford.

Reyes M., R.W. Forfylow, and B. Middleton (2009) "Initial Performance of Foam WMA Mixes in Western Canada," Proceedings, 54th Annual Conference, Canadian Technical Asphalt Association, Vol. LIV, Moncton, New Brunswick, Canada, pp. 397-419.

Roberts F.L., P. S. Kandhal, E. R. Brown, D. Y. Lee, and T. W. Kennedy (2009). "Hot mix asphalt materials, mixture design and construction", 3rd ed. Lanham, MD: National Asphalt Pavement Association Research and Education Foundation.

Robinette C. and J. Epps (2010). "Energy, Emissions, Material Conservation, and Prices Associated with Construction, Rehabilitation, and Material Alternatives for Flexible Pavement," Journal of the Transportation Research Board, No. 2179, Transportation Research Board of the National Academies, Washington, D.C., pp. 10–22.

Romanoschi, S. and T. Scullion (2014). "Validation of the Maximum Allowable Amounts of Recycled Binder, RAP, & RAS Using Accelerated Pavement Testing-Interim Report", Report No. FHWA/TX-14/0-6682-1.

Santero N., E. Masanet, and A. Horvath. (2010). "Life Cycle Assessment of Pavements: A Critical Review of Existing Literature and Research", Lawrence Berkley National Laboratory, Retrieved June 2015 from https://escholarship.org/uc/item/8632v9cc

Scholz T. (2010). "Preliminary Investigation of RAP and RAS in HMAC", Report Number OR-RD-10-12, Kiewitt Center for Infrastructure and Transportation.

Stephens J., J. Mahoney, and C. Dippold (2001). "Determination of the PG Binder Grade to use in RAP mix", Final Report JHR 00-278, Connecticut Department of Transportation, Rocky Hill.

Suh S. (2004). "Functions, commodities and environmental impacts in an ecological–economic model", Ecological Economics, Vol. 48, pp. 451–467.

Tatari O., M. Nazzal, and M. Kucukvar (2012). "Comparative Sustainability Assessment of Warm-Mix Asphalts: A Thermodynamic Based Hybrid Life Cycle Analysis". Resources, Conservation and Recycling Volume 58, pp. 18–24.

Terrel R. L., and J. A. Epps (1989). "Using Additives and Modifiers in Hot-Mix Asphalt — Section A", National Asphalt Pavement Association, Quality Improvement Series (QIP 114 A).

Townsend T., J. Powell, and C. Xu (2007). "Environmental Issues Associated with Asphalt Shingle Recycling", Construction Materials Recycling Association.

Tran N., A. Taylor, and R. Willis (2012). "Effect of Rejuvenator on Performance Properties of Hma Mixtures with High Rap and Ras Contents", National Center for Asphalt Technology, NCAT Report 12-05.

TXDOT (2013). "2013 Special Specifications Update", Texas Department of Transportation Website, Retrieved on May 2015 from https://ftp.dot.state.tx.us/pub/txdot-info/cst/flexible_pavements.pdf

TXDOT (2015). "Warm Mix Asphalt (WMA)", Texas Department of Transportation Website, Retrieved on February 2015 from ftp://ftp.dot.state.tx.us/pub/txdot-info/cmd/mpl/wma.pdf

VDOT (1996). "Recycling hot mix asphalt pavements", Virginia Department of Transportation, Information Series Report No.: IS 123.

Wess J. A., L.D. Olsen, and M.H. Sweeney (2004). "Asphalt (Bitumen)" Concise International Chemical Assessment Document 59, World Health Organization, Geneva, Switzerland.

West R., J. Michael, R. Turochy, and S. Maghsoodloo (2011). "Use of Data from Specific Pavement Studies Experiment 5 in the Long-Term Pavement Performance Program to Compare Virgin and Recycled Asphalt Pavements", Journal of Transportation Record.

Williams R. C., A. Cascione, J. Yu, D. Haugen, M. Marasteanu, and J. McGraw (2013). "Performance of Recycled Asphalt Shingles in Hot Mix Asphalt", Iowa State University, FHWA Report No. TPF-5(213).

Willis R. (2014). "Life Cycle Assessment of 2012 NCAT Pavement Test Track Green Group Mixtures", National Center for Asphalt Technology, NCAT Report 14-02.

World Bank (2015). "World Bank Commodities Price Forecast", Released October 2015, retrieved on December 2015 from http://pubdocs.worldbank.org/pubdocs/publicdoc/2015/10/966751445286237369/CMO-Oct-2015-Historical-Forecasts.pdf

Yang R. (2014). "Development of a Pavement Life Cycle Assessment Tool Utilizing Regional Data and Introducing an Asphalt Binder Model", Master of Science Thesis, University of Illinois at Urbana Champion.

Zaumanis M., and R. B. Mallick (2015). "Review of very high-content reclaimed asphalt use in plant-produced pavements: state of the art", International Journal of Pavement Engineering, Vol. 16, No.1, pp. 39-55.

Zettler R. (2006). "Warm Mix Stands Up to Its Trials," Better Roads, James Informational Media, Inc., Des Plaines, Illinois.

Zhou F., S. Hu, and T. Scullion (2006). "Integrated Asphalt (Overlay) Mixture Design, Balancing Rutting and Cracking Requirements", FHWA/TX-06/0-5123-1, Texas Transportation Institute, College Station, p. 115.

Zhou F., G. Das, T. Scullion, S. Hu (2010). "RAP Stockpile Management and Processing in Texas: State of the Practice and Proposed Guidelines", FHWA Report 0-6092-1, Texas Transportation Institute.

Zhou F., S. Hu , G. Das, and T. Scullion (2011). "High RAP Mixes Design Methodology with Balanced Performance", FHWA/TX-11/0-6092-2, Texas Transportation Institute.

Zhou F., H. Li, S. Hu, J. W. Button, and J. A. Epps (2013). "Characterization and Best Use of Recycled Asphalt Shingles in Hot-Mix Asphalt", FHWA/TX-13/0-6614-2, Texas Transportation Institute.

Zofka A., M. Marasteanu, T. Clyne, X. Li, and O. Hoffmann (2004). "Development of Simple Asphalt Test for Determination of RAP Blending Charts", Report MN/RC-2004-44, Minnesota Department of Transportation, Minneapolis.

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Reza Saeedzadeh was born in Iran. He received his Bachelor of Science degree in 2006 from Nooshirvani College of Engineering of Mazandaran University, Iran. In the same year, he got admitted to the graduate school of Shiraz University in Geotechnical Engineering program. The focus of his research in this program was on geotechnical earthquake engineering and he published multiple conference and peer reviewed journal papers. He also gained some practical experience while was serving as a Geotechnical Engineer for Darya Khak Pay Consulting Engineers. He finished his studies at Shiraz University as the first rank of his batch and received his Master of Science degree in 2010. In January 2012, he decided to continue his education at the University of Texas at Arlington. His fields of study at this school were related to Geotechnical and Pavement Engineering. He served as a graduate research assistant in two pavement projects funded by the Texas Department of Transportation and the New York Department of Transportation. He also had the chance of instructing the Civil Engineering Materials Laboratory to undergraduate students. His dissertation was focused on the sustainability assessment of recycled asphalt mixtures under the supervision of Dr. Romanoschi. In February 2016, the American Society of Civil Engineers selected him among top 80 students in country who received a travel grant to 2016 GI/SEI conference in Phoenix, AZ. Reza Saeedzadeh completed his studies with a PhD degree in Civil Engineering in Spring 2016.