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SUSTAINABLE MATERIAL SOLUTION FOR FLEXIBLE PAVEMENTS: PERFORMANCE EVALUATION AND IMPACT ASSESSMENT OF UTILIZING MULTIPLE RECYCLED MATERIALS IN HMA

by

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ABSTRACT

The demand for pollution-free and recyclable engineering materials has been increased as the cost of energy and environmental concerns have risen. Green material design can lead to better environmental quality and sustainability of civil infrastructure. Road construction is one of the largest consumers of natural resources. Beneficial utilization of recycled materials can result in an important opportunity to save the mining and use of virgin materials, to preserve energy, and to save landfill space.

Two main research questions addressed in this study are: (1) How much pollution, energy, natural resources, time and money can be salvaged by applying recycling materials to Hot-Mix Asphalt (HMA)?, (2) What are the optimum mix designs for those recycled materials in HMA?, and (3) Can multiple recycled materials be used at the same time to compensate each other's drawbacks? This study evaluates the structural performance and environmental-economical cost and benefit by substituting one or a combination of three recycled materials in HMA. The three recycled materials are Recycled Asphalt Shingle (RAS), Municipal Solid Waste Incineration (MSWI) Bottom Ash, and Recycled Concrete Aggregate (RCA). Performance evaluation of the HMA including those recycled materials has been performed by a series of laboratory experimental tests while the environmental impact was investigated by the Life Cycle Assessment (LCA). In addition, Life Cycle Cost Analysis (LCCA) method has been employed to evaluate the benefit of the aforementioned recycled materials.

In 2008, the Florida Legislature established a new statewide recycling goal of 75% to be achieved by the year 2020. The impact of this research aligns with this policy as it introduces a sustainable HMA that reduces the necessity of virgin aggregate and asphalt binder to 50% and 20%, respectively. In terms of environmental and economic impacts, in comparison with the regular HMA, it generates 25% less greenhouse gas emission, and for a period of 20 years, the cost of construction and maintenance would be 65% less.

This work is dedicated to my parents and brother
Without their support, this work would have not been possible.

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Special thanks to Jinwoo An and Tolga Ercan for their friendship and support; I truly enjoyed the time we spent together.

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CHAPTER 1: INTRODUCTION[1]

1.1 Research Motivation

As the world's population increases, the volume of waste production is escalating at an alarming rate. This upsurge of discarded material is quickly taking over our future landfill area; thus, triggering landfilling prices to rise. To overcome this problem, extensive effort is being put into recycling waste materials to reuse them in different aspects instead of just landfilling [1].

The U.S. annually produces over a half billion tons of residuals that can be reusable materials, such as construction and demolition (C&D) debris, combustion products, waste tires, slags, and so on. Many of these waste materials still have worthy physical and chemical properties when recycled as construction material; however, most of them are often disposed of as waste.

Utilizing the recycled waste materials in the construction industry, specifically road and pavement construction, can be an alternative to virgin materials, in addition to saving the landfills. The main components of asphalt mixture are asphalt binder and aggregate, which have the potential to be replaced by recycled materials. Recently, as an alternative to binder substitution, using recycled asphalt shingles (RAS) in pavement systems has been accepted by different transportation agencies. Asphalt roofing shingles constitute one of the highest percentages in municipal solid waste (MSW) stream in the US. About 11 million tons of shingle waste is produced

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[1] A part of this dissertation will appear as peer-reviewed journal papers, co-authored by the author of dissertation.

each year and 90% of it is tear-off shingle [*2*].

In contrast, generally consuming natural resources (including construction industry) is not without side effects. The environment is harmed as natural resources are consumed, while changes in ecosystems ensue. For instance, one of the major human resource consumptions are fossil fuels. In recent years, consumption of fossil fuels have increased, which resulted in an increase in emissions. CO2 is considered a major contributor to climate change, which affects almost all ecosystems (IPCC, 2007; CDIAC, 2009).

The construction industry, essentially road construction has a huge impact on earth's ecosystems. 70% of the projects spending was related to road construction (US Census Bureau, 2010) with 297,090 people employed in the industry (US BLS, 2011). In 2009, there was $12.08 billion allocated to pavement improvement projects under the American Recovery and Reinvestment Act (GAO, 2009). With almost 350 million tons of raw materials used per year, pavement construction is a major consumer of raw materials [*3*]. The transportation of raw materials also contributes to the negative impacts of pavement construction on the environment. In conclusion, the construction of pavement involves many factors that impact the environment, including a large number of people, economic activities, and natural resources.

Currently, in the U.S., limited studies have been performed on economic and environmental impacts of flexible pavement composed of recycled materials. Essentially, there is no study to indicate the impact of multiple recycled materials at the same time in asphalt concrete.

1.2 Research Objectives and Overview

The primary goal of this research is to discover a "sustainable material" solution for Hot Mix Asphalt (HMA). Sustainable materials are defined as highly recyclable materials that can be reprocessed without requiring additional mineral resources. The U.S. Environmental Protection Agency (EPA) is committed to increase the recycling of solid waste materials as part of its Resource Conservation Challenge. One inimitable alternative is to reuse those waste materials as road construction materials.

To advocate the sustainable material solutions for the HMA overlay, I propose to investigate the reuse of tear-off asphalt roofing shingle (referred as recycled asphalt shingle, RAS, in this study), municipal solid waste incineration (MSWI) bottom ash (BA), and recycled concrete aggregate (RCA) in HMA. The shingle contains about 30 to 40% asphalt content; thus, its use in HMA can save liquid asphalt. With equal importance, the RCA and MSWI BA can be alternative materials to replace virgin aggregates in HMA.

The objectives of this research are 1) to investigate the effects of RAS, MSWI BA, and RCA when used in HMA (evaluations from a mechanical perspective), 2) to determine optimum proportioning when those recycled materials are separately used or combinations are used, and 3) to quantify environmental and economic impacts of the use of those recycled materials. The expected outcomes of this study will help 1) to develop the optimum mix design for multiple recycled materials that satisfies engineering criteria and required performance and also 2) to save natural resources and preserve surrounding ecosystems.

The largest portion of pavement in terms of mass and volume are aggregates. The unit price of the aggregates is comparatively low with relatively low environmental impact on production. Correspondingly, because aggregate is exercised in large quantities, is non-renewable, and is incapable to mine near its point of use, it can play a big role in pavement sustainability. In addition, these limitations have occasioned the lack of natural aggregate in some areas. Therefore, aggregate needs to be transported from un-urbanized areas; however, the environmental impact of this transportation depends on the distance traveled, which adversely can be higher than the production impact. To reduce the environmental impact and increase aggregate sustainability, the portion of virgin aggregate needs to be decreased by substituting it with locally recycled materials.

In line with the above criteria, it is essential to evaluate the effects of RAS, MSWI BA, and RCA as substitute materials in HMA and to determine the optimum mix proportion in HMA when these recycling materials are used. A series of laboratory tests were conducted on the asphalt mixture specimens containing varied amounts of each (or combined) recycled material. Particularly, the mixtures' performances associated with rutting and cracking have been evaluated.

To reduce the implications on the environment by pavement construction, researchers have been seeking ways to measure the environmental impacts of pavement construction. Roadprint tool has been employed to accomplish the life cycle assessment (LCA) analysis. In this section, the greenhouse gas emissions as well as the energy and resources consumed are evaluated over the pavement service life. Aggregate and bitumen are the material inputs; electricity is an energy input, but its production is not accounted in this study. CO2 is the only emission evaluated in this study. Finally, the production of aggregate, binder, HMA and the disposal of HMA are appraised. To comply with environmental laws and regulations such as national environmental policy act (NEPA), both cost efficiency and environmental impacts are considered during the analysis.

1.3 Organization of Dissertation

Chapter 2 investigated the effect of tear-off roofing shingles (or called as RAS) as filler material in HMA and also optimum proportion when RAS is used in HMA. Aged binder was extracted from RAS and mechanical behavior of the extracted binder was evaluated. RAS was used as filler materials in HMA with different content ranging from 0 to 6% with 1% increment. RAS-combined HMA was then mechanically characterized by using Marshall Stability and flow test, moisture susceptibility, and rutting tests. Two RAS sources, one from Florida and the other from Minnesota, were used and the mechanical behaviors of the RAS-combined HMA were compared.

In Chapter 3, the effect of MSWI BA and RAS in HMA were investigated. The MSWI BA was used to replace fine aggregate in HMA, and a number of performance tests on the mixtures were conducted. The change of optimum binder content by increasing the BA was also investigated. The optimum BA replacement rate was determined based on physical and mechanical performance. Due to the porous surface of BA particles, they tend to absorb more binder which makes the substitution un-economical. To overcome this issue, RAS has been added to the mixtures at a fixed BA replacement (20% in this study). Knowing that RAS contains 25-35% asphalt binder, different ratios of RAS have been added to identify the optimum proportioning. Indirect tensile strength

(IDT) test and rutting test have been employed to evaluate the influence of RAS (on different proportions). The cost-benefit analysis, including life cycle assessment (LCA) and life cycle cost analysis (LCCA), was conducted for four mixture scenarios.

In chapter 4, in addition to MSWI BA and RAS, recycled concrete aggregate (RCA) was used as an alternative for coarse aggregate substitution. Determination of the optimum proportion of RCA was first investigated by comparing IDT strength and volumetric properties. Based on the finding of the optimum fine aggregate replacement by BA from Chapter 3, a different percentage of RAS was added as an additive in HMA. “Sustainable” mixing design of HMA involves 100% RCA as coarse aggregates replacement, 20% BA as fine aggregates replacement, and more than 1% of asphalt binder in a mixture. LCA and LCCA methods have been employed to evaluate the impact of the use of recycled materials from the environmental and economic perspective.

Chapter 5 presents the summary and conclusions drawn from this study. The limitations of the existing work as well as recommendations for the future research are presented and discussed.

CHAPTER 2: INVESTIGATION ON THE EFFECTS OF RECYCLED ASPHALT SHINGLE AS AN ADDITIVE IN HOT-MIX ASPHALT[1]

2.1 Abstract

With an increase in the price of asphalt binder, the asphalt paving industry has searched for its recycling resources. Recently, using tear-off asphalt roofing shingles in pavement systems have gained large amount of attention by transportation agencies. Beneficial use of tear-off shingle as road construction materials is an attractive option. In this laboratory study, in line with the Florida recycling regulation target, tear-off roofing shingles were used as additives in Hot-Mix Asphalt (HMA) ranged from 0% to 6% with 1% increment. Aged asphalt binder was extracted from the tear-off shingle and its physical properties were tested. Subsequently, mechanical characterization of the asphalt mixtures with respect to strength, moisture susceptibility, and rutting resistance at different RAS (Recycled Asphalt Shingle) ratios were evaluated. Lastly, the optimum mix design for the use of shingle in HMA has been established.

2.2 Introduction

Asphalt roofing shingles constitute one of the highest percentages in municipal solid waste (MSW) stream in the US [*4*]. In the US, about 11 million tons of shingle waste is produced each

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[1] The content of this chapter also appeared in:
Golestani, B., Maherinia, H., Nam, B., and Behzadan, A. Investigation on the Effects of Recycled Asphalt Shingle as an Additive to Hot-Mix Asphalt. Airfield and Highway Pavements 2015: pp. 9-18.
Using the paper as a chapter of this study is **with permission from ASCE (please see the appendix A).**

year and 90% of it is post-consumer scrap (or called as tear-off shingle) [*4, 5*]. Due to the existence of bitumen in roofing shingles (approximately 30 to 40%), the utilization of the shingle in HMA is a promising option. Although several previous researchers have found positive effects of roofing shingles in HMA, many state highway agencies (SHAs) have not formally approved the use of the shingles in HMA.

Several studies have been performed to investigate beneficial use of asphalt roofing shingles [*5-12*]. Sengoz et al. [*5*] tested performance behavior of HMA that contains post-manufactured shingles (leftover after new house construction). Different percentages of the shingle were added to HMA samples at optimum binder content and Marshall Stability and rutting resistance of the specimens were measured. It was concluded that adding more than 1% of shingle would result in a reduction of Marshall Stability, and the asphalt mixture with 1% shingle, exhibited respectable rutting resistance. Hansan et al. [*6*] also studied the effect of post-manufactured shingle and showed that the shingle addition not only improved rutting performance but also delivered cost effective savings for asphalt paving construction. A report prepared by Polk County Waste Resource Management Division for Florida Department of Environmental Protection (FDEP) indicated that 7% of construction demolition and debris (C&D) is tear-off roofing shingles.

Replacing liquid (virgin) asphalt in HMA with shingle, is significantly cost effective [*8*]. Nam et al. [*7*] reviewed the current practice of state DOTs in the US and reported that most of DOTs adopt 5% of shingle addition as additive in their specifications. Newcomb et al. [*9*] used virgin asphalt binder, with penetration grades of 85/100 and 120/150, and both felt-backed (or mat) and fiberglass shingles as additives. Percentages of shingles used in this study were 0%, 5% and 7.5% by the weight of aggregate. It was found that adding 5% and 7% of asphalt shingle to HMA mixture can reduce the optimum binder content by 10% and 25%, respectively. Another finding was that using fiberglass shingles in HMA samples could increase both moisture sensitivity and tensile strength. A study by the Virginia Department of Transportation (VDOT) indicated that volumetric properties of HMA containing tear-off shingle met the VDOT specifications [*10*] and the rut depth of HMA mixes containing shingles was were comparable with that of conventional HMA mixes. The result of fatigue test on the shingle-combined HMA exhibited satisfactory performance compared with control samples. Janisch et al. [*11*] studied in-situ performance of HMA that contains post-manufactured shingles and concluded that the pavement performs over 6 years but the air void was greater than the specification, which is 4% in Minnesota.

The objective of this study is to evaluate the effect of shredded tear-off shingles in a wide range of mechanical performance measures of HMA. Also, the optimum composition of tear-off roofing shingles and virgin binder was investigated based on a modified Marshall Stability and flow and moisture susceptibility tests that accommodate Superpave gyratory pills (6-in. diameter HMA samples). The Marshall Stability test was selected because it is simple and quick, and also we could obtain both strength and deformation resistance parameters indicated by Stability and Flow, respectively. All HMA samples used in this study were designed in accordance with the Superpave Mixture Design method that is currently adopted by most SHAs in the US.

2.3 Materials

2.3.1 *Binder*

The most commonly used asphalt binder in the state of Florida is PG 67-22 which is relatively high in viscosity. However, a number of studies have shown that adding shingle to HMA hardens the mixture; thus, lower PG binder: PG 52-28, in this study, was selected to accommodate this stiffening consequence.

2.3.2 *Aggregate*

Aggregate used in this study was from three different limestone stockpiles produced by a local supplier in Orlando, Florida. The first, second, and third stockpiles involve the maximum sizes of 19 mm, 2.36 mm, and 0.6 mm, respectively. A sample from each stockpile was tested according to the ASTM C 136 Sieve Analysis. The sieve analysis result of job mix formula is presented in Figure 2-1. In the job-mix formula, the first, second, and third stockpiles were 50%, 30%, and 20% respectively and met the aggregate criteria of Superpave design.

2.3.3 *Tear-Off Shingle*

Tear-off roofing shingle was obtained and shredded to small pieces. The FDOT Specifications require the particle size of shredded shingles to be added to the HMA less than 12.5 mm. A finer shingle can be more easily blended with other ingredients in the mixture. Minnesota tear-off shingle was also used to compare the performance of Florida shingle. The particle distributions of two shingles are presented in Figure 2-2. By a visual inspection, the Florida shingle includes some more impurities such as wood and plastics; thus, it was sieved out by Sieve #8 (with the opening size of 2.36 mm) to separate the impurities. For the Florida shingle, the materials smaller than 2.36 mm were used for the HMA specimens.

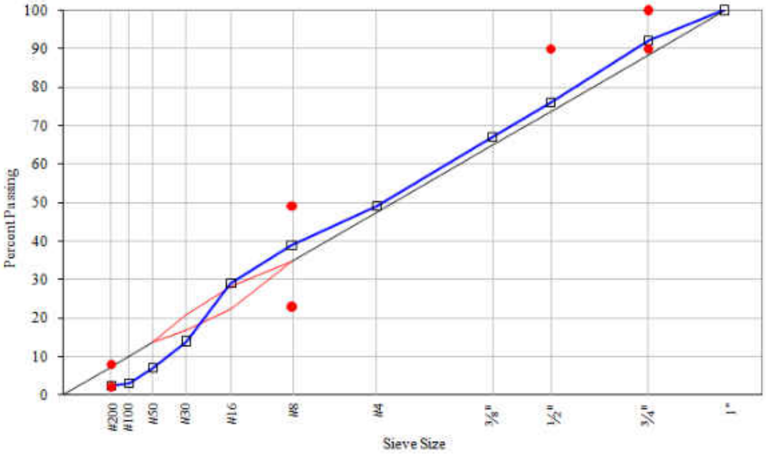

Figure 2-1. Aggregates gradation curve

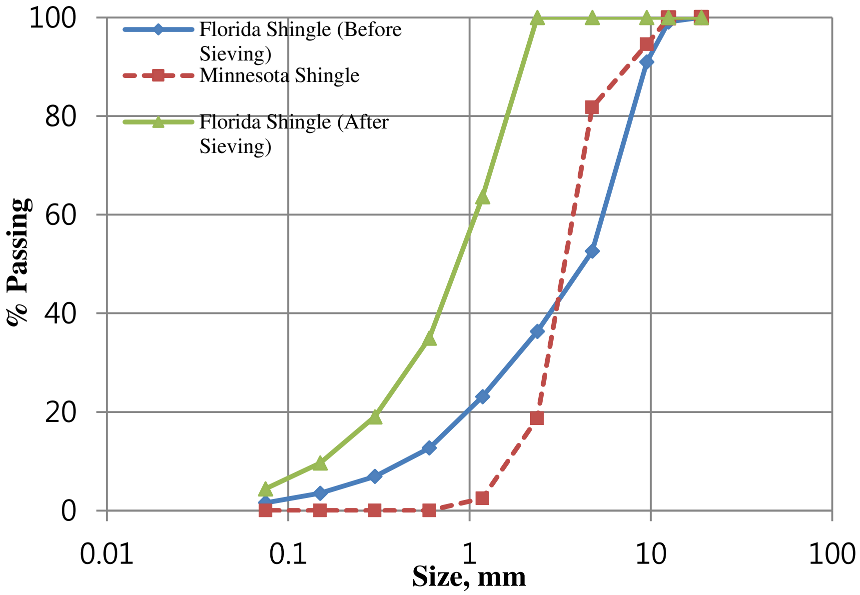

Figure 2-2. Gradation Curves for Florida and Minnesota Source Shingles

2.4 Sample Design

2.4.1 *Finding an Optimum Binder Content*

With control samples, the optimum binder content was first determined. Bulk, apparent, and specific gravities of aggregate were calculated based on AASHTO T84 and AASHTO T85 for fine and coarse aggregates, respectively. After estimating the percentage of optimum asphalt binder (EOAB), four different mixtures with different binder contents were then made at EOAB, EOAB±1% and EOAB-0.5%. Bulk and maximum specific gravities of the mixtures were measured based on ASTM D2726 and ASTM D2041, respectively. The binder content which produced 4% air voids was selected and the other corresponding volumetric properties passed the Superpave Design criteria. The optimum binder content was selected as 5.77% for the control sample.

2.4.2 *Sample Preparation*

For the Marshall test, three sets of shingle-mixed HMA samples were prepared at three binder contents of 5.77%, 4.77% and 3.77%. The Florida shingle was added as an additive from 0 to 6% with 1% incremental rate by the weight of aggregate. For comparison purposes, Minnesota shingle was also added to HMA specimens at 4.77% binder content. Three identical samples were made for each mix design. Thus, the total 84 specimens were prepared and the detailed experimental design is summarized in Table 2-1. For the moisture susceptibility test, two sets of shingle-mixed HMA specimens were made at two different binder contents of 4.77% and 3.77%. Amount of added shingle was 0%, 3% and 6% by the weight of aggregates. For each mix case, six specimens were prepared and two extra samples were made for the measurement of bulk and specific gravity. To clearly see the effect of shingles on the performance of moisture resistance, no anti-strip materials were used in this study.

Table 2-1. Matrix for RAS mix design for laboratory test (binder content + shingle)

Marshall Test	Marshall Test	Marshall Test	Marshall Test	Moisture Test	Moisture Test
5.77%+0% FL	4.77%+0% FL	3.77%+0% FL	4.77%+0% MN	4.77%+0% FL	3.77%+0% FL
5.77%+1% FL	4.77%+1% FL	3.77%+1% FL	4.77%+1% MN	-	-
5.77%+2% FL	4.77%+2% FL	3.77%+2% FL	4.77%+2% MN	-	-
5.77%+3% FL	4.77%+3% FL	3.77%+3% FL	4.77%+3% MN	4.77%+3% FL	3.77%+3% FL
5.77%+4% FL	4.77%+4% FL	3.77%+4% FL	4.77%+4% MN	-	-
5.77%+5% FL	4.77%+5% FL	3.77%+5% FL	4.77%+5% MN	-	-
5.77%+6% FL	4.77%+6% FL	3.77%+6% FL	4.77%+6% MN	4.77%+6% FL	3.77%+6% FL

(* FL=Florida shingle, MN=Minnesota shingle)

2.5 Experimental Work

2.5.1 *Binder Extraction and Test*

The asphalt binder was extracted from the tear-off shingles and the asphalt content and its properties were measured. The extraction method included reflux extraction (ASTM D2172) and rotary evaporator (ASTM D5404) methods. Solvent vapor, generated by hot plate, passes through the mixture placed in two wired mesh cones. After the extraction, asphalt binder was separated from its solvent using the rotary evaporator. Due to the high stiffness of the extracted binder, only the penetration test was conducted. Considering high pavement temperature during the summer in Florida, the researchers performed the penetration tests at different temperatures of 45 °C and 60 °C.

2.5.2 *Mixture Test*

Marshall Stability and Flow Test: The Marshall Stability and flow test (ASTM D5581) was conducted. The testing setup was modified to accommodate 6-in. breaking head to test 6-in. diameter specimens from the Superpave gyratory. The selected strain rate was 2 in./min. The stability was defined as the peak load of the load-displacement curve, and the flow was defined as the displacement corresponded to the peak load. Marshall Quotient (MQ), defined as the ratio of the stability to the flow, was used as an indicator of the stiffness of the specimens. Samples with higher MQ represent stiffer behavior.

Moisture Susceptibility Test: The moisture susceptibility test, also known as Lottman Test (ASTM D4867), was conducted. In this test, each set of samples were divided into two preconditioning: dry and wet conditioning. The total air void of each sample was required to be in the range of 7±1%. The used strain rate was 2 in./min and testing temperature was 25^0C. Wet-conditioned samples were submerged in the water of 60^0C for 24 hoursand then conditioned in the water of 25^0C for an additional hour prior to the test. Indirect tensile strength test was conducted, and the ratio of the peak load of the wet-conditioned sample to that of the dry sample was determined as the Tensile Strength Ratio (TSR).

Rutting Test: Rutting test was performed by using the Asphalt Pavement Analyzer (APA) based on AASHTO T 340-10. The APA is designed to evaluate the rutting resistance of HMA mixtures. A total of six samples were made containing the shingle from 1 to 6%. The virgin binder content of 4.77%, which was an optimum binder content for the shingle-combined HMA, was used for all six samples. APA testing was conducted following AASHTO TP 63-03. With 6-inch diameter HMA specimen with 4±1% air voids, rutting performance was evaluated after 8000 cycles of wheel-load repetition.

2.6 Test Results

2.6.1 *Behavior of Extracted Binder*

Four shingle samples were tested and their average asphalt content was 34.77 % (see Table 2-2). In general, unused scrap shingles involve 20 - 30% asphalt content while tear-off shingles include 30 – 40 % asphalt content. This 34.77% asphalt content falls within the typical asphalt content of 30 – 40 % for the tear-off shingles. A large variation is also observed. Typically, roofing shingles have a service life of 15-20 years, and they are under severe weathering conditions. The extracted binder was too stiff to conduct other binder tests except the penetration test. The result of penetration test is also summarized in Table 2-2.

Table 2-2. Properties of recovered asphalt binder from roofing shingles.

Properties	Sample 1	Sample 2	Sample 3	Sample 4	Average
Asphalt content	46.96 %	32.36 %	35.54 %	24.23 %	34.77 %
	Trial 1	Trial 2	Trial 3	Trial 4	Average
Penetration at 25 °C	2 dmm	2 dmm	1 dmm	1 dmm	1.5 dmm
Penetration at 45 °C	1 dmm	2 dmm	2 dmm	3 dmm	2 dmm
Penetration at 60 °C	4 dmm	5 dmm	5 dmm	6 dmm	5 dmm

(note: 1 decimilimeter (dmm) = 0.1 mm)

2.6.2 *Marshall Stability and Flow*

The results of Marshall Stability test are presented in Table 2-3. At the same binder content, it was observed that increasing the shingle increases the stability. This was expected because the shingle contains aged binder and results in higher viscosity of total binder of the mixture. The maximum stability for each set was observed at 6% shingle. The mixture at 3.77% virgin binder and 6% shingle exhibited the maximum stability of 78.6 kN. The performance of Florida and Minnesota RASs are compared in Figure 2 by showing the load-displacement curves. The slope of linear section represents material stiffness, and it increases with increasing the shingle addition. Steeper slope means stiffer mixture. Considering climate conditions in two states, Florida's tear-off shingles likely contain more aged binder and may cause higher stability and stiffness. Figure 2-3. Comparing Marshall Results for 4.77% set with Florida and Minnesota shingles. shows that the Florida shingle exhibited higher stability and stiffness (or Marshall Quotient) except 2% addition of shingle.

Table 2-3. Marshall Results for Florida shingles sets of 3.77%, 4.77%, and 5.77%

	3.77%-FL Shingle					4.77% - FL Shingle					5.77% - FL Shingle				
Added Shingle	Stability (kn)	Avg. Stability	Flow (mm)	Avg. Flow (mm)	M.Q. (kN/mm)	Stability (kN)	Avg. Stability	Flow (mm)	Avg. Flow (mm)	M.Q. (kN/mm)	Stability (kn)	Avg. Stability (kN)	Flow (mm)	Avg. Flow (mm)	M.Q. (kN/mm)
0	41.5	38.6	4.8	4.9	7.9	29.5	30.6	5.1	5.0	6.1	21.4	27.8	3.5	4.2	6.6
	40.1		4.7			31.2		5.0			24.2		4.2		
	34.1		5.1			31.2		5.0			37.9		4.8		
1	46.6	42.6	5.5	5.2	8.1	38.2	36.4	4.6	4.7	7.7	33.2	36.1	5.4	5.2	7.0
	37.3		4.9			28.7		4.8			33.6		5.1		
	44.0		5.3			42.3		4.8			41.5		5.1		
2	52.1	45.1	5.0	4.9	9.2	44.0	44.2	4.7	4.9	8.9	31.6	38.7	5.0	5.0	7.7
	40.6		4.8			47.9		4.9			40.0		5.1		
	42.6		4.9			40.6		5.3			44.4		5.1		
3	53.3	54.2	5.5	5.6	9.7	48.7	49.0	4.8	5.1	9.7	39.3	40.9	3.5	4.4	9.3
	60.0		4.8			53.1		5.4			38.8		4.9		
	49.3		6.4			45.1		4.9			44.7		4.8		
4	70.4	61.5	4.9	4.9	12.7	54.7	58.4	5.7	5.4	10.8	48.1	52.2	5.5	5.4	9.7
	59.4		5.0			59.0		5.1			52.5		5.4		
	54.7		4.7			61.5		5.4			56.0		5.2		
5	70.5	76.9	5.1	4.8	16.1	63.2	60.7	4.7	5.3	11.4	37.7	41.0	6.0	5.4	7.6
	76.8		4.5			61.0		5.8			39.6		5.0		
	83.4		4.7			58.0		5.4			45.7		5.2		
6	79.8	78.6	5.3	5.5	14.2	80.1	75.4	5.3	5.4	14.0	48.2	53.3	5.6	5.3	10.0
	78.3		5.4			64.3		6.0			59.0		5.5		
	77.7		5.9			81.7		5.0			52.7		4.9		

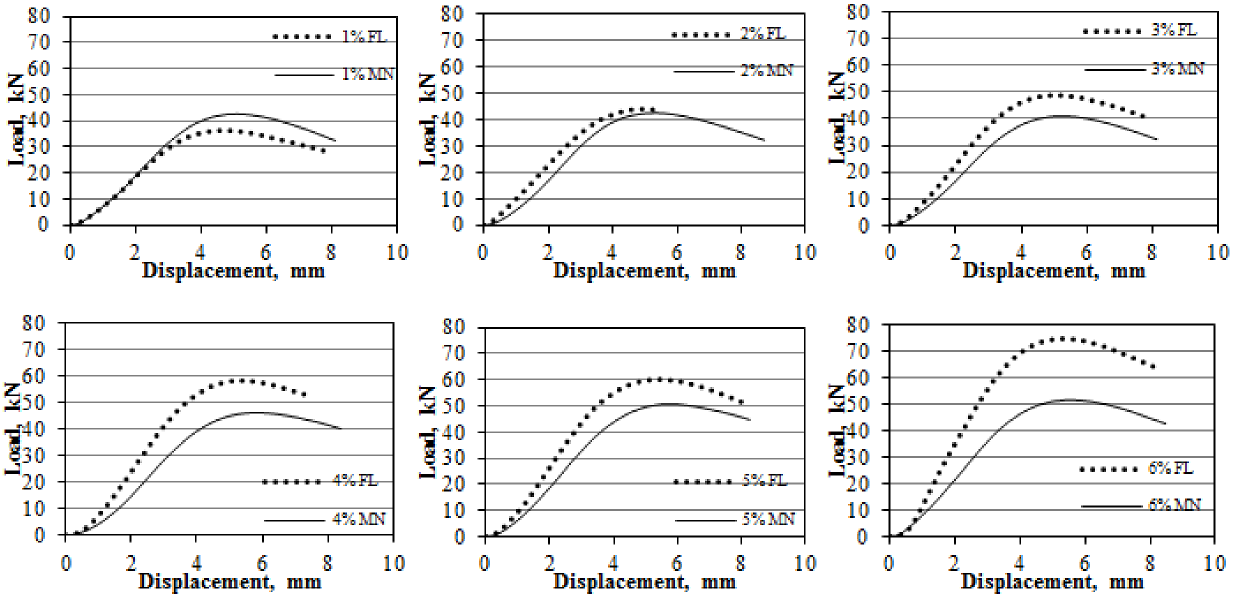

Figure 2-3. Comparing Marshall Results for 4.77% set with Florida and Minnesota shingles.

2.6.3 *Moisture Susceptibility Test*

In order to maximize the effect of shingles in the moisture damages of asphalt pavement, no anti-strip agent was used in this study. The results indicated that mixture with 4.77% binder content had higher strength compared to the other set with 3.77% binder content. Compared with the control sample, shingle addition of 3% and 6% with 4.77% binder content increased the TSR by 53% and 61%, respectively. Detail of moisture susceptibility test is shown in Table 2-4. Based on the Supersave specifications, TSR should not be less than 0.8. All sample sets with 3.77% binder content were considered as “fail” although there was an increase in TSR when shingle addition is increased. The maximum TSR (0.855) was observed for the sample with 4.77% binder content and 6% shingle. The sample set with 4.77% binder content and 3% shingle exhibited the

TSR of 0.826. TSR values of the moisture susceptibility test along with the minimum threshold are presented in Figure 2-4.

Table 2-4. Moisture susceptibility test results

	3.77% Virgin Asphalt Binder				4.77% Virgin Asphalt Binder			
	Sample's Condition	Tensile Strength (kPa)	Ave. Tensile Strength (kPa)	TSR	Sample's Condition	Tensile Strength (kPa)	Ave. Tensile Strength (kPa)	TSR
0% Shingles	Dry	463.6	488.7	0.468	Dry	460.2	456.6	0.539
		503.5				429.6		
		498.8				479.9		
	Wet	120.1	228.6		Wet	252.9	246.3	
		147.3				219.4		
		418.5				266.5		
3% Shingles	Dry	1121.7	1173.8	0.489	Dry	1104.3	1078.8	0.828
		1137.7				928.1		
		1262.0				1204.0		
	Wet	583.9	573.8		Wet	805.4	893.1	
		516.5				951.1		
		621.1				922.8		
6% Shingles	Dry	1242.2	1155.5	0.694	Dry	1594.3	1445.9	0.869
		1151.7				1747.5		
		1072.5				996.0		
	Wet	790.8	802.3		Wet	1239.5	1256.4	
		572.3				1262.1		
		1043.7				1267.6		

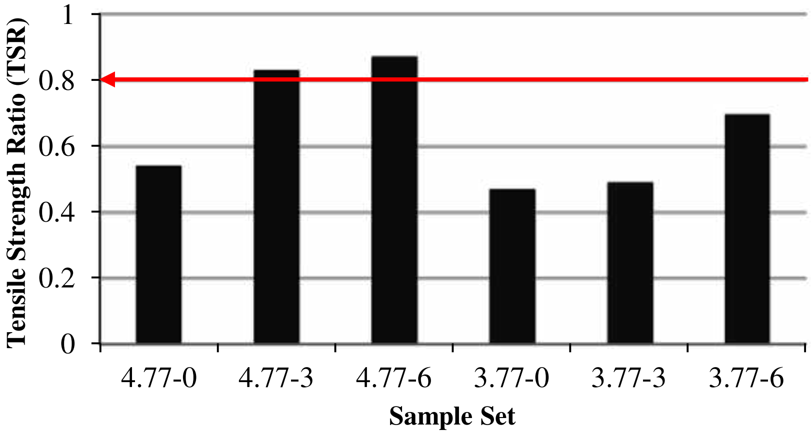

Figure 2-4. Tensile Strength Ratio for Six Different Sample Sets.

2.6.4 *Rutting Test*

Rutting test was performed by using the Asphalt Pavement Analyzer (APA). The difference between the initial (after 25 cycles) and final rut depth (after 8000 cycles) were calculated and averaged. The result of APA test is presented in Table 2-5. Testing results indicate that rut depth decreases with increasing the amount of tear-off shingle in the mixtures. The average rut depth for the control sample (0% shingle) was 3.7 mm after 8,025 cycles while the averages of rut depth for 3% and 5% RAS are 2.9 mm and 1.4 mm, respectively. This decrease in rutting depth is due to the increase of stiffer binder contributed by the shingle to the HMA. Increasing the amount of RAS in the HMA decreases the rut depth with a given load repetition.

Table 2-5. Asphalt Pavement Analyzer Testing Results.

% Shingle	Air Voids, %	Rut depth at 8025 Cycle, mm	Average Rut Depth, mm
0	4.4	3.2	3.7
	4.3	4.1	
3	4.4	3	2.9
	4.6	2.8	
5	4.6	1.3	1.4
	4.4	1.4	

2.7 Discussion

The authors present three things to be discussed.

- The maximum stability was observed with the specimen mixed at 3.77% virgin binder and 6% shingle. For this mix, the ratio of shingle's binder to the virgin binder in the mixture is the highest. The aged binder of tear-off shingles can lead to the increase of binder viscosity of total binder in the mixture. At a given shingle amount, with increasing the virgin binder content, the mixture got a more "lubricating" effect and can result in the reduction of stability (seen in Table 3).
- After completing the moisture susceptibility test, fractured surface of all specimens were visually inspected (see Figure 4). It was observed that all dry samples mixed at 4.77% binder content were cracked through the aggregates (probably partially) while other specimens mixed at 3.77% binder content were cracked in the interface between aggregate and binder. This indicates that the 3.77% binder content was insufficient to coat the aggregates in the mixture and resulted in weaker bonding.

- Compared to post-manufacturer scrap, the shingle has gone through more weathering and aging over its service life (about 10 to 15 years), resulting in higher viscosity. This can explain the observation that Florida's shingle exhibit a higher stability than Minnesota's shingle. Florida involves higher temperature and heat radiation than Minnesota.


(a) (b)

Figure 2-5. Fractured surface of specimens used in IDT tests: (a) 3.77% binder and 6% shingle (dry) and (b) 4.77% binder and 6% shingle (dry).

2.8 Summary and Conclusions

Different percentages of shredded tear-off shingle were added into HMA, and its effect on the mechanical performance was evaluated by using several laboratory binder and mixture tests. The optimum proponing of the shingle as filler material in HMA was investigated. It was found that the optimum binder content is 5.77% for the control sample (no shingle). In the specimen preparation, the shingle from 0% to 6% with 1% increment was added into the mixture with three virgin binder contents of 5.77%, 4.77%, and 3.77%.

Conclusions obtained from this study are summarized as below.

- The asphalt binder was extracted from the tear-off shingle. The average value is 34.77% which falls into a typical range of 30–40%. The average penetration depth is 1.5, 2, and 5 dmm at 25 °C, 45 °C, and 60 °C, respectively while the typical range of manufacturer scrap is between 23 and 70 dmm at 25 °C.
- At a given virgin binder content, all sample sets show that the stability and flow increases with increasing shingle amount. The maximum stability occurs with the mixture at 3.77% virgin binder and 6% shingle.
- The slope of linear portion in the load-displacement curve represents the stiffness of mixture materials. Increasing the shingle addition causes steeper slope of the curve. In other words, the aged binder (with high viscosity) from shingle, results in stiffness increase in HMA mixtures.
- The Minnesota RAS is more uniform than the Florida RAS, but it results in less stability values at the same mix proportioning. The uniformity of shingle may not be a significant factor in material stability. Florida's climate likely causes more significant binder aging.
- In the moisture susceptibility test, increasing the shingle increases the TSR ratio. The visual inspection in the fractured surface illustrate that the specimens at 4.77% virgin binder content cause optimum bonding condition between aggregate and binder.
- It is suggested that the optimum mix proportioning involves 4.77% virgin binder content and up to 6% shingle in HMA. Although 3.77% virgin binder resulted in the maximum

stability, the result of moisture susceptibility indicates that the 3.77% virgin binder content exhibited poor bonding between the aggregate and binder.

CHAPTER 3: PERFORMANCE EVALUATION AND COST-BENEFIT ANALYSIS OF HOT-MIX ASPHALT INCLUDING MUNICIPAL SOLID WASTE BOTTOM ASH AND RECYCLED ASPHALT SHINGLE[1]

3.1 Introduction

This chapter presents the study on evaluation of mechanical performance of hot-mix asphalt (HMA) containing different amounts of municipal solid waste incineration (MSWI) bottom ash (subsequently referred to as BA) in the asphalt mixtures as well as optimum binder content for the asphalt mixture containing the optimum BA; however, so far few studies have been conducted on characteristics of the physical, mechanical and long-term pavement performance of HMA with bottom ash [*13, 14*]. The BA was used as replacement of fine aggregate which is smaller than sieve No. 4 (4.75 mm). The Marshall Mix design was used for the specimen preparation and the HMA specimens were prepared by replacing the virgin aggregate with 10, 20, 30 and 40 % of BA by the total weight of the virgin fine aggregate. The optimum substitution portion of BA has been selected for further investigation in combination with different ratios of recycled asphalt mixture (RAS).

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[1] The partial content of this chapter also appeared in:
An, J., Golestani, B., Nam, B., and Lee, J. (2015) Sustainable Utilization of MSWI Bottom Ash as Road Construction Materials, Part I: Physical and Mechanical Evaluation. Airfield and Highway Pavements 2015: pp. 225-235. Using the paper as a chapter of this study is **with permission from ASCE (please see the appendix A).**

An, J., Kim, J., Golestani, B., Tasneem, K.M., Al Muhit, B.A., Nam, B.H., and Behzadan, A.H., Evaluating the Use of Waste-to-Energy Bottom Ash as Road Construction Materials.(2014)
Using the paper as a chapter of this study is **with Courtesy of the Florida Department of Transportation (please see the appendix A).**

As HMA performance tests, the Marshall Stability and flow test, indirect tensile test (IDT) and rutting test were employed. Finally, the proposed ratios of material combination were selected for cost-benefit analysis. Details of testing procedure as well as testing results are presented herein.

3.2 Literature Review

As the world's population increases, the volume of waste production is increasing at an alarming rate. This increase is quickly taking over our future landfill area and causing an increase in the price of landfilling. To overcome this issue, extensive effort is being put into recycling waste materials to reuse these kind of waste materials in different aspects instead of just landfilling [*1*].

Incineration of municipal solid waste (MSW) with energy recovery and management of municipal solid waste incineration (MSWI) ashes have been receiving a growing attention around the world. Many countries have addressed the issue of beneficial utilization of MSWI ashes by executing strategic management plans and regulations [*15-19*]. For example, many European countries beneficially utilize MSWI bottom ash as a sustainable transportation material with environmental criteria set by their strategic regulations [*16, 17*]. In the U.S., MSW are being produced more than any other country in the world; however, the recycling rate is considerably low [*20*]. The total MSW generation in the U.S. has increased up to 65% since 1980, to the current level of 250 million tons per year with 53.6% landfilled, 34.7% recycled and composted, and 11.7% incinerated with energy recover [*21*]. The total of 86 MSW Waste to Energy (WTE) plants are being operated in 24 states of the U.S. as of 2010 [*22*], where major users of MSWI plants are Connecticut, New York, New Jersey, Pennsylvania, and Virginia [*23*]. Typical residue produced from these incineration plants are MSWI bottom ash (BA) and fly ash (FA), and those are mostly combined to be disposed of in sanitary landfill in the U.S.[*24*]

The main components of asphalt mixture are asphalt binder and aggregate, which can be replaced by recycled materials. The reuse of MSWI BA as replacement of fine aggregate in HMA has been reviewed. Based on the researches that has been done so far, due to the high porosity of BA, which can vary in asphalt absorptions, it may make using of this material uneconomical [*25, 26*]. However, in some studies, it is recommended that the substitution ratio of BA to be limited to less than 25% [*27*].

BA is a potential road construction material. By decreasing in virgin aggregates sources, increasing transporting distances, and dwindling landfills, reusing of waste materials proves to be more important and favorable especially in construction and highway pavements [*28*].

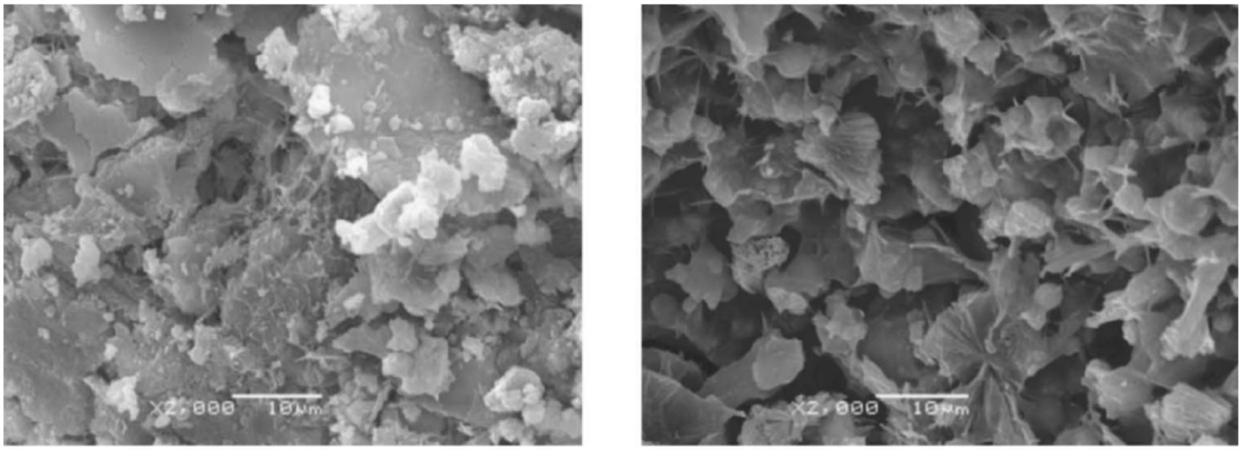
3.2.1 *Beneficial Use of MSWI BA as road material*

Almost 50% of the bottom ash produced in Netherland and Denmark is used in the construction area, however, lower percentages were used in France and Germany [*29*]. Typically, BA is used in granular road base applications.

In Taiwan, there has been a long practice for BA utilization. BA produced by the 19 waste to energy facilities was used as an aggregate substitution for construction projects. This country also limited usage of BA to first meet the engineering and environmental requirements.

Garrick et al. (1993) [*30*] evaluated the use of up to 32% BA in HMA. They found that BA needs more binder than regular aggregates in mixture, but couldn’t indicate a bottom line for potential toxicity of the BA in the mixture.

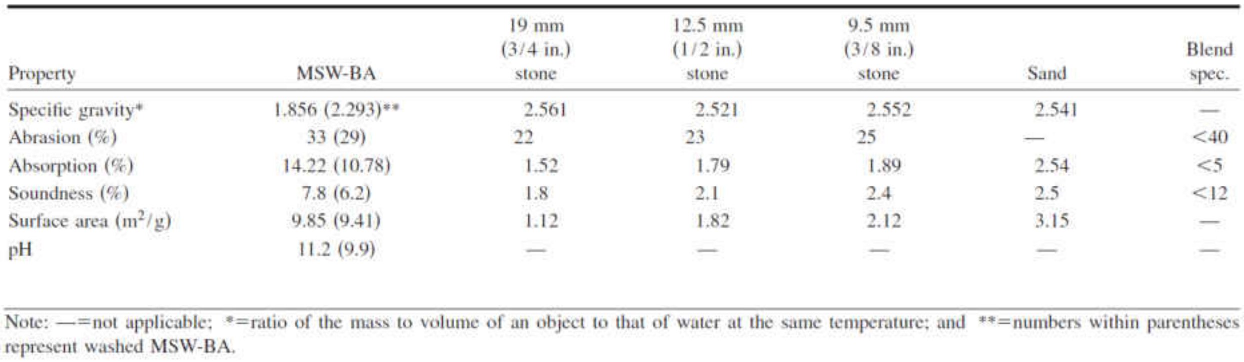
Chen et al. (2008) [*31*], studied the effects of 10, 20, 30 and 40 % replacement of BA with virgin aggregates by the total mass of the mix. Physical and mechanical properties, as well as the environmental impact of the mixtures were evaluated and compared with the control sample (0% replacement). To measure the impact of heavy metal, leaching tests were performed. Material characterization indicated that BA is a light-weight, porous, and absorptive material. This indicates why the requirement for optimum asphalt binder is higher in BA mixture than the virgin aggregate mixture. Figure 3-1 shows a scanning electron micrograph of BA and virgin aggregate. As shown virgin aggregate (lime stone) consists of solid particles with a dense structure. In contrast, the grayish BA particles have an irregular porous surface. The porous structure represents some of the material characterization in Table 3-1. Additionally, the properties of BA improved after the washing process.



(a) (b)

Figure 3-1. Micrographs of natural aggregate and MSW-BA particles: (a) natural aggregate; (b) MSW-BA aggregate [*31*]

Table 3-1: Basic properties of BA and virgin aggregates [*31*]



Property	MSW-BA	19 mm (3/4 in.) stone	12.5 mm (1/2 in.) stone	9.5 mm (3/8 in.) stone	Sand	Blend spec.
Specific gravity*	1.856 (2.293)**	2.561	2.521	2.552	2.541	—
Abrasion (%)	33 (29)	22	23	25	—	<40
Absorption (%)	14.22 (10.78)	1.52	1.79	1.89	2.54	<5
Soundness (%)	7.8 (6.2)	1.8	2.1	2.4	2.5	<12
Surface area (m^2/g)	9.85 (9.41)	1.12	1.82	2.12	3.15	—
pH	11.2 (9.9)	—	—	—	—	—

Note: —=not applicable; *=ratio of the mass to volume of an object to that of water at the same temperature; and **=numbers within parentheses represent washed MSW-BA.

The mechanical characterization of the mixtures are summarized as follows:

- The amount of asphalt binder content increased about 0.86% by each 10% increment in substitution ratio.
- The water sensitivity test results indicated that by increasing BA replacement, tensile strength ratio of the mixture decreased. The results also suggested, that if the replacement percentage is limited to less than 20%, the tensile strength ratio can be controlled within 75%.
- BA mixtures also showed relatively lower rutting resistance by increasing replacement ratio.
- It is recommended that the replacement ratio be limited up to 20% by total weight of the mix for the base course and 10% in surface mix.
- The leaching tests also showed that due to isolation of the BA particles by the asphalt binder, the concentration of heavy metals was significantly reduced and all the results met the standard limitations.

Eighmy et al. (1995) [*32*] studied the environmental effect of BA and the results showed 45 elements in BA. Among those elements, Ca, SO4, K, Cl, Na, Mg, and Al had the largest potential for leaching in the mixture with presence of BA.

Garrick et al. substituted up to 32% the BA in HMA, and found that HMA containing the BA requires higher asphalt content than the mixture containing virgin aggregate [*33*]. Chen et al. investigated the physical properties of asphalt mixtures containing the BA as aggregate substitution. The used BA contents used were 0, 10, 20, 30, and 40% by weight of the total mixture. The BA-mixed mixture exhibited lower rutting resistance compared with the control sample. The results of moisture susceptibility test indicate that the tensile strength ratio of the asphalt mixtures decreased with the increase of substitution amount of the BA [*31*].

3.2.2 *Beneficial Use of RAS in HMA*

With increases in the price of asphalt binder, asphalt industry has developed strategies to recycle resources. Recently, using recycled asphalt shingles (RAS) in pavement systems has been accepted by different transportation agencies. Currently, there are two sources for RAS: manufacturer waste scrap shingles and recycled tear off roofing shingles (TORS). TORS account for one of the largest portions of the overall waste stream in the U.S. [*5*]. There are about 11 million tons in disposal in US landfills each year [*2*]. Using this kind of waste material in hot mix asphalt (HMA) has its own limitations; as the RAS proportion increases, due to the high stiffness of the aged binder, so does the potential for increasing mixture stiffness and decreasing in resistance to cracking.

In the U.S. in the mid-1970s, a practical effort started using recycled materials such as RAS and reclaimed asphalt pavement (RAP). RAP can be partially substituted for both asphalt binder and aggregate and has been widely accepted due to its cost effectiveness advantage and less impact on environment. RAS can be just partially substituted with asphalt binder [*34*]. In 2010, the Illinois Department of Transportation, Springfield, used about 1.7 million tons of recycled materials in highway construction projects in the state of Illinois [*35*]. Several studies have been conducted through the U.S. on the evaluation of using RAS in hot mix asphalt. The reason that RAS is interesting for the researchers is that it contains a high percentage of asphalt binder (18% to 40%) which can be substituted with asphalt mixture's virgin binder.

In a study conducted by Sengoz et al. in 2004, the performance of HMA has been evaluated while RAS used as an additive. Different ratios of post-manufactured RAS's were added to the HMA and the mixtures samples were made by a 4-inch diameter mold. Marshall Stability and rutting resistance of the specimens were measured. The study concluded that adding more than 1.00% of RAS will result in a reduction of Marshall stability value and the HMA with 1.00% RAS exhibited a good performance in rutting resistance [*5*].

Hansan et al. (1997) reported that mixtures with RAS show better performance in terms of improving the rutting resistance and also result in cost savings in road paving projects [*6*].

The Polk County Waste Resource Management Division for Florida Department of Environmental Protection (FDEP) studied the economical aspect of using TORS (FDEP 2010). In terms of benefit, the report states that 7.00% of construction and demolition (C&D) debris in the state of Florida is RAS, therefore; RAS substitution with virgin binder can potentially make a significant difference in project cost.

In 1993, researchers at the University of Minnesota conducted a research on the effect of using shredded RAS in HMA. The used RAS percentages, were 0%, 5% and 7.5%, by the weight of aggregate. Under the compaction load mixture, densification increases due to the decrease of the air voids [*36*]. The results showed that adding 5.00% and 7.00% of RAS to HMA mixture can reduce the optimum binder content by 10% and 25%, respectively. Fiberglass RAS also could increase the tensile strength of the samples.

Maupin (2003) also used RAS as an additive to HMA. The experimental volumetric properties of the mixtures with RAS fulfilled the Virginia Department of Transportation (VDOT) specifications. Rutting test results were also comparable with conventional HMA mixtures. In contrast, hand, fatigue test results demonstrated satisfactory performance in comparison with the conventional HMA's [*10*].

In another study by Janisch and Turgeon, the in situ performance of HMA with manufactured scraps was investigated. The subjected pavement air void was 4 percent greater than Minnesota DOT standards. However, the condition of the pavement was satisfactory, even 6 years after the construction [*11*].

3.3 Plan of Study

The plan of study for this project included replacing 10, 20, 30 and 40% of the virgin fine aggregate with BA, the proposed ratio in terms of mechanical properties has been added 1, 2, 3, 4, 5 and 6% by weight of the aggregates of one source RAS to find the optimum ratio. The resultant HMA mixtures were tested for their engineering properties; all sample test results were compared with each other and control mix. In addition, cost-benefit analysis including life cycle assessment (LCA) and life cycle cost analysis (LCCA) were performed in order to evaluate samples from environmental and economic point of view.

Table 3-2: Prepared mixtures

Sample Codes	Description
V100B0A5.7R0	100% virgin coarse and fine aggregates @ 5.7% OAC
V100B20A5.7R0	100% virgin coarse+80% virgin fine+ 20% BA fine agg. @ 5.7% AC
V100B20A6.8R0	100% virgin coarse+80% virgin fine+ 20% BA fine agg. @ 6.8% OAC
V100B20A5.7R1	100% virgin coarse+80% virgin fine+ 20% BA fine agg. +1% RAS@ 5.7% AC
V100B20A5.7R2	100% virgin coarse+80% virgin fine+ 20% BA fine agg. +2% RAS@ 5.7% AC
V100B20A5.7R3	100% virgin coarse+80% virgin fine+ 20% BA fine agg. +3% RAS@ 5.7% AC
V100B20A5.7R4	100% virgin coarse+80% virgin fine+ 20% BA fine agg. +4% RAS@ 5.7% AC
V100B20A5.7R5	100% virgin coarse+80% virgin fine+ 20% BA fine agg. + 5% RAS@ 5.7% AC
V100B20A5.7R6	100% virgin coarse+80% virgin fine+ 20% BA fine agg. +6% RAS@ 5.7% AC

3.4 Performance Evaluation

3.4.1 *Materials*

The binder grade used in this research was PG 67-22, which is the most commonly used asphalt binder in the state of Florida. The physical properties of the asphalt binder are summarized in Table 3-3. It should be denoted that the used based binder was not a modified binder [*37, 38*].

The virgin aggregate used in this study was limestone obtained in Orlando. Limestone aggregate was supplied by CEMEX Co. (Orlando, FL) with a maximum size of 25 mm. The sand was also limestone by fracturing the bigger particles.

Table 3-3: Physical properties of the asphalt binder

Test	Test method	Specification	Test results
Rotational viscosity @ 135 ºC, 20 rpm spindle # 21	T 316	3.0 Max	0.465 Pa.s
Rotational viscosity @ 165 ºC, 20 rpm spindle # 21	T 316	3.0 Max	0.128 Pa.s
Dynamic shear (G*/sin δ, 10 rad/s)	T 315	1.0 min @ 67 ºC	1.09 kPa
Ring and ball soft point	T 53	-	54 ºC
Penetration @ 25 ºC	T 49	-	59 dmm
Flash point	T 48	230 ºC	344 ºC

(note: Pa.s = pascal-second)

The BA appears a grayish lightweight, porous and absorptive material. A visual inspection of the ash indicated that it contained small amounts of unburned organic material such as chunks of broken glasses, metal and papers, which was separated manually before sieving. The photograph of BA sample ‘as is’ is shown in Figure 3-2. The BA that passes sieve No. 4 (4.75 mm) was used as replacement of virgin fine aggregate in the mixture. Physical properties of MSWI BA are summarized in Table 3-4.

Figure 3-2: Visual inspection of BA aggregate

Table 3-4: Physical properties of MSWI bottom ashes

Properties	Bottom ash	Test methods
Specific gravity (oven dry)	2.20	ASTM C127 [*39*]
Absorption capacity, %	12.8	ASTM C127 [*39*]
Unit weight (oven dry), kg/m^3	2,195	ASTM C29 [*40*]
L.A. abrasion mass loss, %	43	ASTM C535 [*41*]

3.4.2 *Sample Preparation*

3.4.2.1 Sample Design for the HMA containing MSWI BA

Mixture Proportioning: The BA was used to replace the fine aggregate in the mixture; thus the BA was sieved out and particles smaller than sieve No. 4 (4.75 mm) was used in this study. The aggregate was tested according to ASTM C136 and the gradation of the aggregate used in the mixture is shown in Figure 3-3. The asphalt mixture contains the BA with percentages of 0 % (control mix), 10 %, 20 %, 30 % and 40 % by the total of fine aggregate in weight. The virgin and ash aggregates were fractioned into individual sieve sizes to provide the requirement of fine aggregate, and then recombined again to meet the requirement of gradation. Table 3-5 presents the detailed information how each fraction of fine aggregate was replaced with the BA. Since the gradation of BA has the same gradation as the virgin aggregate to be replaced, the gradations of total aggregate for all HMA specimens are same.

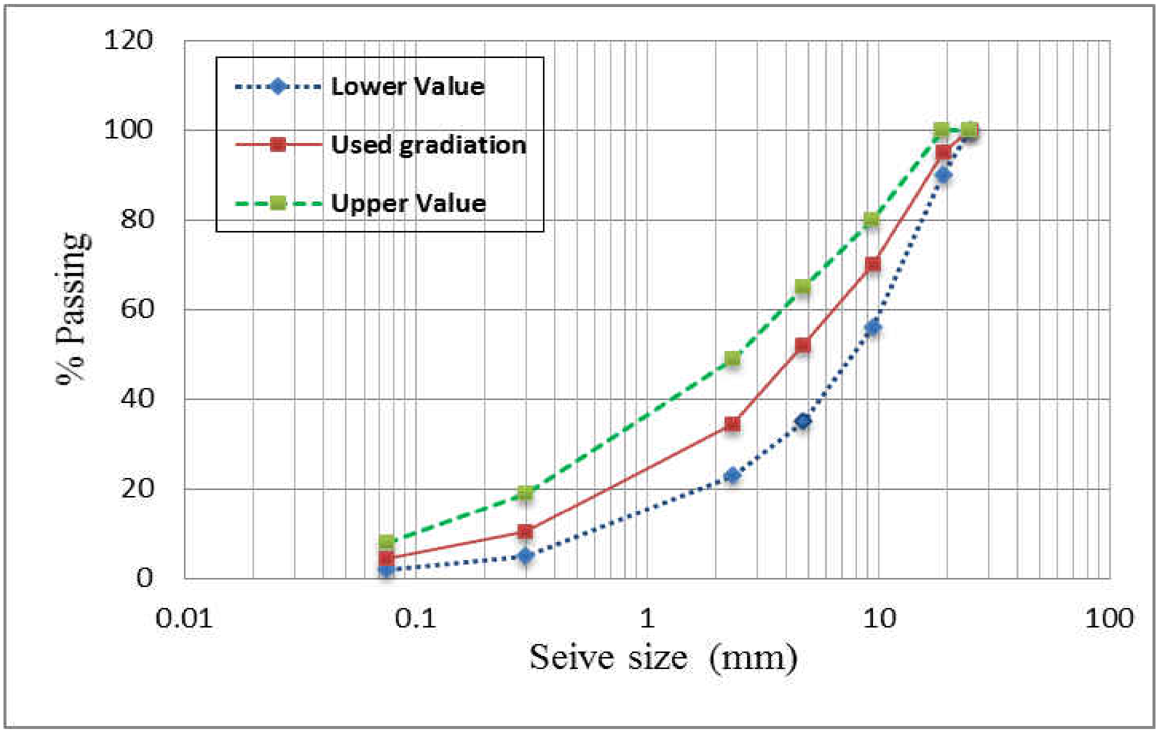


Figure 3-3. Gradation curve of used aggregate and limits

Table 3-5. Aggregate replacement with the BA of 0, 10, 20, 30, and 40%

Sieve No. (size)	Replacement ratio of BA				
	0%	10%	20%	30%	40%
	Virgin agg (g)	BA (g)	BA (g)	BA (g)	BA (g)
19 mm	58	0	0	0	0
12.5 mm	173	0	0	0	0
9.5 mm	115	0	0	0	0
# 4	207	0	0	0	0
# 8	201	20	40	60	80
# 16	109	11	22	33	44
# 30	92	9	18	28	37
# 50	75	7	15	22	30
# 100	40	4	8	12	16
# 200	31	3	6	9	12
Pan	49	5	10	15	20

(Note: Each cell represents the weight of each fraction used in the total mixture)

Due to the limited amount of BA, it was decided to make smaller specimens (4-in. diameter HMA); thus the Marshall Mix design was used for the sample preparation. For each proportioning, three specimens were prepared for performance tests and the average value of three specimens is reported later sections. The aggregate was batched to 1,200 g per specimen. At first, asphalt mixture specimens were prepared with 0% BA (control mix) to determine the optimum binder content for the virgin aggregate. Then, the mixtures with 10, 20, 30 and 40% of replacement by the BA were prepared at 5.7% of binder content, which is the optimum binder content for the control mix.

Optimum Binder Content (for the control sample): The aggregate was heated and then mixed with different amounts of asphalt binder so that some were above and some were below the expected optimum asphalt content. In general, the optimum asphalt content is ranged from 4% to 7%. The trial binder contents were 4%, 4.5%, 5%, 5.5%, 6% and 6.5% by total weight of the mixture. The samples were compacted with 75 blows on each side with the standard Marshall hammer as specified in ASTM D6927. Three samples were prepared at each binder content. A total of 18 samples were prepared (3 at each asphalt content for 6 different asphalt content).

After compaction the samples were removed from the molds and allowed to cool. The samples were weighted dry in air (W_D), allowed to soak 3 minutes in water and weighted submerged in water (W_{sub}), removed from the water, blotted dry and again weighted in air (W_{SSD}). The bulk specific gravity of the sample G_{mb} is then determined by:

$$G_{mb} = \frac{W_D}{W_{SSD} - W_{sub}} \tag{3.1}$$

The volume of sample in ml is equal to W_{SD} - W_{sub} when weighted in grams.

The Voids in Total Mix (VTM) are determined for each sample by comparing the average bulk density for each asphalt content to the theoretical max density (TDM) for that asphalt content. Max theoretical specific gravity of the mixtures were conducted following ASTM D2041.

$$VTM = \left(1 - \frac{G_{mb}}{G_{mm}}\right)100 \tag{3.2}$$

Where G_{mb} is the specimen bulk density and G_{mm} is the max theoretical specific of the mixtures.

The voids filled with asphalt (VFA) are determined by the following equation:

$$VFA = \left[\frac{VMA - VTM}{VMA}\right]100 \tag{3.3}$$

After the samples were weighted in air and water, the samples were then tested for stability and flow according to ASTM D6927. After all data was collected, plots were developed to show the relationship between the various properties and asphalt content as shown in Figure 3-4. Each data point on the figures represents the average of three specimens. For the selection of the optimum asphalt content, the specifications presented in Table 3-6 were considered. With respect to the above graphs, the binder content at 4% void is 5.7 % of the total mix which meets the other specification criteria. This content has been used to make samples with 0, 10, 20, 30 and 40 percent ash replacement.

Table 3-6: Optimum asphalt binder specification limits

Test Property	Specification	Results
Marshall Stability (lbf)	1500 minimum	3005
Flow 0.01 inch	8-16	14.8
Void in Total Mix (percent)	3-5	4
Void filled with Asphalt Cement	70-80	78

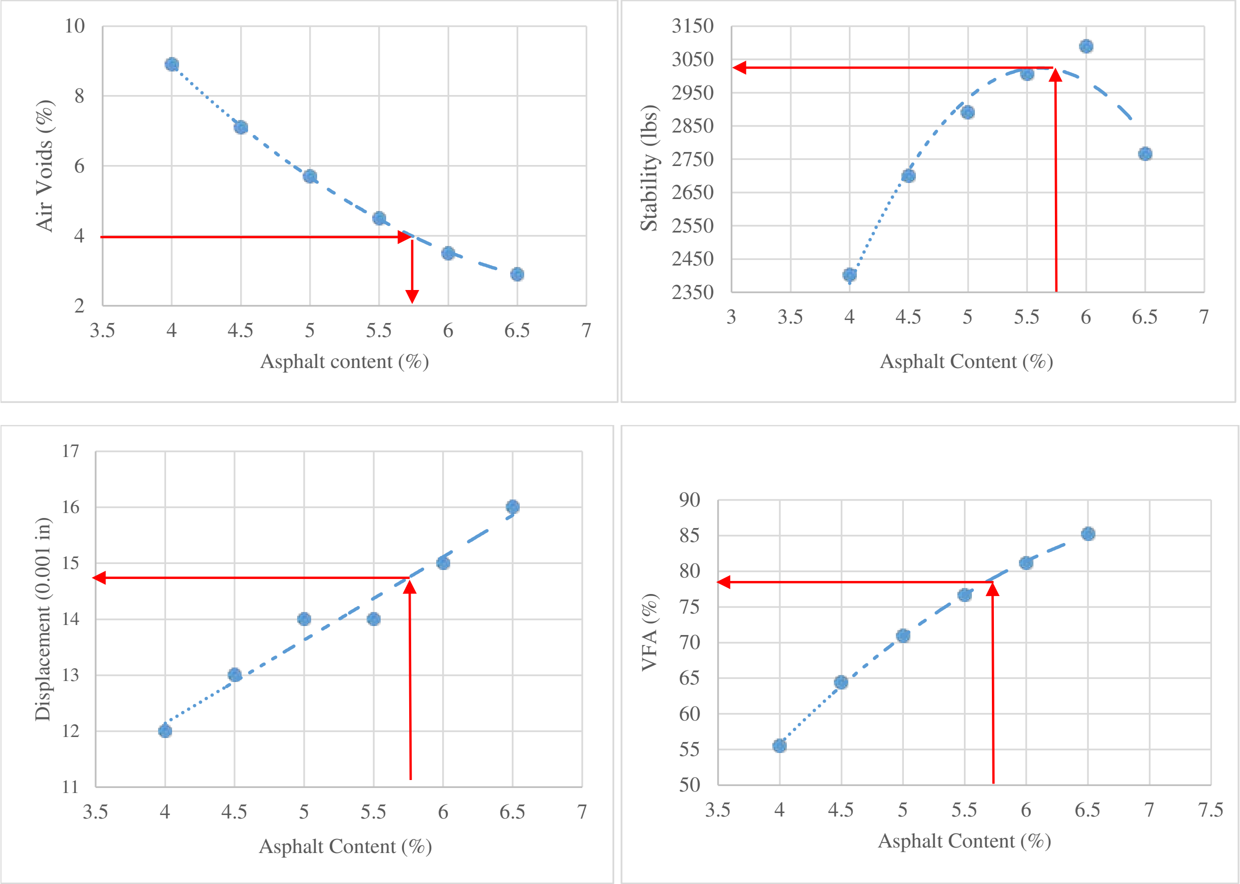


Figure 3-4. Graphical Illustration of determining optimum asphalt binder of virgin aggregate by Marshall Method

3.4.2.2 Sample Design of the HMA Containing MSWI BA and RAS

Mixture Proportioning: As mentioned earlier the aim of this research is to design and develop a sustainable HMA by maximum possible replacement ratio of the virgin materials. By substituting only 20% of the virgin fine aggregates with BA, the increment in optimum asphalt content was 1.1% (wt.%). To overcome this increment percentage, RAS as an alternative for asphalt binder substitution, has been added to trial mixture in the order of 1, 2, 3, 4, 5, 6 percentage by the mass of total aggregate.

Optimum Binder Content for the HMA containing 20% BA: According to the Marshall and moisture susceptibility tests, the optimum content of BA was determined as 20% replacement of fine aggregate in the mixture. Since the BA is lightweight aggregate that absorbs higher asphalt due to higher porosity, it may require higher amount of virgin asphalt to maintain optimum film thickness. Therefore, it is necessary to find out the optimum binder content for the 20% replacement of BA. The Marshall mix design was used and the procedure to find out the optimum binder content is shown in Figure 3-5. The procedure involves stability, air voids, flow and VFA as criteria for determining the optimum binder. As seen in the figure, the optimum binder content has been determined at 6.8 % by the total weight of the mix. As compared in Figure 3-4 and 3-15, the optimum binder contents for the specimens of 0% BA and 20% BA are 5.7% and 6.8%, respectively. In other words, increasing the BA up to 20% in the total aggregate requires greater amount of binder content. Although the optimum binder content is 6.8% for the 20% BA, 5.7% binder content still meet the criteria of stability, air voids, flow and VFA.

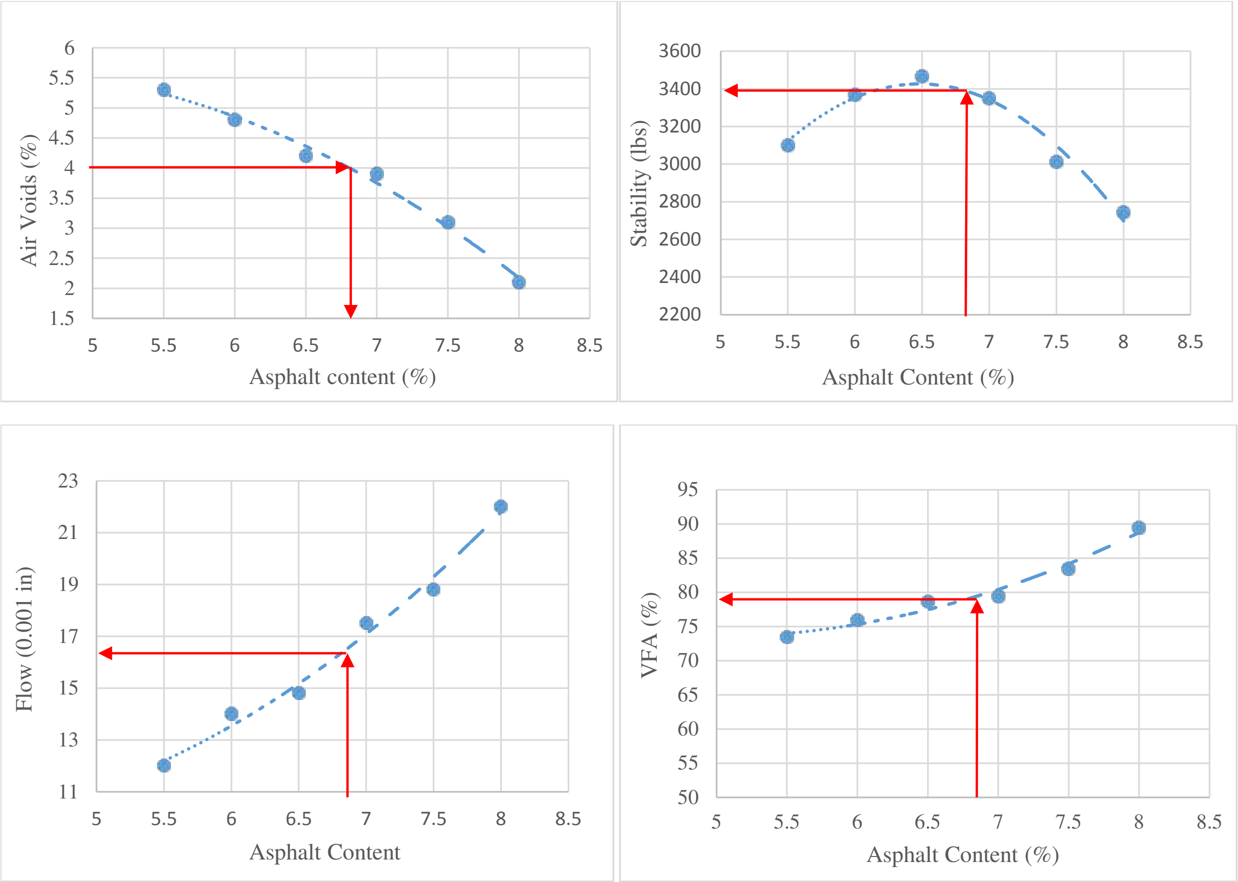


Figure 3-5: Graphical illustration of determining optimum asphalt binder at 20% BA replacement by Marshall Method

Table 3-7: Optimum asphalt binder at 20% BA replacement

Test property	Specification	Results
Marshall Stability (lbf)	1500 minimum	3080
Flow 0.01 inch	8-16	16.2
Void in Total Mix (percent)	3-5	4
Void filled with Asphalt Cement	70-80	78

3.4.3 *Experimental Procedure*

3.4.3.1 Experiments for the HMA containing MSWI BA

<u>*Marshall Stability and Flow Test*</u>: The Marshall Stability and Flow test has been conducted according to ASTM D 6927 with 4-in. diameter samples. The testing setup is shown in Figure 3-6. The "Stability" and "Flow" values obtained from the Marshall test indicate the strength and deformation characteristics of HMA samples, respectively. For each set, three specimens were prepared, and testing results were averaged. Specimens were placed in a water bath at 60℃ for 30-40 min and then loaded at a ratio of 50.8 mm/min (2 in./min.) and the stability and flow values were recorded. Laboratory compaction was prepared by using 75 blows of the Marshall hammer per side.

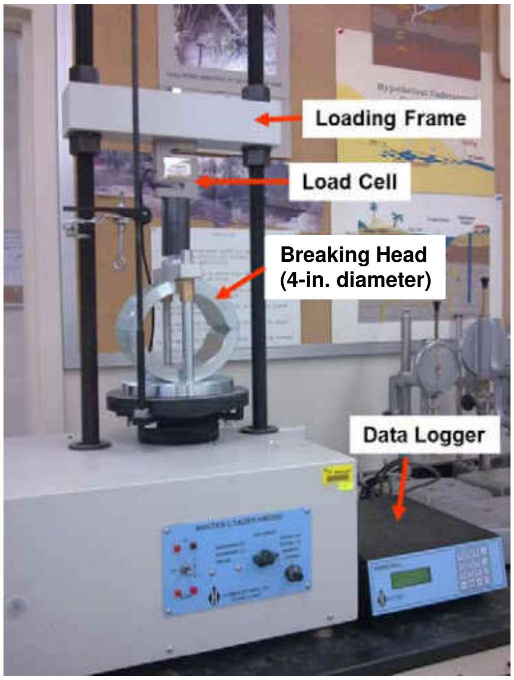


Figure 3-6: Marshall Test apparatus and 4-in. breaking head at the UCF geotechnical laboratory

<u>*Moisture Susceptibility Test:*</u> The moisture susceptibility test, also known as Lottman test (ASTM D4867), was conducted to measure the effect of water on the tensile strength of HMA paving. Following the test procedure, each set of samples is divided into two subsets with approximately same air voids (7±1 %.). One subset is maintained dry while the other wet-conditioned. Test temperature is at 25 ^{0}C. The procedure of moisture susceptibility test is shown in Figure 3-7 through 3-9. Dry samples were sealed and kept in water bath at 25^{0}C for adjusting the temperature. Wet samples, after partially saturation (see Figure 3-7) had to be soaked in distilled water at 60^{0}C for 24 hours (see Figure 3-8), and soaking in a water bath at 25^{0}C for an hour (see Figure 3-9) for adjusting the temperature. Strain rate was at 2 (in./min). Indirect tensile strength of each sample is determined using the Indirect Tensile Test (IDT) device. Calculation formula is as follow:

$$S_t = 2P/\pi tD \ (psi) \tag{3.4}$$

Where, S_t is tensile strength (psi), P is maximum load (lbf), t is specimen thickness (in.), D is specimen diameter (in.)

$$TSR = \left(\frac{S_{tm}}{S_{td}}\right)100 \tag{3.5}$$

Where, *TSR* is tensile strength ratio (%), and S_{tm} and S_{td} are average tensile strength of the moisture conditioned subset and the dry subset, respectively (psi).

Several state Departments of Transportations (DOTs) require using anti-strip agents as an additive in HMA pavements. Florida specifications allow adding anti-strip agent with 0.25% to 0.50% by weight of asphalt binder. To clearly observe the impact of ash in HMA on its moisture damages, no anti-strip agent was used to the mixtures. The results are shown in Figures 6.10 and 6.11. Each data on the figures represents the average of three specimens.

Figure 3-7: Partially saturating wet-subsets using vacuum

Figure 3-8. Wet subsets, soaking in distilled water at 60 ºC for 24 hours

Figure 3-9. Wet subsets, adjusting the temperature by soaking in a water bath at 25 ºC

3.4.3.2 Laboratory Experiments for the HMA Containing MSWI BA and RAS

Indirect Tensile Strength (IDT) Test: IDT testing was employed to evaluate the mechanical behaviors of the HMA containing MSWI BA and RAS. Testing procedure followed ASTM D6931 method. A cylindrical specimen is loaded diametrically across the circular cross section. Strain rate was at 2 (in./min). The loading causes a tensile deformation perpendicular to the loading direction, which yields a tensile failure. By registering the ultimate load and by knowing the dimensions of the specimen, the indirect tensile strength of the material could be computed. The tensile strength was calculated with the formula as below.

$$S_t = 2P/\pi tD \text{ (psi)} \tag{3.6}$$

Where, S_t is tensile strength (psi), P is maximum load (lbf), t is specimen thickness (in.), D is specimen diameter (in.)

Rutting Test: Rutting performance of each mixture, associated with substituted materials, was evaluated using APA testing. Since APA measurement represents mixture stiffness, this test was used to keep the results comparable. Additionally, APA testing maintains simplicity because it directly measures the sample rut depth. In this study, 75-mm dry SGC-compacted HMA cylinders with 7.0 ± 0.5 percent air voids were tested at 64 degrees Celsius to 8000 cycles. Superpave has defined limits on the angularity of fine aggregates used in HMA using the National Aggregate Association (NAA) test, Method A (also exists as AASHTO TP 33). The purpose of these limits is to increase the mix's ability to resist excessive permanent deformation or rutting under traffic loading. The theory behind this test is that the more angular the aggregate particles are, the higher the resistance to shear failure caused by the increased aggregate interlock. A review of the literature regarding the subject of permanent deformation indicates that the phenomenon is complex. Studies cite multiple causes for rutting including: (1) asphalt content, (2) performance grading, (3) aggregate affinity for asphalt, (4) aggregate size, (5) coarse aggregate shape, (6) coarse aggregate texture, (7) fine aggregate shape (angularity), (8) mineral filler properties, (9) aggregate gradation, (10) aggregate absorption, (11) plastic fines in the fine aggregate, and (12) performance graded asphalt [*42-53*].

3.4.4 *Testing Results and Discussion*

3.4.4.1 Results and Discussion for the HMA containing MSWI BA

Marshall Stability and Flow Test: The results of the stability and flow are shown in Figure 3-10 and Figure 3-11, respectively. As the content of bottom ash in the mixture increases from 0 to 10, 20, 30 and 40 percent the Stability increased 2, 16.5, 13.3 and 0.5 percent and the Flow increased 4, 8, 38 and 61 respectively. Due to the particle surface roughness of the bottom ash aggregate, the stability increased from 0% to 20% replacement, but the lack of binder content caused decreasing in stability after 20 % replacement.

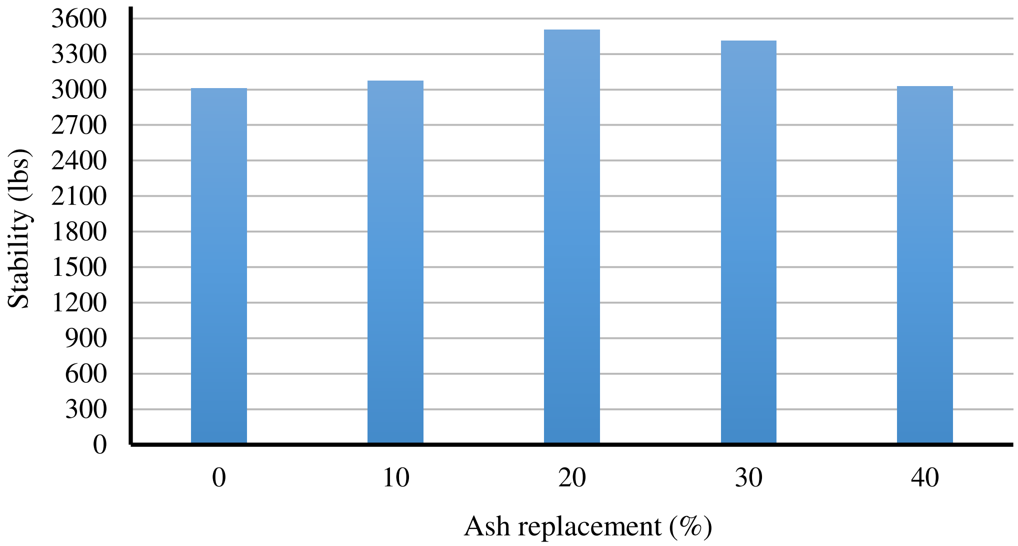


Figure 3-10: Marshall Stability results

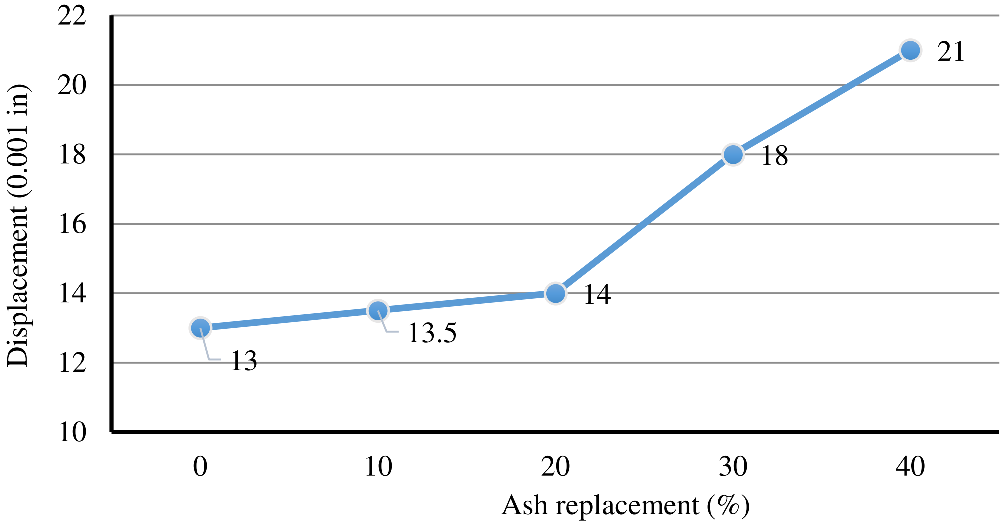


Figure 3-11: Flow test results

Moisture Susceptibility Test: The results of the moisture susceptibility test are presented in Figure 3-12 and Figure 3-13. Similar to the results of Marshall Stability test, the trend indicates that 20% replacement of BA exhibits the maximum tensile strength (1720 kPa), which is 288 kPa higher than the control specimen (1432 kPa). It is important to note that the tensile strength of all BA-combined HMA (except 40% BA replacement) is higher than the control. However, the tensile strength ratio (TSR) results show that only the HMAs with 10% and 20% replacement by BA have higher TSR than the control. Considering the 80% as a minimum criterion, which is commonly adopted by highway agencies, the only 20% replacement of BA meets the requirement. Compared with normal aggregates such as granite and limestone, MSWI BA has higher absorption due to greater porosity; thus, the BA-combined HMAs likely have reduced effective asphalt binder, which is an adverse effect on the moisture resistance in HMA. It is important to note that evaluation of cracking resistance was not performed. Although the stability and TSR increases with MSWI BA till 20%, there is a possibility that the mixture has low cracking resistance.

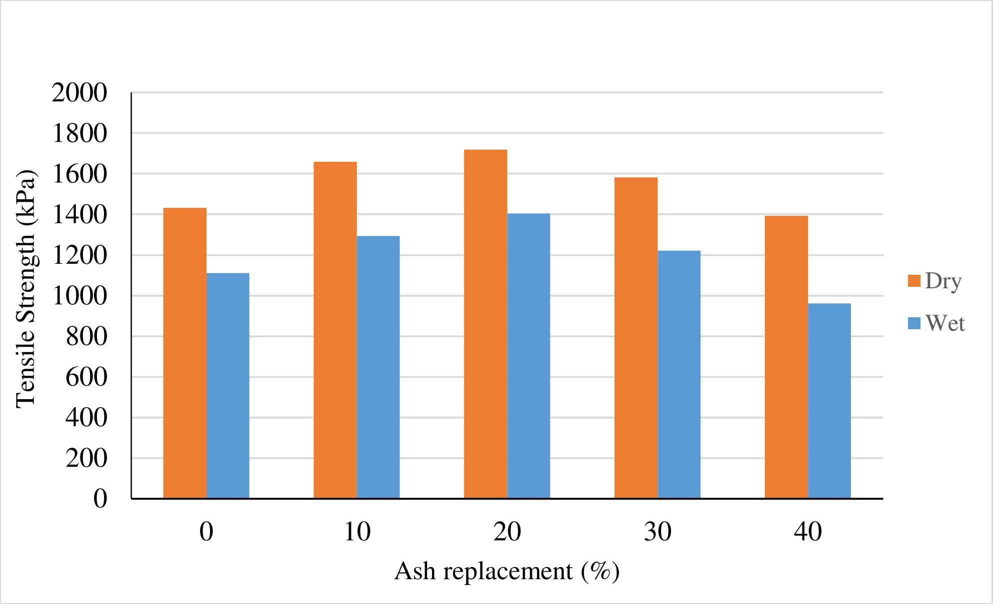


Figure 3-12: Tensile strength of dry and wet samples

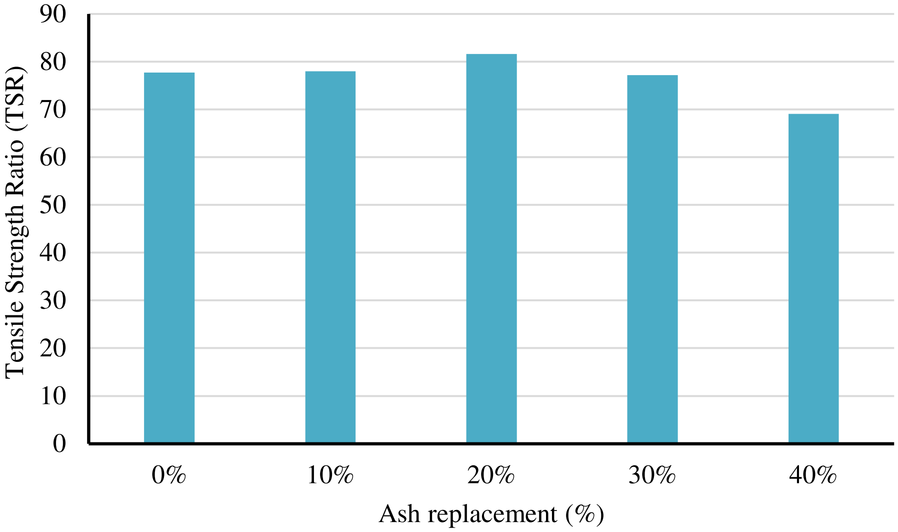


Figure 3-13: Tensile strength ratio

3.4.4.2 Results and Discussion with the HMA containing MSWI BA and RAS

Indirect Tensile Strength (IDT) Test: As mentioned earlier the aim of this research is to design and develop a sustainable HMA by maximum possible replacement ratio of the virgin materials. By substituting only 20% of the virgin fine aggregates with BA, the increment in optimum asphalt content was 1.1% (wt.%). To overcome this increment percentage, RAS as an alternative for asphalt binder substitution, has been added to trial mixture in the order of 1, 2, 3, 4, 5, 6 percentage by the mass of total aggregate and the results are shown in Figure 3-14.

Increasing RAS percentage increases binder viscosity and consequently tensile strength, as this increment is 29.5% more in 5% ratio rather than 0%. The decrement in 6% is due to excess amount of binder which turned the state of the mixture to the ductile. Additionally, 6% RAS has the potential to raise 60% the portion of fine aggregates and filler materials in the mixture. Extra filler moves the state of the mixture from visco-elastic to plastic.

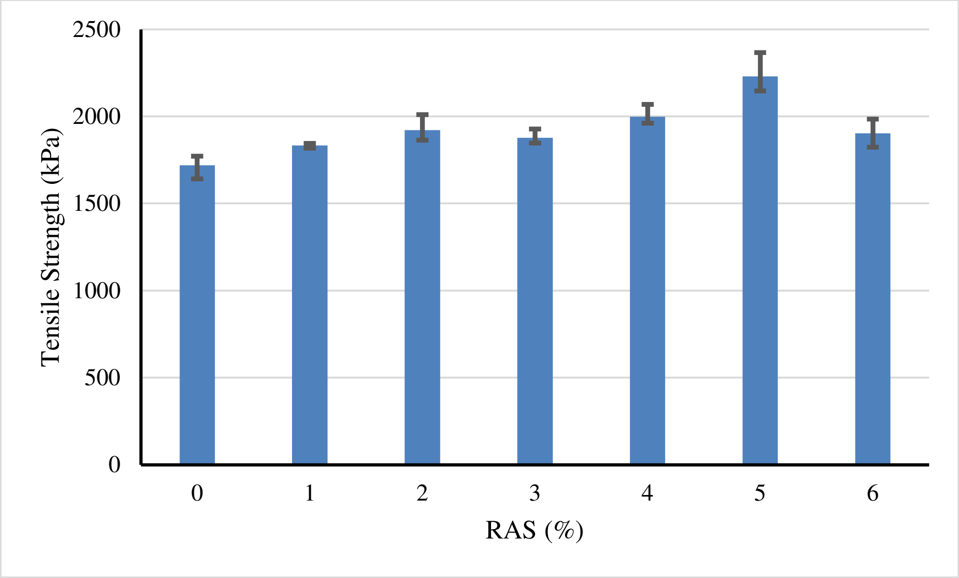


Figure 3-14. Tensile strength of the samples with RAS percentage

Rutting Test: Figure 3-15 shows the outcomes of the rutting test results as well as the effective binder content (EBC) of the proposed samples. Despite the tensile strength results' trend, rutting test results do not follow a consistent stream due to the changes in EBC. The amount of EBC directly is related to the mixture binder content; thus, replacing 20% of fine aggregates with BA reduces the EBC and consequently reduces the resistance to a permanent deformation (samples 'V100B20A5.7R0"). Adding 1, 2, and 3 percent of RAS does not significantly changes the EBC due to the existing porous on the surface of the BA particles; hence, the extra RAS' fillers facilitate increasing plastic deformation. EBC increased in the samples with 4, 5 and 6 percent RAS and the influence of EBC was more than the RAS' fillers on rut depth; however, the EBC percentage on sample with 6 percent RAS is slightly higher than the control sample, resulting in rutting increment.

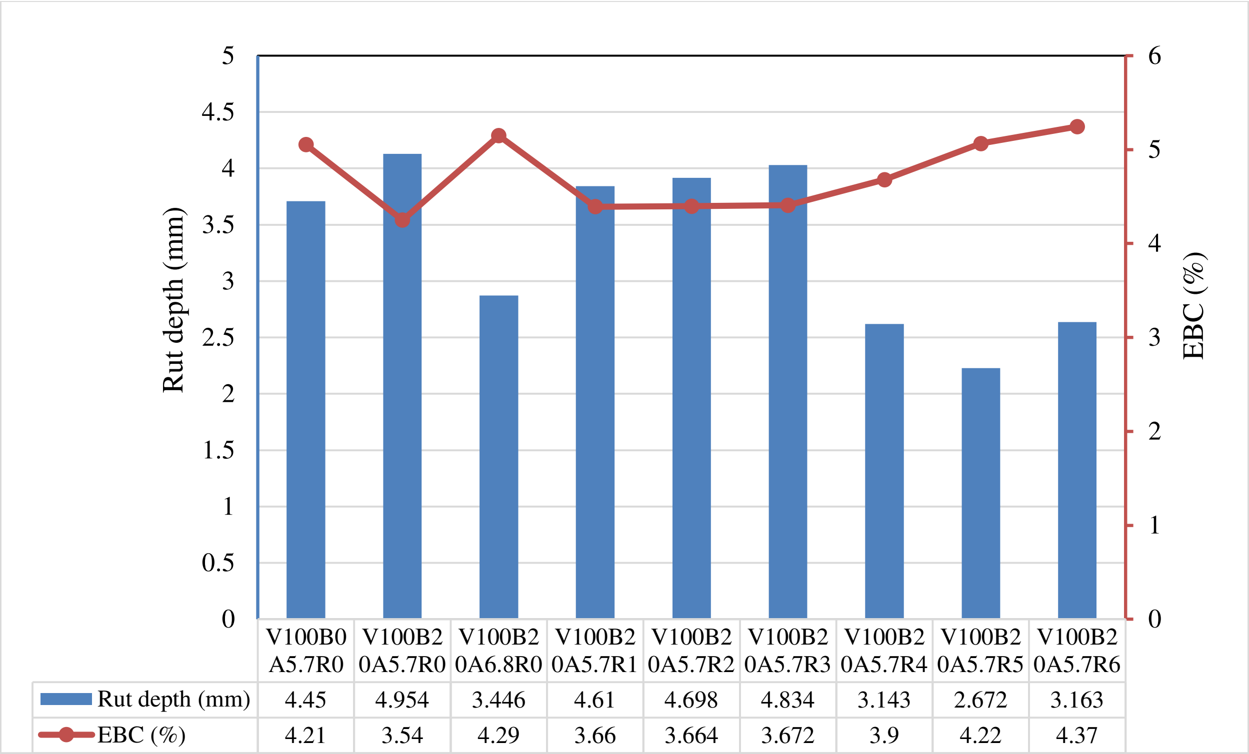


Figure 3-15.Rutting results versus EBC

3.4.5 *Correlation Between Tensile Strength and Rutting Results*

3.4.6 *Construction of IDT ‘Stiffness’ Method*

To find the correlation between the rutting and tensile strength, a new stiffness index has been proposed. This index is the slope of load and displacement from IDT testing. The slope determined from the load-displacement curve can be referred to as IDT ‘stiffness’ hereafter and denoted as ‘k’ value. Steeper slopes indicate stiffer materials which lead to higher resistance to plastic deformation.

Figure 3-16 indicates the load-displacement curves obtained from IDT testing (tested under dry condition) and the associated slope is shown in Figure 3-17. The development process was calculated by using Matlab software 2013. The max slope representing the point with max stiffness while zero slope (after the max) indicating the failure point. Under monotonic loading, the mixture has linear behavior at certain data points before and after the max stiffness. The data points in the range of 95% of the max slope value were selected to Polyfit the best fit line according to Figure 3-18. The slope of the best fit plotted line represents “k” value.

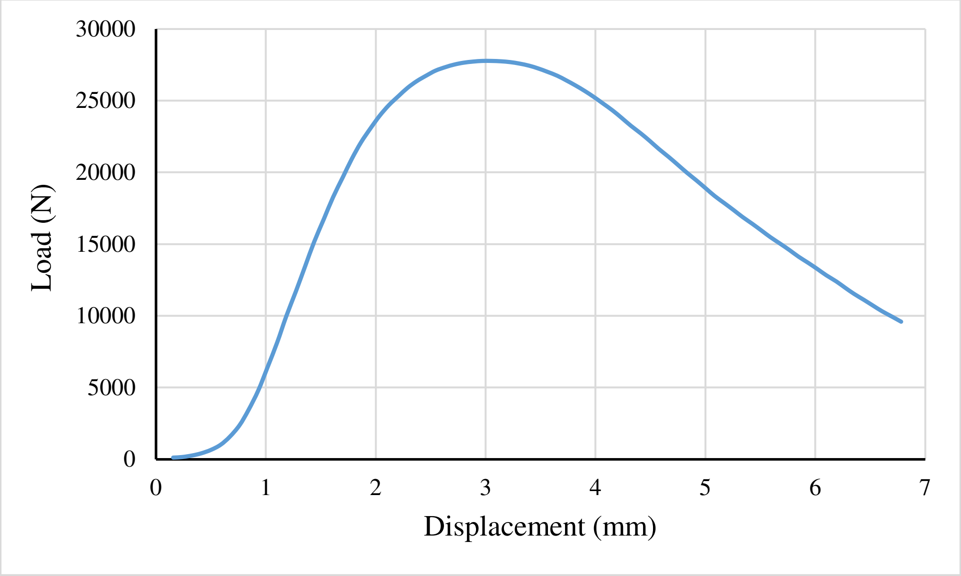


Figure 3-16: IDT Load-displacement curve

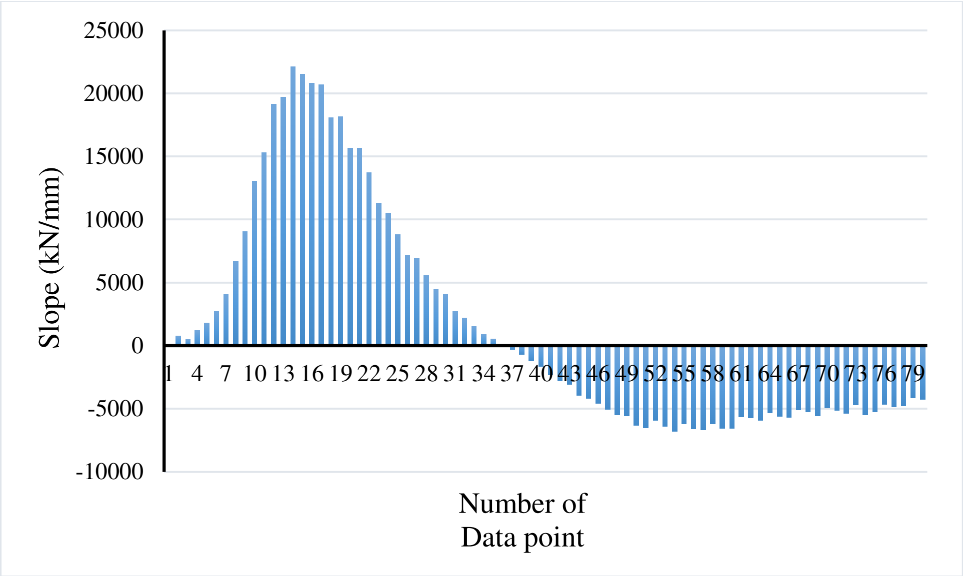


Figure 3-17: Slope of load-displacement IDT test

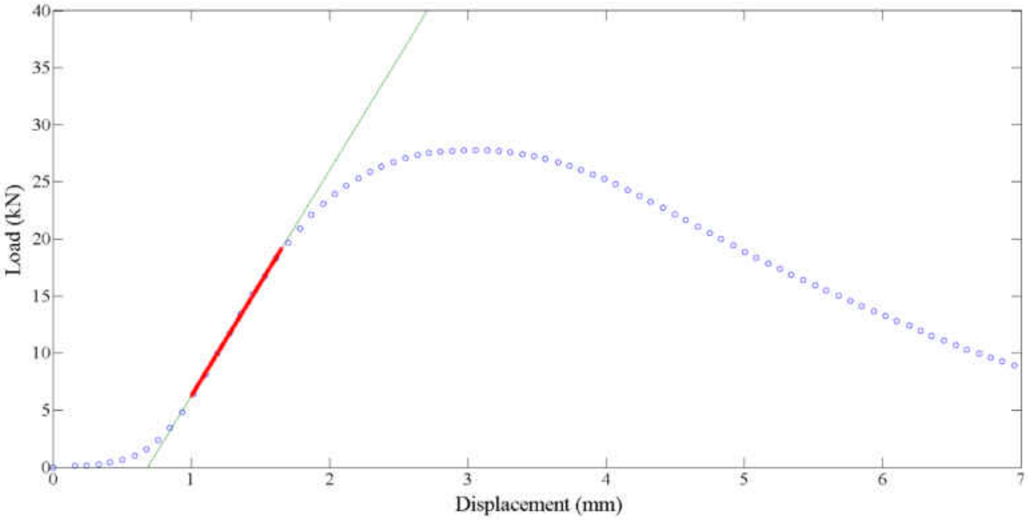
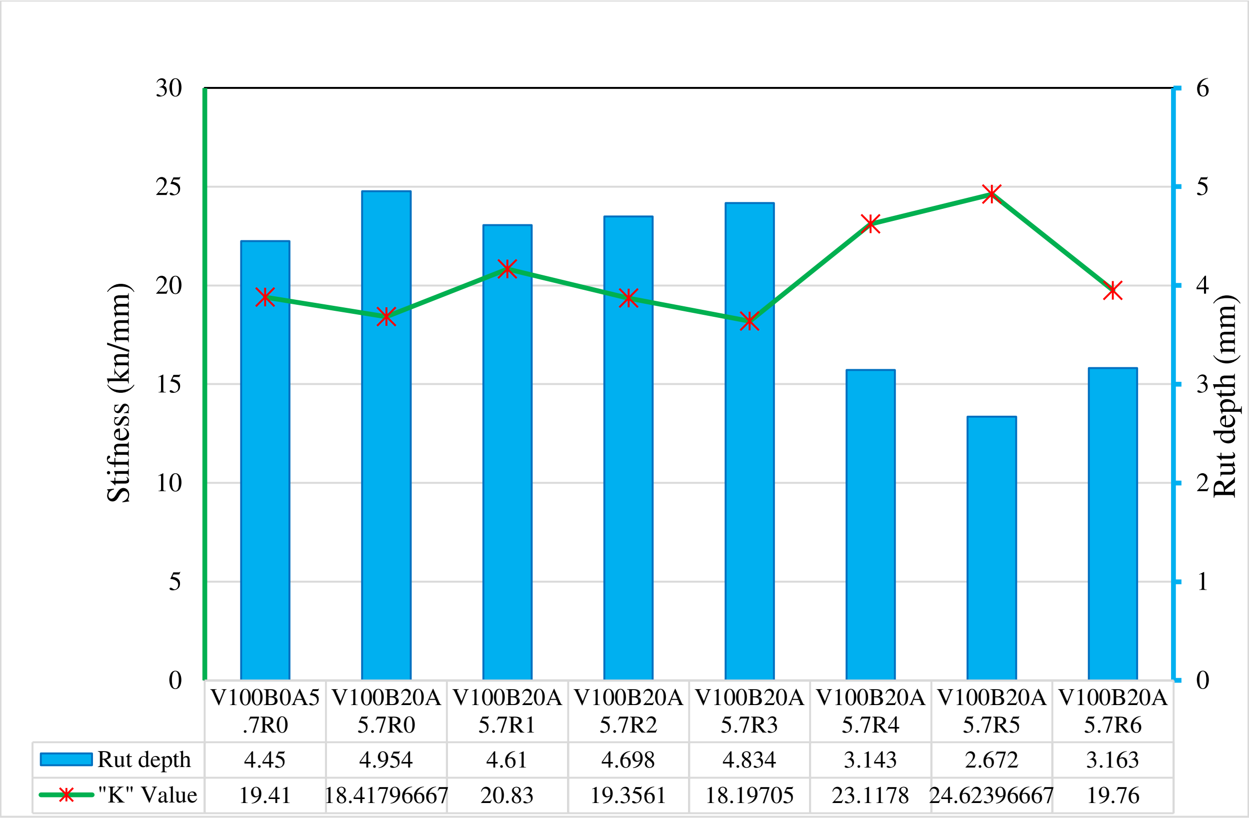


Figure 3-18: The best fit line representing linear behavior (Matlab output)

To better understand the correlation between rutting and "k" value, both testing results have been plotted in Figure 3-19. The higher “k” value the lower rut depth.



	V100B0A5.7R0	V100B20A5.7R0	V100B20A5.7R1	V100B20A5.7R2	V100B20A5.7R3	V100B20A5.7R4	V100B20A5.7R5	V100B20A5.7R6
Rut depth	4.45	4.954	4.61	4.698	4.834	3.143	2.672	3.163
"K" Value	19.41	18.41796667	20.83	19.3561	18.19705	23.1178	24.62396667	19.76

Figure 3-19. Rut depth

3.4.6.1 Pearson Correlation Coefficient

To verify the correlation (linear dependence) between the “K” value and the rutting results, Matlab 2013 has been employed to perform a statistical analysis by calculating the “Pearson product-moment correlation coefficient” (PCC). PCC is a measure of the linear correlation among two variables, giving a value between +1 and −1. The higher positive correlation represents the higher direct correlation, 0 is no correlation, and −1 is total negative correlation [*54*].

$$\rho_{X,Y} = \frac{\operatorname{cov}(X,Y)}{\sigma_X \sigma_Y}$$

Where:

- COV is the covariance
- σ_X is the standard deviation of X
- σ_Y is the standard deviation of Y

The calculated σ value for the data presented in Figure 3-19, is -0.82, which means there is a strong negative (reverse) correlation between two major HMA performance tests. This correlation provides researchers an idea in regards to performance estimation of the trial samples. Since rutting test-sample preparation is a time consuming work, measuring tensile strength (under dry condition) is faster and easier and can save time a lot.

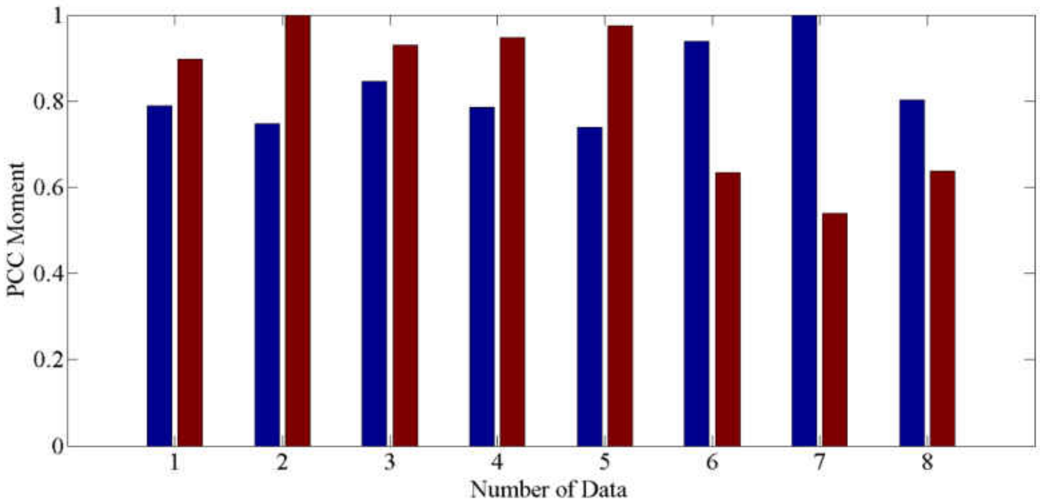


Figure 3-20. Pearson Correlation Coefficient between the rutting and “K” value

3.5 Failure Energy

The area under the load-displacement curve, can present the required amount of energy to fail the sample. As shown in Figure 3-21, failure means due to the monotonic loading the initiated crack, has been propagated through the entire specimen; thus no support for the additional load. Many parameters are involved like binder content, aggregate shape and angularity, aggregate gradation and mixture stiffness.

Hence the resistance to the failure is an important parameter in HMA service life, this has been used to predict the mixture service life in cost-benefit analysis section.

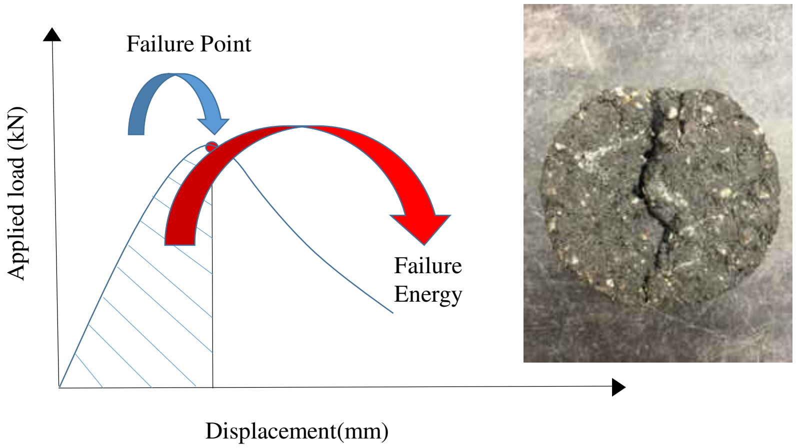


Figure 3-21. Failure Energy

3.6 Cost-benefit Analysis

3.6.1 *Overview*

The demand for pollution free, recyclable engineering materials has increased as the cost of energy and the environmental concern have risen. A large supply of material is required to construct a roadway. Materials can be used in creative ways to more effectively apply them. In

Europe and the United States, recycled construction materials are classified either industrial byproducts, road byproducts, or demolition byproducts ,depending on the type of material [*55*]. In an effort to save energy and natural resources, substituting virgin aggregate with recycled construction materials has become a new practice. Utilization of recycled material instead of virgin materials in road construction, saves landfill space, resources, and omit impacts associated with their extraction and transportation [*56*].

As mentioned earlier, the goal of this research is to design a sustainable HMA. A sustainable pavement which not only meets its engineering design requirements, but also meets human needs, uses materials efficiently, and prevents further harm to the environment. By definition, “sustainability” is a broad term; its meaning connotatively changes by content, and can therefore take on a variety of interpretations. For this reason, the word 'sustainability' is not constant and can change by pavement variation. Measuring pavement sustainability is helpful in quantifying, managing, and improving current practices. Three measurement methods are further explained in this text [*57*].

1. Performance assessment determines the overall pavement performance based on its original intention and the properties needed to meet its intention.
2. Life-cycle cost analysis (LCCA) uses economic principles to estimate the total cost of an investment during its life-cycle [*58*] . Despite the fact that a LCCA is not assessed for every investment, most state DOTs use LCCAs when deciding between pavement alternatives [*59*]. Many software tools can be used to help conduct a LCCA, however, the FHWA's

RealCost (FHWA 2011) is the most widely used [*57, 59*].

3. Life-cycle assessment (LCA) is used to gauge the impacts of a system or process on the environment. LCA is a dynamic field of study. Although a specific guideline for pavements is still being refined, the International Standards Organization (ISO) provides general advisement for LCA. Due to this, pavement LCA results generally differ among tools and studies. Thus, LCA results can be used to analyze improvements made to specific pavements, but cannot be relied on to compare pavement types [*57*].

In the previous sections, we evaluated the mechanical performances of the mixtures by trial samples which contained different recycled materials ratios. The samples which satisfying the design criteria and having higher performances were selected for environmental and economic impact evaluation. The Selected samples hereafter being called “Proposed Mixtures”. The aim of this section is to study the cost benefit impacts of the Proposed Mixtures using LCA and LCCA methods. In fact, these methods have been employed to evaluate the level of suitability.

3.6.2 *Life Cycle Assessment (LCA)*

Santero, 2009 and UCPRC 2010 [*60, 61*] described, six phases which are usually considered in a pavement's life-cycle when calculating sustainability analysis (Figure 3-22)

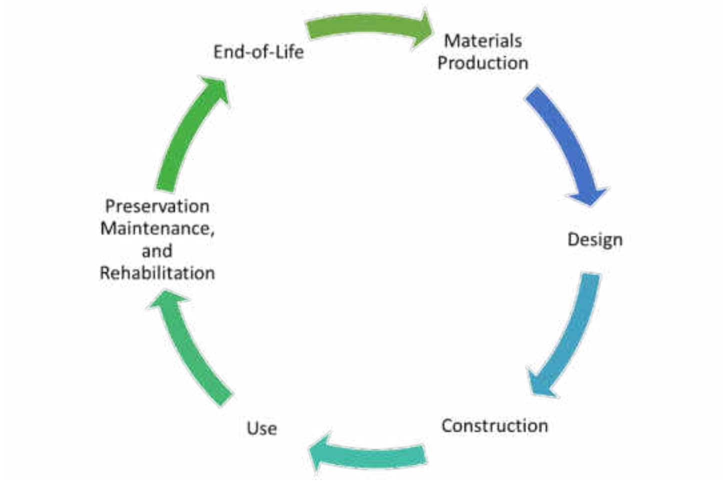


Figure 3-22: Pavement life cycle phases [*57*]

The overall sustainability of a system is dependent upon the energy used and the emissions from gathering, processing, transporting materials during construction [*62, 63*]. Pavement performance during the design phase is impacted by the materials used which influences the impacts during the use stage. Pavement sustainability in terms of material point of view usually involves:

- Substituting virgin materials with recycled or waste materials
- Improving mix design and the life-cycle of the pavement to decrease the need for virgin material
- Increasing efficiency and reducing emissions to reduce the effects of material production.

Typically, energy consumption and generated emissions in material's production stage, are consist of gathering and processing the materials as well as transportation to the plant or construction area. Pavement design is the process by which data is collected and analyzed to determine the proper materials and structure of the asphalt mix. Construction involves building the physical pavement systems, and includes both new structures and repaving of old pavements. The use phase accounts for the aspects of the pavement that affect automobile emissions, energy use, and the environment. The preservation, maintenance, and rehabilitation phase may aid in the prevention of deformation or may remedy existing defects. Finally, the end-of-life phase involves the reuse, processing, or recycling of pavement that can no longer be used [*57*]. LCA is used in different industries to evaluate the energy and emissions of different processes, such as in green energy [*64-66*].

Life cycle assessments have been used in the industries, and have extended the methodology into so called "green design" and "green engineering". In 2001, the Swedish Environmental Research Institute reported a broad study which considered a 40 year life cycle assessment to keep track of inventory [*67*]. In another study, Energy consumption, gas emission, and resources used for a 1 km road were accounted by using a procedure defined under the Society of Environmental Toxicity and Chemistry. According to the study, almost 23 trillion joules (TJs) of energy were consumed throughout the life cycle. While just in construction step, 8 TJs were consumed. During the operation service, which includes the lighting and traffic control, 12 TJs were consumed. Maintenance accounted for only 3 TJs.

Many industries use life cycle assessments to aid in the decision involving the choice of design and construction method, Figure 3-23 describes the general structure of the LCA methodology presented in ISO 14040 [*68, 69*]. This framework represent goal and scope definition, inventory analysis, impact assessment, and interpretation. Since the inventory analysis phase has been used in the industry for a long time, it is easy to find other data. As a result, inventory analysis is the least questioned phase of ISO 14040. Since the impact assessment phase utilizes an impact index that is calculated with a characteristic transformation or weighted multiplication, it is hard to analysis the results. Only experts on the environment are currently able to assess impact due to the complexity and time it takes [*68*].

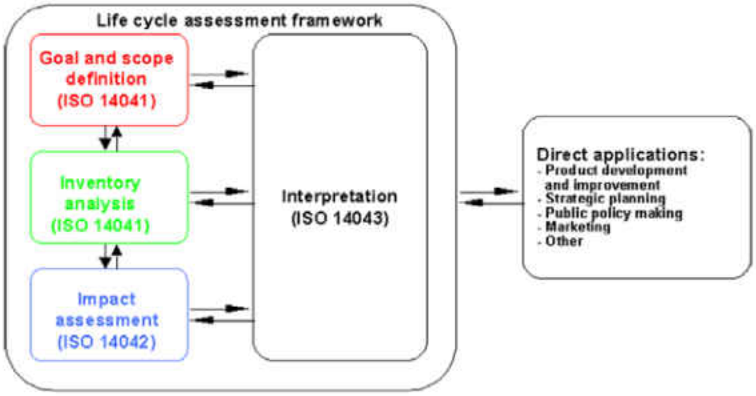


Figure 3-23. Life cycle assessment framework according to ISO 14040 [*68, 69*]

3.6.3 *Methodology of LCA Analysis*

A pavement LCA tool, Roadprint, is used to quantitatively evaluate the environmental impacts of a pavement project [*70*]. This tool applies the process-based LCA approach and contains an appropriate Life Cycle Inventory (LCI) database.

Roadprint is an Excel-based tool that was developed to establish an LCA framework and data inventory. This software helps to standardize pavement LCA's, conduct probabilistic analysis, and organize results to better understand LCA data.

Six pavement designs, 3 case studies, and four other pavement LCA tools were used to evaluate the usefulness of Roadprint. The study showed that:

- Roadprint is better than other tools in terms of scope, system boundary, and data quality, since it has the ability to evaluate different parameters according to project conditions.
- The environmental effects of pavement construction can be minimizing by improving the process of material production.
- The feedstock energy introduced separately, because it can increase energy consumption by two to three times.
- Comparing results from different LCA tools may be inaccurate due to the differences between tools.
- The scope, system boundary, and data quality of the LCA tool must be matched to the goal of the LCA comparison or accounting.

Roadprint system boundary is shown in Figure 3-24. In this LCA, the produced emissions as well as the energy and resources consumed are evaluated over the course of the project's entire life. In contrast, aggregate and bitumen are the material inputs; electricity is an energy input, but its production is not used in this study. Finally, the production of aggregate, binder, and HMA and the disposal of HMA are evaluated.

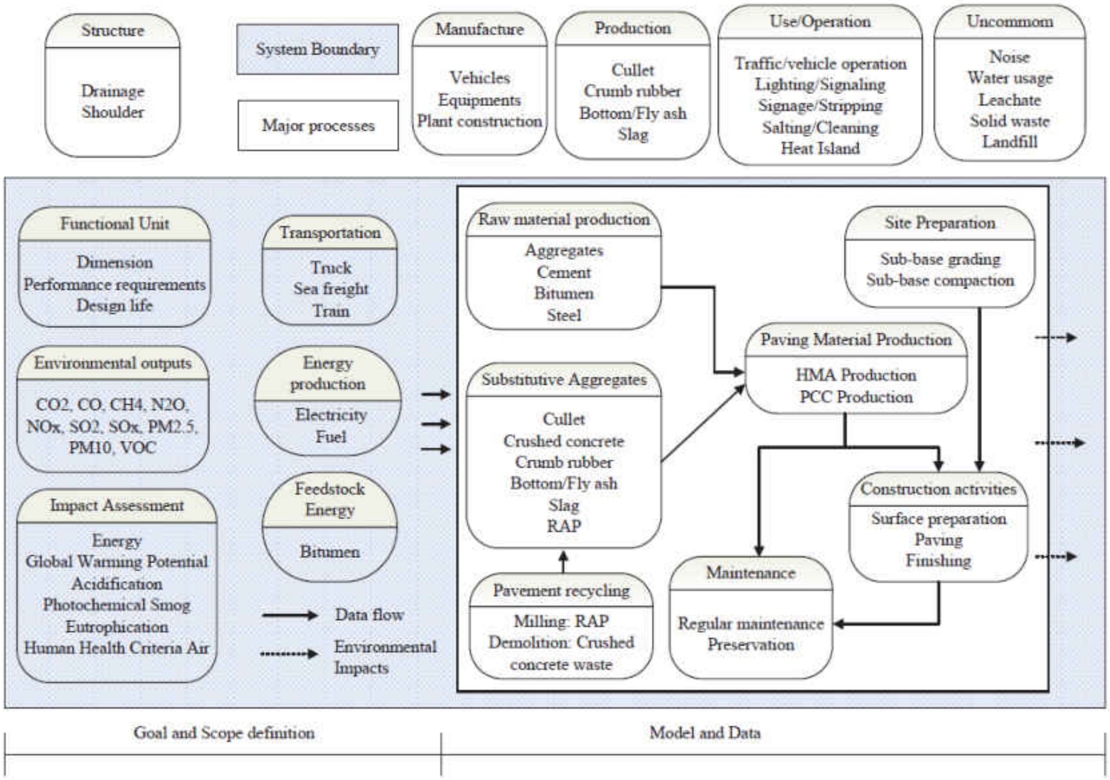
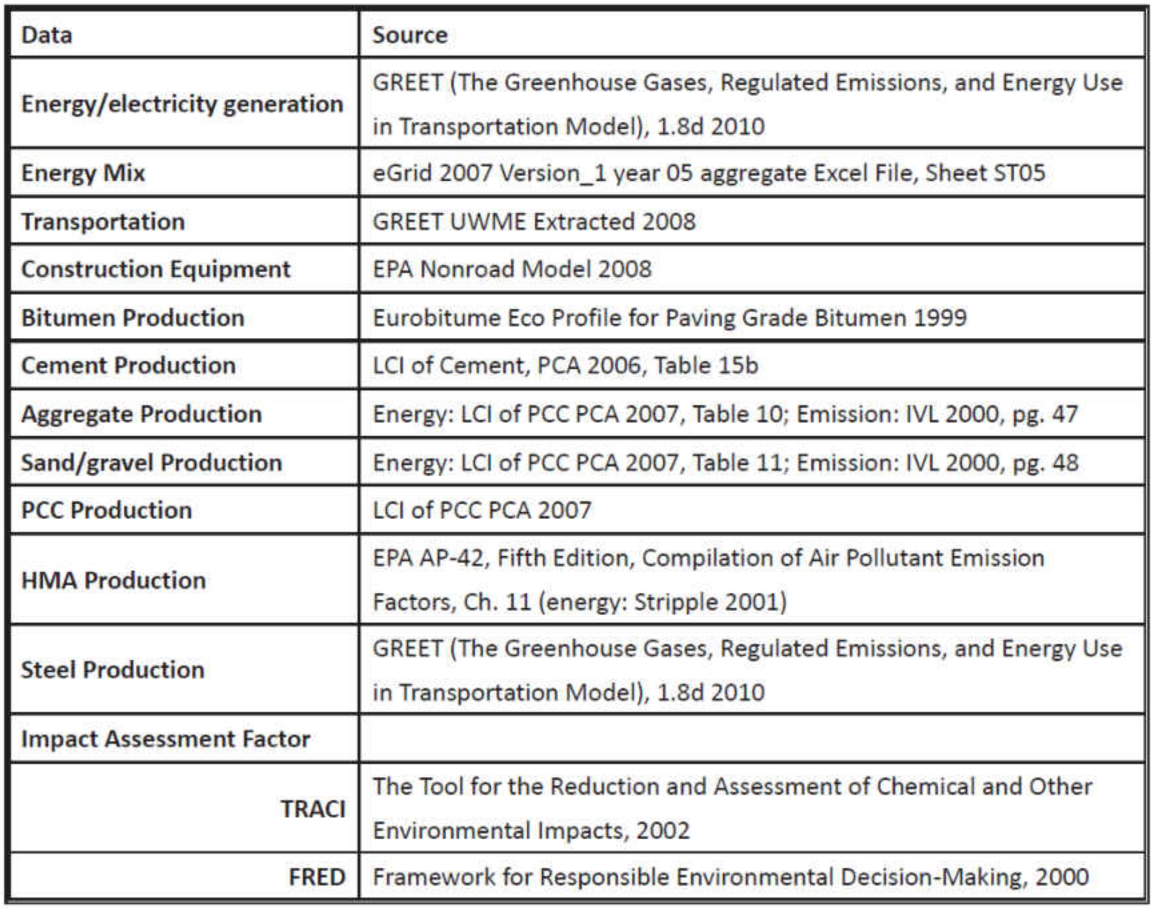


Figure 3-24. System boundary of Roadprint LCA model [*70*]

The major element in pavement’s construction sustainability analysis is data inventory, essentially for asphalt binder production; thus, the system boundary and different resources can significantly change the results. The assumed data quality score for the inventory in Roadprint as well as flow chart and system boundary for asphalt binder production are shown in Table 3-8 and Figure 3-25, respectively.

Table 3-8. Data quality score for the inventory in Roadprint [*70*]



Data	Source
Energy/electricity generation	GREET (The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model), 1.8d 2010
Energy Mix	eGrid 2007 Version_1 year 05 aggregate Excel File, Sheet ST05
Transportation	GREET UWME Extracted 2008
Construction Equipment	EPA Nonroad Model 2008
Bitumen Production	Eurobitume Eco Profile for Paving Grade Bitumen 1999
Cement Production	LCI of Cement, PCA 2006, Table 15b
Aggregate Production	Energy: LCI of PCC PCA 2007, Table 10; Emission: IVL 2000, pg. 47
Sand/gravel Production	Energy: LCI of PCC PCA 2007, Table 11; Emission: IVL 2000, pg. 48
PCC Production	LCI of PCC PCA 2007
HMA Production	EPA AP-42, Fifth Edition, Compilation of Air Pollutant Emission Factors, Ch. 11 (energy: Stripple 2001)
Steel Production	GREET (The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model), 1.8d 2010
Impact Assessment Factor	
TRACI	The Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts, 2002
FRED	Framework for Responsible Environmental Decision-Making, 2000

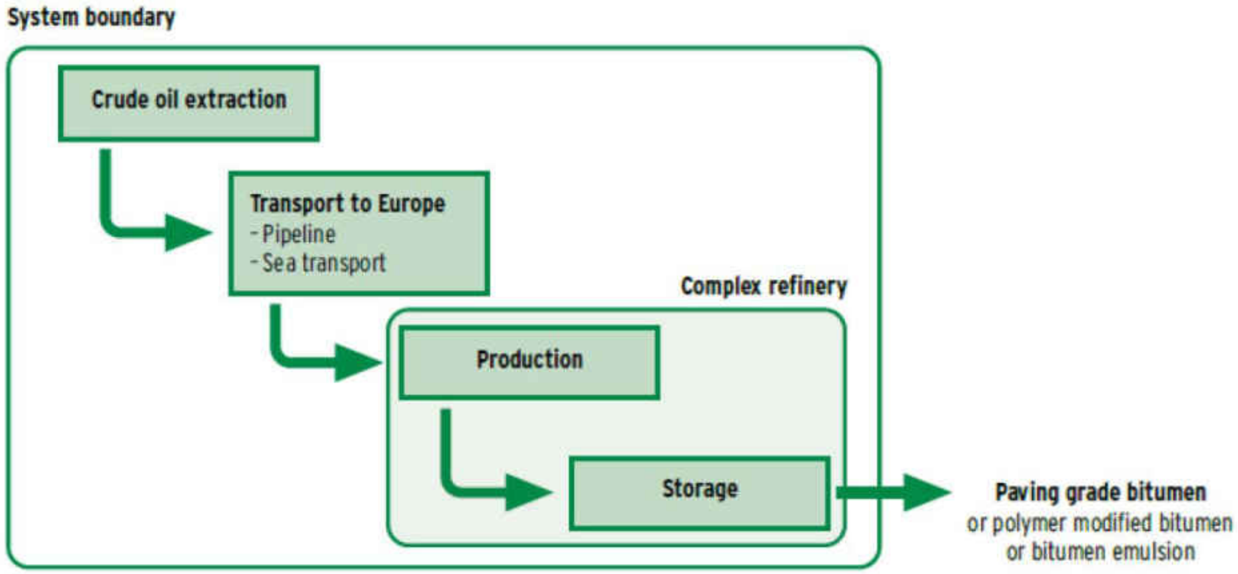


Figure 3-25. Flow chart and system boundary for bitumen[*70*]

System boundary of the current study is shown in Figure 3-26. Material production including mining and processing for virgin aggregate and feed stock energy for binder have been considered. All transportation from production to the process factory as well as HMA plant and construction place are part of the scopes. As shown, Tack coat and fuel production have not been considered.

BA and RAS are by-products of particular manufacturing procedures, so the energy inputs and emission outputs can be theoretically accounted for that main product. Therefore, these two materials can be viewed as "free products," which act as a zero process (no energy inputs are required and no emissions are generated for their production) in the LCA calculation.

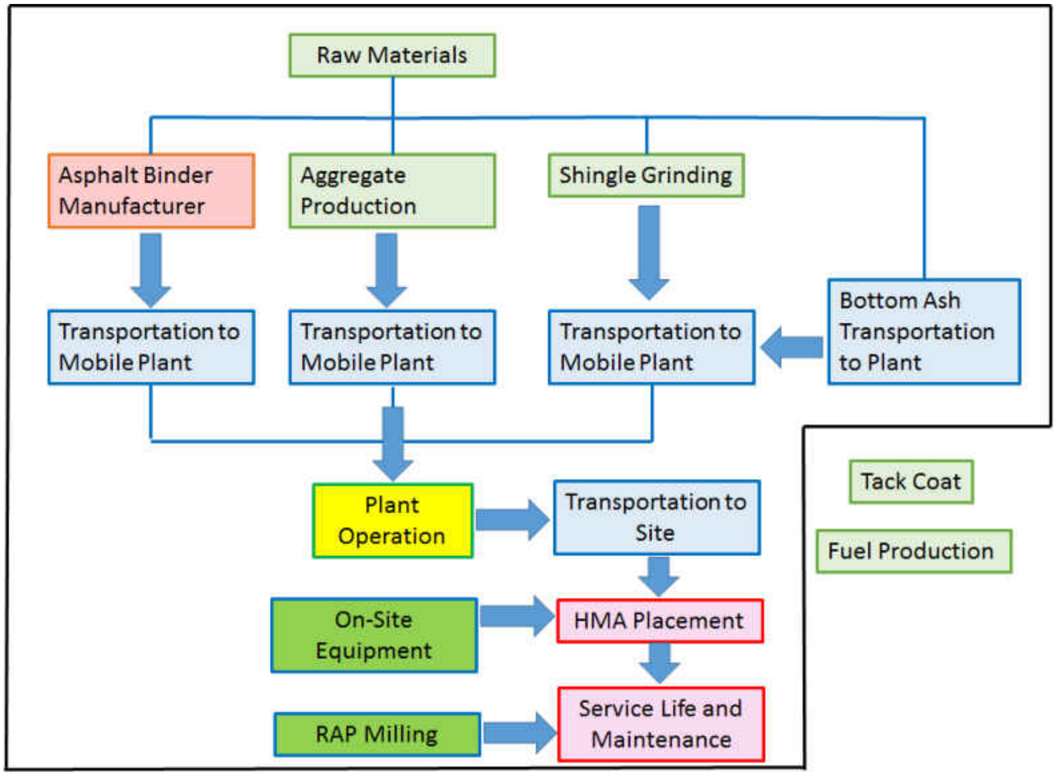


Figure 3-26. LCA system boundary

3.6.4 *Determination of the Service Life for the Proposed Mixtures*

Maintenance is a part of keeping pavements in full service. This preservation depends on the materials quality, traffic volume, climate conditions, pavement design and many other parameters; the service life might be varied from one pavement to another. Typically, after certain number of maintenances, the road needs to be reconstructed because the maintenance will be unable to keep the road in full service. In this study, in all scenarios the HMA with different recycled materials is considered as an overlay with 2 in. thickness. In addition, the service life of the HMA with virgin materials and pavement life time assumed to be 5 and 20 years, respectively.

Currently, there are no field data avaible to be implemented as the overlay service life with the used materials; thus, the laboratory testing results have been employed to estimate the overlay service life and maintenance frequency in the defined life time period. IDT strength, rut depth and fracture energy, as main representative of HMA cracking and deformation with linear and variable impact assessment deliberated to construct the service life (Table 3-9). It was assumed to be a linear relationship between the factors (test results) and the responses (service life); however, some other researchers reported a non-linear relation Figure 3-27. Although this assumption may affect the calculation values, but as comparing the alternative all scenarios will be affected the same.

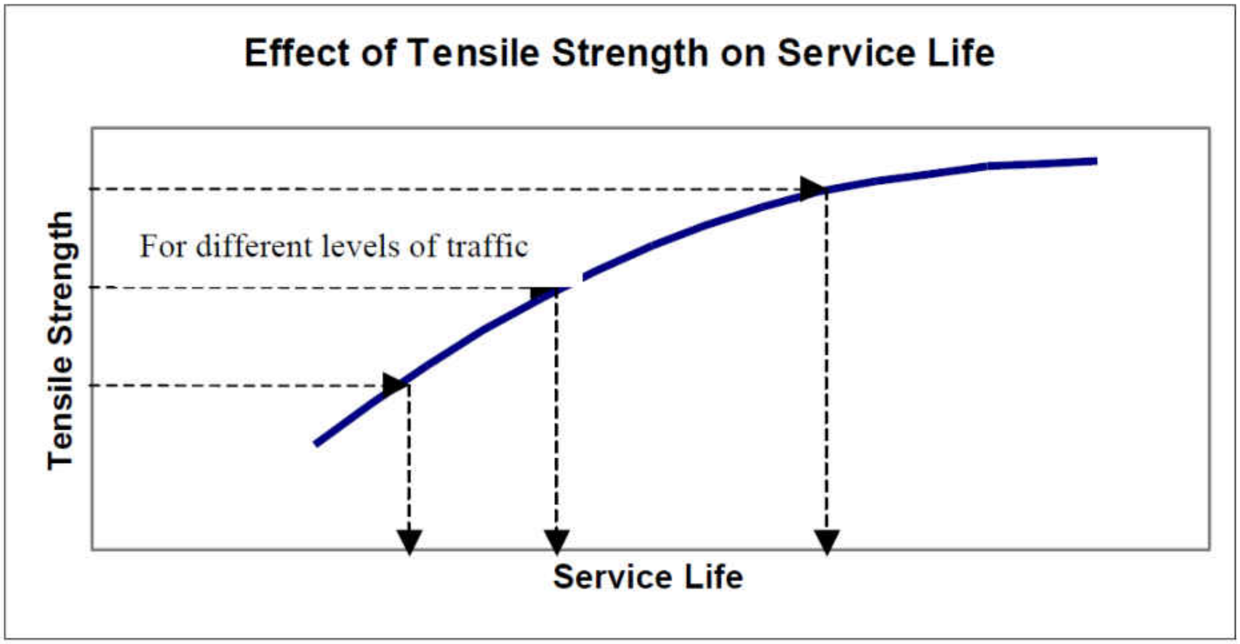


Figure 3-27. Typical Relationship between Tensile Strength and Service Life [*71*]

Table 3-9. Estimated service life

Sample codes	IDT strength (kPa)	Rut Depth (mm)	Fracture Energy (N.mm)	Service Life (yrs.)
Impact Assessment	30%	40%	30%	100%
V100B0A5.7R0	1432.44	4.45	15640.37	5
V100B20A5.7R0	1719.95	4.954	14874.20	4.68
V100B20A5.7R5	2228.95	2.672	17348.68	6.46
V100B20A6.8R0	1984.62	3.446	17747.5	6.32

3.6.4.1 Data Interpretation

Assuming the thickness of the asphalt overlay is 2 in. and the service life is 5 years, the pavement description for four proposed mixtures as alternatives are presented in Table 3-10.

Table 3-10. Pavement description

Sample code	Length (mi)	Width (ft)	Surface Depth (in)	Base Depth (in)	RAP Removal (in)	Density (ton/m^3)	Overlay Mass (tons)	Maintenance Frequency
V100B0 A5.7R0	1	12	2	0	2	2.19	662.46	4
V100B20A5.7R0	1	12	2	0	2	2.11	638.26	4.27
V100B20A5.7R5	1	12	2	0	2	2.17	656.41	3.09
V100B20A6.8R0	1	12	2	0	2	2.15	650.36	3.16

Materials contained in surface layer as well as transportation to the HMA plant are listed in Table 3-11.

Table 3-11. Materials Contained in surface layer

Sample code	Material	% of mix by weight	Front haul Transport (ton truck)	Front haul Distance (mi)	Backhaul Transport (ton truck)	Backhaul Distance (mi)
V100B0 A5.7R0	VA	94.3	20	30	20	30
	Binder	5.7	20	50	20	50
V100B20A5.7R0	VA	84.3	20	30	20	30
	Binder	5.7	20	50	20	50
	BA	10	20	30	20	30
V100B20A5.7R5	VA	84.3	20	30	20	30
	Binder	5.7	20	50	20	50
	BA	10	20	30	20	30
	RAP	0	20	30	20	30
V100B20A6.8R0	VA	83.2	20	30	20	30
	Binder	6.8	20	50	20	50
	BA	10	20	30	20	30

HMA paver, Grader and HMA pavement milling are the typical necessary pavement equipment, which were considered in the construction stage. The properties and assumed parameters are listed in Table 3-12.

Table 3-12. Initial Construction Equipment (Grader)

Sample code	Working Time (%)	Efficiency Factor (%)	Production Rate (ft/min)	Moldboard Width (ft)	Overlap (in)	Passes	Engine Horsepower (hp)
All scenarios	25%	85%	300	12	12	2	175

Table 3-13. Initial Construction Equipment (HMA paver)

Sample code	Working Time (%)	Efficiency Factor (%)	Production Rate (ft/min)	# of lifts	Paving Width	Engine Horsepower (hp)
All samples	100%	85%	35	1	12	175

Table 3-14. Initial Construction Equipment (HMA Pavement Milling)

Sample code	Working Time (%)	Efficiency Factor (%)	Production Rate (ton/hr)	Engine Horsepower (hp)
All samples	50%	60%	600	750

Table 3-15. Initial Construction Equipment (HMA Plant)

Sample Code	Supply Rate (ton/hr)	Fraction of HMA supplied (%)	Distance to site (mi)	Wait Time At Plant (min)	Wait Time At Sites (min)	Avg Haul Speed (mph)
All samples	200	50	10	10	10	50

Table 3-16. CO2 emission for Initial construction stage

Initial Construction(*)						
Sample code	VA. Production	Binder Production	VA. Transportation	Binder Transportation	BA Transportation	RAS Transportation
V100B0A5.7R0	1.393	11.983	4.660	0.469	0.000	0.000
V100B20A5.7R0	1.245	11.983	4.166	0.469	0.494	0.000
V100B20A5.7R5	1.245	11.983	4.166	0.469	0.494	0.247
V100B20A6.8R0	1.229	14.296	4.111	0.560	0.494	0.000

*. All units are (ton/lane mile)

Table 3-17. CO2 emission for a 20-year maintenance

Maintenance (*)						
Sample code	VA Production	Binder Production	VA Transportation	Binder Transportation	BA Transportation	RAS Transportation
V100B0A5.7R0	5.573	47.932	18.639	1.878	0.000	0.000
V100B20A5.7R0	5.337	51.167	17.851	2.004	2.110	0.000
V100B20A5.7R5	3.848	37.027	12.872	1.451	1.527	0.763
V100B20A6.8R0	3.884	45.174	12.992	1.770	1.562	0.000

*. All units are (ton/lane mile)

Table 3-18. CO2 emission by asphalt plant and equipment for initial construction and maintenance period

Sample code	Asphalt Plant		Equipment		BA saving credit	RAS saving credit
	Production	Transportation	Initial Construction	maintenance		
V100B0A5.7R0	13.736	0.824	0.675	2.698	0.000	0.000
V100B20A5.7R0	13.186	0.791	0.648	2.765	-0.552	0.000
V100B20A5.7R5	13.598	0.815	0.668	2.852	-0.552	-0.116
V100B20A6.8R0	13.461	0.807	0.661	2.823	-0.552	0.000

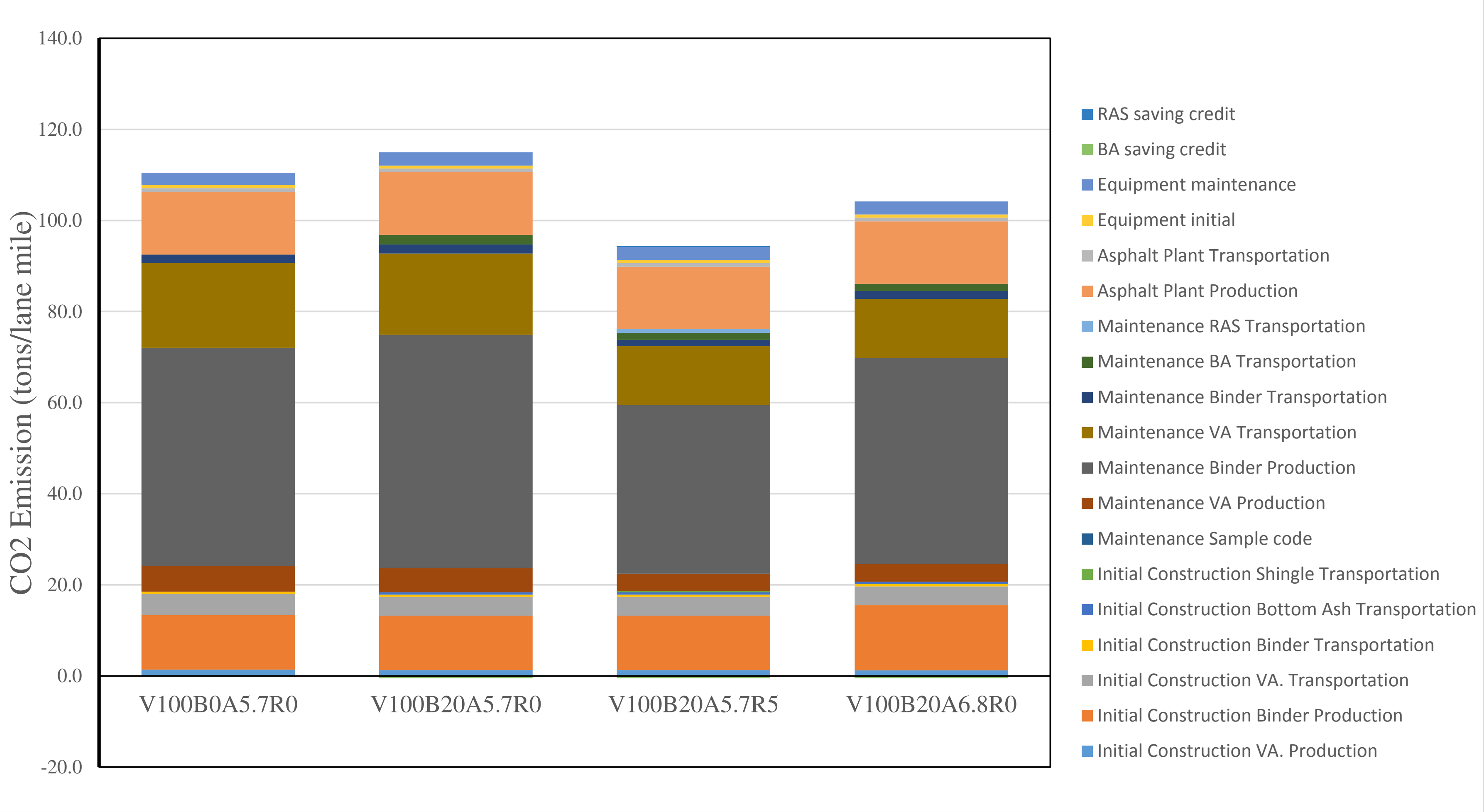


Figure 3-28. Total CO2 generated for initial construction and a 20 year maintenance period

As shown, in a period of 20 yrs., the total CO2 generated by construction and maintenance of the HMA “V100B20A5.7R5” is 15.5 % less than a HMA with virgin materials. Nevertheless, the initial construction emission of HMA “V100B20A5.7R0” is 1% less than a control HMA but due to a more maintenance frequency in a period of 20 yrs., generated emission turns into 3% more than the control HMA. The only parameter that plays a big role in the scope of this study, is the asphalt binder for the maintenance period; thus, it is recommend for the future studies to invest more how to minimize the a ratio of virgin binder by increasing the RAS percentage in the mixture. As denoted in the mechanical characterization of the alternatives, increasing RAS ratio has another side effects which makes the analysis more complicate; hence, changing the mix design criteria (e.g. gradation limits) seems to be helpful.

The reduction of CO2 emission by substituting virgin aggregates with BA in not noticeable in initial construction stage; however in a maintenance period the reduction is 3.6%.

Table 3-19. Energy consumption for the initial construction stage

Maintenance (*)							
Sample code	VA Production	Binder Production	VA Transportation	Binder Transportation	BA Transportation	RAS Transportation	Feedstock Energy
V100B0A5.7R0	35.369	200.404	59.736	6.018	0.000	0.000	1743.262
V100B20A5.7R0	31.619	200.404	53.402	6.018	6.335	0.000	1743.262
V100B20A5.7R5	31.619	200.404	53.402	6.018	6.335	3.167	1743.262
V100B20A6.8R0	31.206	239.082	52.705	7.179	6.335	0.000	2079.708

*All units are (Gj/Lane mile)

Table 3-20. Energy consumption for a 20-year maintenance period

Maintenance (*)							
Sample code	VA Production	Binder Production	VA Transportation	Binder Transportation	BA Transportation	RAS Transportation	Feedstock Energy
V100B0A5.7R0	141.476	801.618	238.944	24.071	0.000	0.000	6973.049
V100B20A5.7R0	135.491	855.727	228.836	25.696	27.050	0.000	7443.729
V100B20A5.7R5	97.701	619.250	165.012	18.595	19.575	9.787	5386.680
V100B20A6.8R0	98.611	755.499	166.548	22.686	20.018	0.000	6571.877

*All units are (Gj/Lane mile)

Table 3-21. Energy consumption by HMA plant and equipment for initial construction and maintenance period

Sample code	Asphalt Plant		Equipment	
	Production	Transportation	initial	maintenance
V100B0A5.7R0	227.476	10.558	7.789	31.156
V100B20A5.7R0	227.476	11.270	8.314	33.259
V100B20A5.7R5	175.725	8.156	6.017	24.068
V100B20A6.8R0	179.706	8.340	6.153	24.613

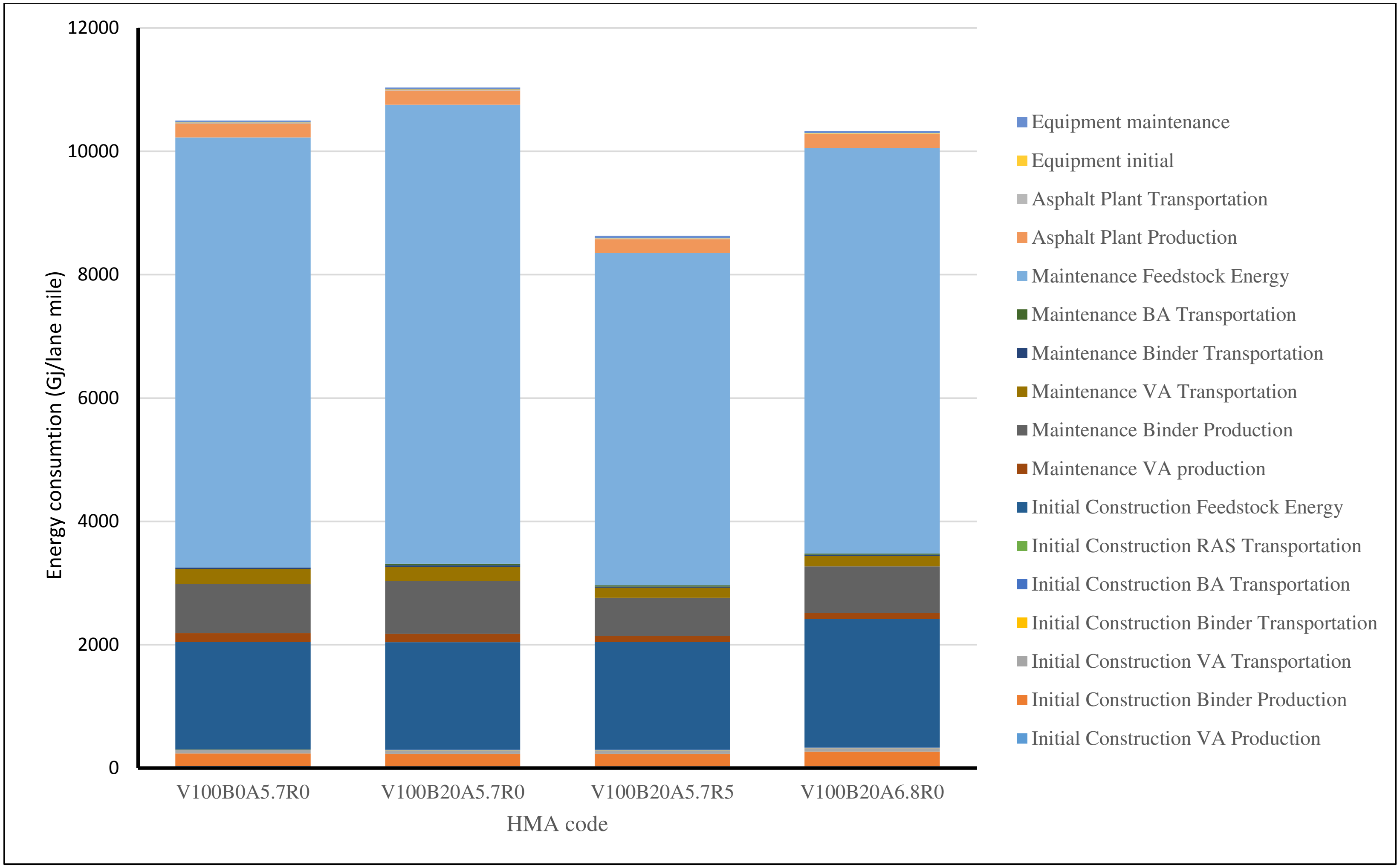


Figure 3-29. Total Energy consumption for construction and maintenance for a 20 year

As shown in Figure 3-29, the amount of energy consumption will be different using different materials. The energy consumption decreases from 10500 Gj/lane mile to 8574 Gj/lane mile in a life cycle (20 years) by replacing 20 percent of virgin aggregated with bottom ash as well as adding 5 percent RAS to the HMA. The decrease occurs mainly in the maintenance phase of binder production under feed stock energy and little or no change occurs in the operation and equipment. The reduction of energy consumption is not noticeable by switching from the HMA with all virgin materials (V100B0A5.7R0) to the HMA with just replaced BA but more asphalt binder (V100B20A6.8R0).

The inclusion of feedstock energy within the LCA structure is evidently ascertained by the ISO 14044 standards. Asphalt binder is a hydrocarbon with a significant amount of feedstock energy, so it falls under the ISO 14044 commission [*60*].

The feedstock energy is often excluded in LCAs since it is fundamentally an accounting number and not a truthful expectation that the asphalt binder will be burned for fuel in the future. For this reason, the better LCAs usually show what it is but separate it from the other energies so the user can choose whether to include/exclude it [*60*].

3.6.5 *Life Cycle Cost Analysis (LCCA)*

LCCA is a method used to make long-term investment decisions considering cost effectiveness. During the LCCA, all of the costs associated with a project are considered, not just the initial cost but the likely future costs associated with a project over time. This tool is effective in conveying multiple scenarios of alternative investment to decision makers [*72-74*] . The LCCA is defined in Section 303 of the National Highway System Designation Act of 1995 as " (The) process for evaluating the total economic worth of a usable project segment by analyzing initial costs and discounted future costs, such as maintenance, reconstruction, rehabilitation, restoring, and resurfacing costs, over the life of the project segment (NHS 1995)".

The Federal Highway Association (FHWA) advocates the use of a life-cycle cost assessment to help choose a cost-effective project alternative and to help convey the benefits of the alternative chosen to the public [*75*]. The FHWA's Life-Cycle Cost Analysis in Pavement Design – Interim Technical Bulletin details the procedure for conducting LCCA of pavement projects. LCCA incorporates discounted long-term agency cost, user cost, other cost, and performance period [65]. The discount rate used for an LCCA can have a significant influence on the final results; an acceptable discount rate for LCCA ranges from 3 - 5% [*76*]. The user costs are those that are incurred by users traveling on a highway because of detours during construction of projects. Similar costs between alternatives should not be used for LCCA calculations because they will cancel out each other in LCCA calculations, but should be mentioned in the text.

In this study, an excel base LCCA tool has been developed to convey the cost effectiveness analysis at both initial construction and 20 years maintenance period. The scope of this analysis will be the same as Figure 3-26.

All costs are based on 2014 dollars. The presented prices are the average of different states. Due to a varied range in the asphalt binder cost and land filling tipping fee, Monte Carlo simulation has been employed to reflect the uncertainty on the data.

Table 3-22. LCC components based on 2014 prices

LCC Components	Unit	Value	Reference
Virgin Aggregate	$ / ton	$50	[*77*]
Asphalt Binder	$/ ton	$505 - $697	[*78-80*]
Trucking	$/ ton / mile	$0.13	(Horvath 2004)
Tipping Fee	$ /ton	$24.3 - $91	[*81*]
Shingle Grinding	$ /ton	$14.80	[*82*]
Asphalt Inflation Rate	% / year	%1.1	[*83*]
Trucking Distance [Mine to Plant]	Miles	30	
Trucking Distance [Refinery to Plant]	Miles	50	
Trucking Distance [Plant to Site]	Miles	10	

3.6.5.1 Monte Carlo Simulation

LCA analysis require comprehensive data collection phase in order to consider all related products or services. However, it is common to gather ranges for some of the related products in LCA analysis. In order to overcome this issue, Monte Carlo simulation is widely used with LCA and LCC analyses in literature such as in green power [*84*], sustainable transportation [*85*], and sustainable pavement design [*86*] and other aspects in civil engineering [*87-89*]. Since Monte Carlo simulation use probabilistic method for accounting uncertainty on data, LCA and LCC analyses results could be presented with point values with variable distribution. Hereby, LCCA results could be presented with a range, instead of certain points. Finkel (1995) [*90*], McCleese and LaPuma (2002) [*91*], and Peters (2007) [*92*] are some of key literature that is used Monte Carlo simulation on LCI data. Especially, McCleese and LaPuma's studies are a supportive reference to highlight the importance of uncertainty on LCI data for electric vehicles. For pavement design's LCC analysis there are two components that have ranges for price information such as asphalt binder and tipping fee. Asphalt binder's role is more significant than other pavement components due to cost intensive. Asphalt binder's cost also fluctuates with petroleum barrel prices and regions. Moreover, tipping fee also highly varies for each region, county, and state. Therefore, asphalt binder's monthly and state based prices and tipping fee's state based prices are normally distributed and calculated the overall LCCA results (Figure 3-30 and Figure 3-31).

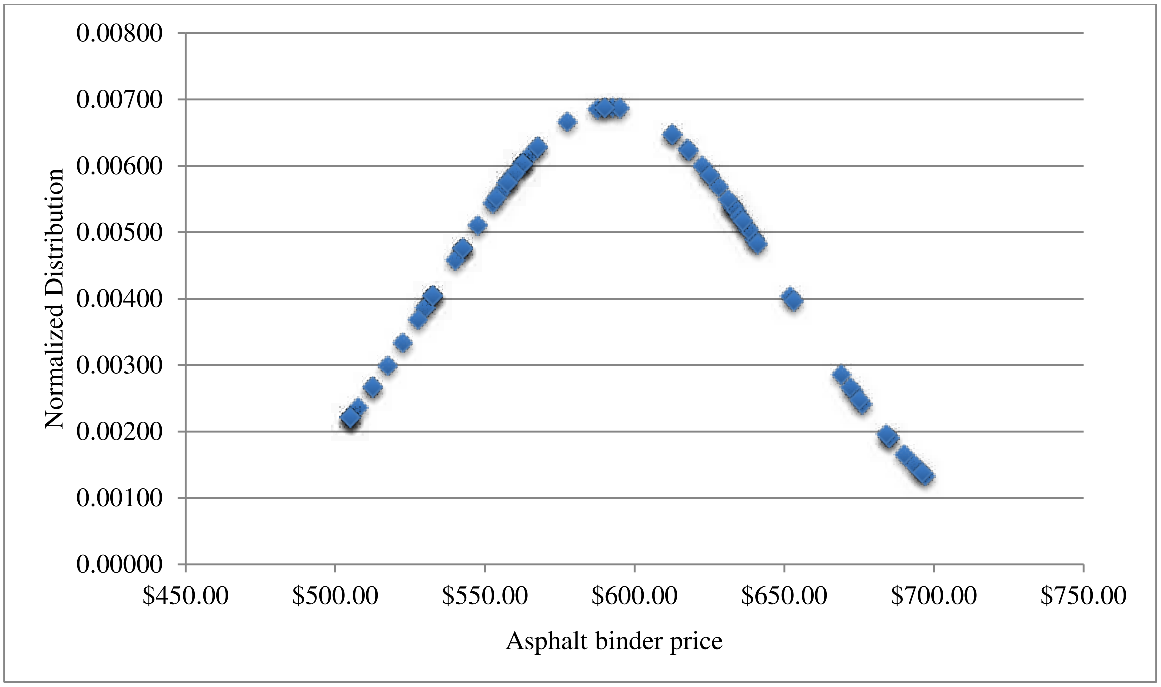


Figure 3-30. Binder cost distribution

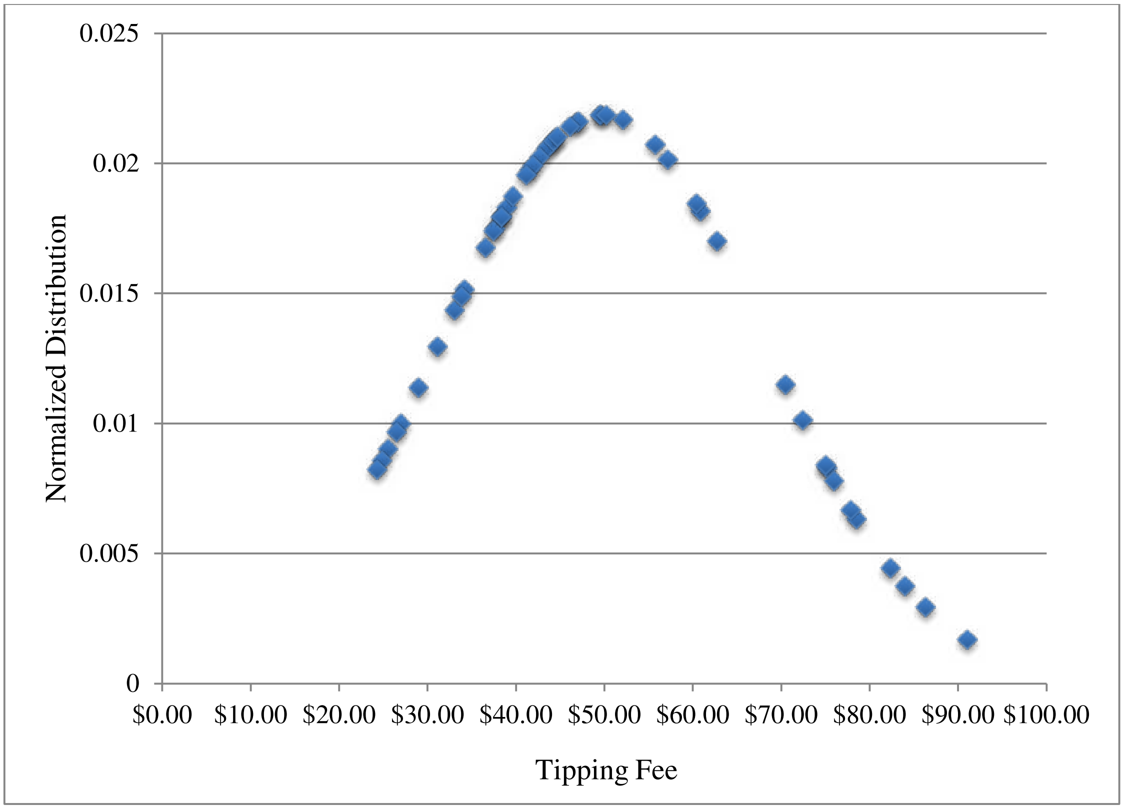


Figure 3-31. Tipping fee distribution

3.6.5.2 Annual Escalation Rate of Asphalt Construction Cost

Part of the LCC analysis, maintenance expenditures should be calculated for future years. However, for 20 years of life span, the maintenance costs will be changing based on inflation of relative materials or services. Lindsay et al. [*83*] investigated the construction material's cost projection based on inflation and volatility. Lindsay et al.' study [*83*] consists of major construction materials' cost data from Bureau of Labor Statistics, which could allow them to analyze these historical data in order to project annual escalation rate of prices in next 50 years. Monte Carlo simulation method is utilized so the uncertainties and volatilities on historical prices could be minimized. Based on these calculation steps, annual mean cost escalation rate for asphalt is determined as 1.01%. Hereby, this average rate could be utilized on maintenance cost of this study's pavement scenarios, annually. In other words, this study's results present total LCC analysis results in 2014 dollars while considering the increase of cost in next 20 years for maintaining pavements.

Table 3-23. Cost calculations for the proposed mixtures

HMA Code			**V100B0A5.7R0**	**V100B20A5.7R0**	**V100B20A5.7R5**	**V100B20A6.8R0**
Initial Construction		VA Cost	$31,234.90	$26,902.61	$27,667.61	$27,054.91
		Binder Cost	$22,318.57	$21,503.28	$22,114.75	$26,139.35
	Transportation	VA Trucking	$2,361.36	$2,033.84	$2,091.67	$2,045.35
		BA+RAS Trucking	$0.00	$241.26	$372.18	$245.84
		Binder Trucking	$237.89	$229.20	$235.72	$278.61
		Plant to Site Trucking	$834.70	$804.21	$827.07	$819.45
		BA Cost	$0.00	$3,132.30	$3,221.37	$3,191.68
		RAS Cost	$0.00	$0.00	$1,124.94	$0.00
Maintenance		VA Cost	$141,954.84	$130,230.01	$92,178.73	$98,178.53
		Binder Cost	$101,432.33	$104,092.97	$78,324.10	$94,856.07
	Transportation	VA Trucking	$10,731.79	$9,845.39	$6,968.71	$7,422.30
		BA+RAS Trucking	$0.00	$1,167.90	$1,318.17	$892.10
		Binder Trucking	$1,081.14	$1,109.50	$834.84	$1,011.05
		Plant to Site Trucking	$3,793.49	$3,893.00	$2,929.26	$2,973.68
		BA Cost	$0.00	$15,162.81	$11,409.16	$11,582.16
		RAS Cost	$0.00	$0.00	$3,984.22	$0.00

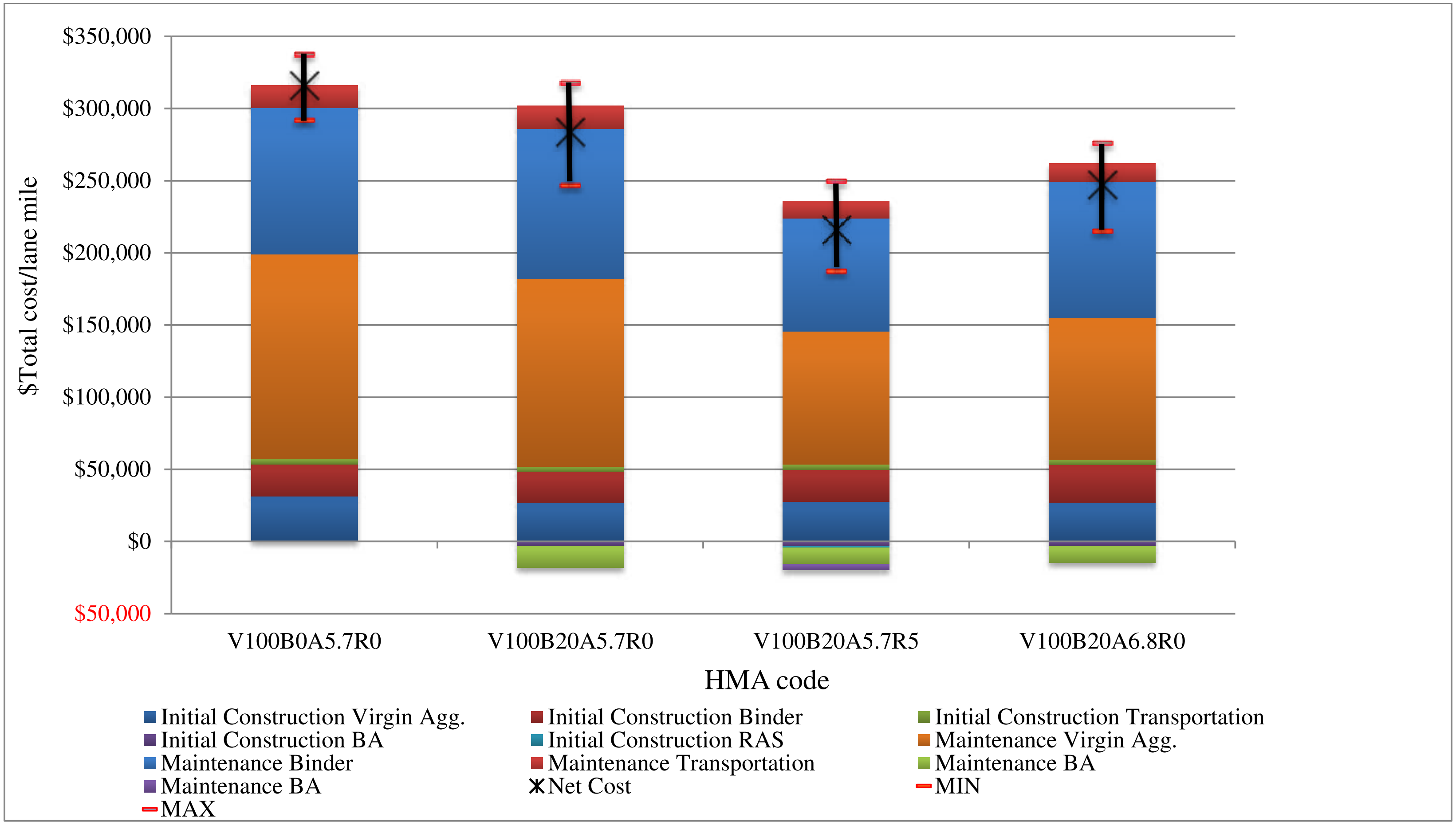


Figure 3-32. Total cost/lane mile for initial construction and maintenance in a 20 year period

The cost analysis was accomplished by calculating the savings of implemented BA and RAS in each 4 case scenarios. Taking into the difference in service life with different material, affects the amount of required material for the pavement life time.

The total cost of the virgin and recycled materials used are evaluated based on the assumption of a one-lane road in a mile as an overlaying of 2 inches in a different maintenance frequency for a period of 20 years. The total volume of the assumed pavement overlay is 302.49 (m^3). This volume accounted the same for all the scenarios. The calculated density and materials mass are presented in Table 3-10. The quantities of the recycled and virgin materials required for the asphalt pavement can be found based on the mix design.

It must be noted that, RAS and BA accounted as by products materials; thus, no cost associated with their production. However, landfilling tipping fees related to the aforementioned recycled materials, considered in the analysis. In contrast with the LCA results, the influence of virgin aggregate production cost is more than asphalt binder in the maintenance stage. Overall, the net cost for the construction and maintenance of an overlay with HMA “V100B20A5.7R5” is 46% cheaper than HMA with virgin materials. This huge decrement in costs indicates the potential of saving millions of dollars annually in pavement construction.

3.7 Summary and Conclusion

This study explored the beneficial utilization of MSWI BA and RAS in HMA. MSWI BA and RAS were used as fine aggregate replacement and additive in HMA, respectively. Performance evaluation and cost-benefit analysis on HMA including MSWI BA and RAS were conducted. The performance evaluation includes Marshall Stability, indirect tensile strength, and moisture susceptibility tests and the cost-benefit analysis which includes both LCA and LCCA. Conclusions drawn from the laboratory experiments and the LCA and LCCA are summarized below.

- When MSWI BA are used as fine aggregate replacement in HMA, 20% replacement ratio is recommended because this proportion exhibited the highest stability (or strength) and moisture resistance. However, the higher absorption capacity of MSWI BA, requires higher optimum binder content compared with the control (HMA with limestone aggregate).
- RAS was used to overcome the limitation of the higher optimum binder content with MSWI BA. In HMA, including MSWI BA (fixed at 20%) and RAS, as the RAS addition increases, the strength increases, exhibiting the highest strength at 5% RAS. All mixes, including RAS, exhibit higher strength than the control.
- The rutting test results indicated that there is a reverse correlation between effective asphalt binder and resistance to the permanent deformation. Samples with the amount of binder less than OAC, showed higher rut depth. Although, adding RAS increases the mixture stiffness; meanwhile, the excess amount of RAS filler may facilitate increasing plastic deformation; thus, increasing rut depth.

- The amount of energy consumption will be different using different materials. The energy consumption decreases from 10500 Gj/lane mile to 8574 Gj/lane mile in a life cycle (20 years) by replacing 20 percent of virgin aggregate with bottom ash as well as adding 5 percent RAS to the HMA. The decrease occurs mainly in the maintenance phase of binder production under feed stock energy and little or no change occurs in the operation and equipment. The reduction of energy consumption is not noticeable by switching from the HMA with all virgin materials (V100B0A5.7R0) to the HMA with just replaced BA but more asphalt binder (V100B20A6.8R0).
- Due to the large portion of aggregate in HMA, considering a life time in service period, the impact of virgin aggregate production cost is more than asphalt binder in the maintenance stage. Overall, the net cost for the construction and maintenance of an overlay with HMA "V100B20A5.7R5" is 46% cheaper than HMA with virgin materials.

CHAPTER 4: UTILIZING MULTIPLE RECYCLED MATERIALS AS VIRGIN MATERIALS SUBSTITUTION IN HMA

4.1 Introduction

The primary goal of this research is to search for sustainable materials solutions that utilize beneficial reuse of multiple recycled materials as construction materials. The objective of this chapter is to investigate the effects of recycling materials as filler material or replacement of aggregate in HMA, particularly a combination of multiple recycling materials. The selected recycling materials are the MSWI bottom ash (BA), recycled asphalt shingle (RAS), and recycled concrete aggregate (RCA). As discussed in Chapters 2 and 3, the RAS contains 30-40% of aged binder, and, when the RAS was added as an additive, the stability and stiffness of the asphalt mixtures increased. On the other hand, MSWI BA is one of the highly porous aggregates; thus, due to its high absorption capacity, it requires a higher amount of liquid asphalt in the mixture. The RAS can be used as an alternative material to supply the required asphalt binder induced by high absorption aggregate such as MSWI BA and RCA. In this chapter, the combination of RAS, MSWI BA and RCA in HMA is proposed and its performance evaluation is presented and discussed. In addition, the cost-benefit analyses for the use of the aforementioned recycling materials have been performed in order to estimate environmental and economic impacts.

4.2 Literature Review

4.2.1 *Use of MSWI BA in HMA*

The demand for pollution free, recyclable engineering materials has increased as the cost of energy and the environmental concerns have risen. A large supply of material is required to construct a roadway. Materials can be used in creative ways to more effectively apply them. For example, the best part of the soil–rock mixture can be used as the aggregates of the asphalt or concrete, the part with average quality can be used as road embankment filler, and the remaining part can be stabilized and used as the material of road bed. Waste materials are usually called "resources in the wrong places" and can be used or recycled. In Europe and the United States, recycled construction materials are classified as either industrial byproducts, road byproducts, or demolition byproducts ,depending on the type of material [*55*]. In an effort to save energy and natural resources, substituting virgin aggregate with recycled construction materials has become a new practice. Utilization of recycled material instead of virgin materials in road construction, saves landfill space, resources, and omits impacts associated with their extraction and transportation. [*56*]

MSW-BA plays an important role in the waste management. MSW-BA is the by-product during the incineration of municipal solid waste in solid waste combustor facilities. Incineration of MSW with energy recovery and management of municipal solid waste incineration (MSWI) ashes have been receiving growing attention around the world. Many countries have addressed the issue of beneficial utilization of MSWI ashes by executing strategic management plans and regulations [*23, 24, 93-96*]. For example, many European countries beneficially utilize MSWI bottom ash as a sustainable transportation material with environmental criteria set by their strategic regulations [*95-97*]. In the U.S., MSW are being produced more than any other country in the world; however, the recycling rate is considerably low [*14, 98*]. The estimated annual MSW generation in the U.S. has increased up to 65% since 1980, to the current level of 250 million tons with 53.6% landfilled, 34.7% recycled and composted, and 11.7% incinerated with energy recovery [*99*]. Furthermore, about 10% of BA is used in road construction. A total of 86 MSW Waste to Energy (WTE) plants are being operated in 24 states of the U.S., as of 2010, where major users of MSWI plants are Connecticut, New York, New Jersey, Pennsylvania, and Virginia. Typical residue produced from these incineration plants are MSWI bottom ash (BA) and fly ash (FA), which are usually combined to be disposed of in sanitary landfills in the U.S. [*24*].

4.2.2 *Use of RAS in HMA*

In the U.S. in the mid-1970s, a practical effort started using recycled materials such as RAS and reclaimed asphalt pavement (RAP). RAP can be partially substituted for both asphalt binder and aggregate and has been widely accepted due to its cost effectiveness advantage and less impact on environment. RAS can be just partially substituted with asphalt binder [*34*]. In 2010, the Illinois

Department of Transportation, Springfield, used about 1.7 million tons of recycled materials in highway construction projects in the state of Illinois [*35*]. Extensive literature in regards of the beneficial use of RAS in HMA has been reported in chapters 2 and 3.

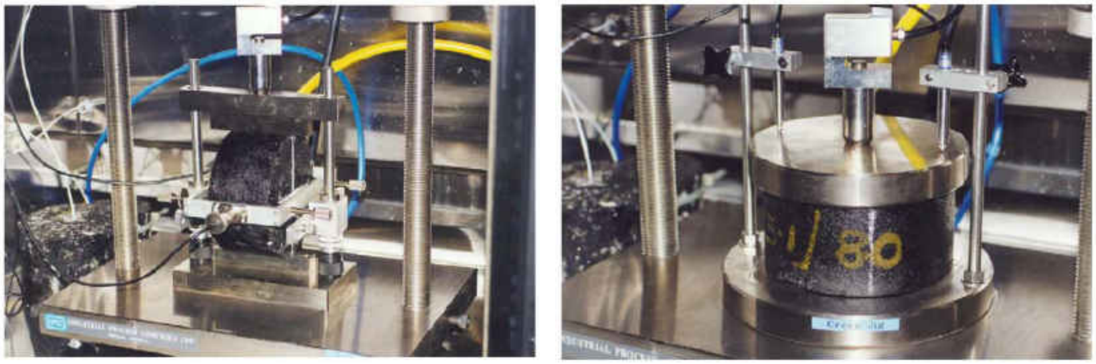
4.2.3 *Use of RCA in HMA*

Another type of recycled material that can be reused as construction materials is recycled concrete aggregates (RCA). RCA is made of waste concrete, which is the major component of construction and demolition (C&D) waste and is usually recycled by crushing and sieving it for reuse as aggregate material in concrete products [*100-104*].

The initial usage of RCA were just landfilling; however after extensive research [*105-112*], RCA is now being used as road sub base material and nonstructural concrete application. Additionally, RCA can be replaced by coarse or fine aggregate in HMA.

After RCA recycling process, due to the attached cement paste to the surface of the virgin aggregates makes the RCA differ from virgin aggregates. The cement paste has a highly porous surface which contributes to the lower particle density. High porosity and other contaminations (such as glass, rubber, asphalt and other soft or breakable particles) [*113-119*] of the recycled particles leads to a higher water absorption and a variation in the quality of the RCA. The higher porosity the higher binder absorption; thus, as the substitution ratio increases, the extra binder demand makes the mixture production uneconomical.

Sumeda et al. (2006) [*1*] investigated the effect of RCA on the characteristics of asphalt mixture. RCA were replaced with coarse aggregates and the properties were compared with the control mix (virgin coarse aggregate). RCA replacement conduced to decreasing in bulk density, voids in mineral aggregates, voids filled with asphalt and film thickness in mixture samples. Resilient modulus and creep tests were done as shown in Figure 4-1. The pulse width and pulse repetition period for resilient modulus were performed under 0.1 and 3 s, respectively. For the creep test, pulse width of 0.5 s and pulse repletion period of 2 s were used. The deformations were measured using linear variable differential transducers (LVDT).



(a) (b)

Figure 4-1: (a) Resilient modulus test, (b) Creep test [1]

Resilient modulus of the mixtures containing RCA showed significantly lower value in comparison with control mixtures. This decrement was concluded due to the low strength mortar and consequently low quality of the aggregates in the mixtures. However, resilient modulus value still met the recommended limits by the Austroads Pavement Research Group.

Creep test results are shown in Figure 4-2. It shows the creep increases as binder content increases and decreases with the increase in compaction effort.

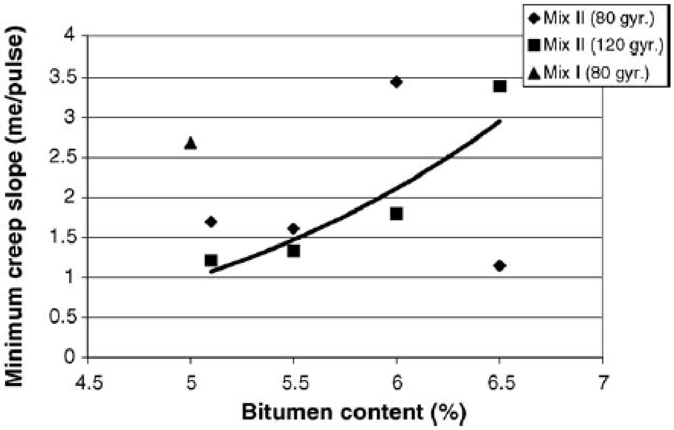


Figure 4-2: Effect of binder content and compaction effort on creep of Mix II containing RCA as coarse aggregates and Mix I containing fresh aggregates [1].

According to that conducted research, RCA particle densities were relatively much lower than the virgin aggregates (crushed basalt) and also the water absorption of RCA particles were much higher in comparison with the virgin aggregates. This difference was due to the highly porous and low density cement mortar attached onto RCA particles.

Although the researchers recommended using the RCA, future investigations were mentioned to examine their findings.

Beale et al. (2009) [*120*], they characterized the mechanical properties of HMA with partial RCA substitution for low volume roads. The RCA was substituted at the rate of 25, 35, 50 and 75. The rutting potential using Asphalt Pavement Analyzer (APA), Dynamic Modulus (E*), Moisture susceptibility, Indirect Tensile Test (IDT) resilient modulus were performed to evaluate the field performance of the substituted mixtures. All the substituted mixtures met the minimum rutting specification of 8 mm. The master curves for the mixes (illustrated in Figure 4-3) show that the dynamic stiffness of the samples with RCA are less than that of the virgin aggregates (control mix) and the stiffness decreases when the RCA substitution ratio is increased.

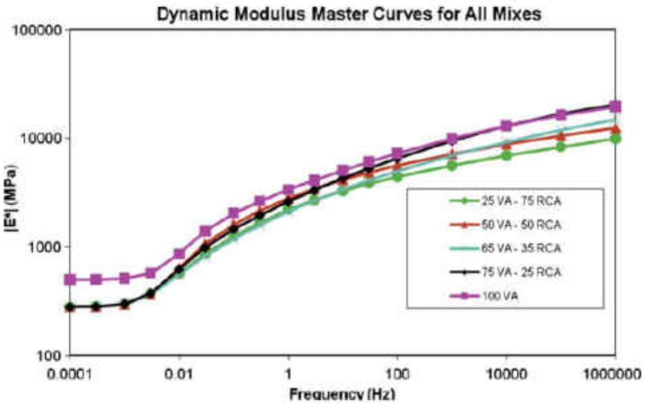


Figure 4-3: Dynamic modulus of selected VA-RCA [*120*]

The moisture susceptibility test also showed that by increasing the RCA substitution ratio, tensile strength ratio decreased. Only 75% replacement failed to meet the specification criterion. Based on the resilient modulus test results (Figure 4-4), as expected, the resilient modulus decreased as the RCA substitution ratio increased, regardless of the test temperatures. To establish the effect of RCA replacement in the mix, an ANOVA test at 5% significance level was conducted. The analysis indicated that the test temperature (5, 25 and 40 °C) had more contribution for the differences in results, rather than the percent of RCA in the mix.

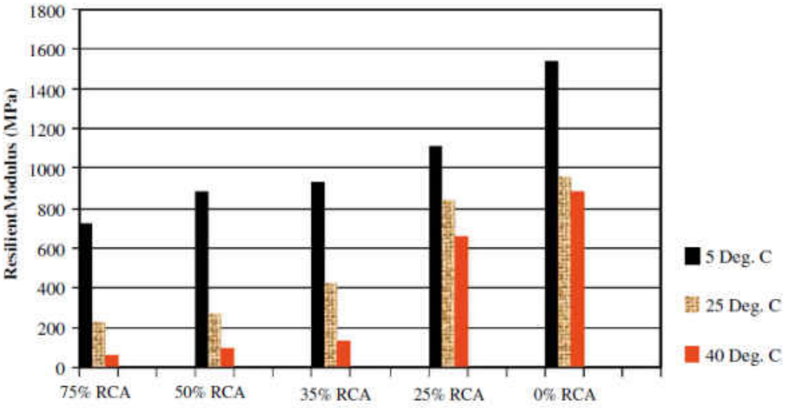


Figure 4-4: Resilient modulus test results [*120*]

It is recommended that a certain amount of RCA in HMA is acceptable for low volume roads.

4.3 Plan of Study

In Chapters 2 and 3, the impacts of RAS and BA, separately and combination of the two, were investigated. In this chapter, firstly the effect of RCA as coarse aggregate substitution with different proportions is evaluated. Secondly, the effect of the combined RAS, MSWI BA, and RCA in HMA is evaluated. In this combination, RAS, MSWI BA, and RCA were used as an additive, fine aggregate and coarse aggregate replacement, respectively. One of the findings in Chapter 3 was that the 20% (wt.) replacement of virgin fine aggregates with MSWI BA, exhibited higher performance; thus, in all combined mixes, 20% of the virgin fine aggregates were replaced with BA at the same correspond gradation. For the given substitution ratio with BA (20%) and RCA (100%), different proportions of RAS (0% to 6%) were added. All samples were made under Superpave Mix Design. Tensile strength and Rutting tests were employed to mechanically characterize the mixes. The environmental and economic analysis accomplished, using LCA and

LCCA, respectively.

4.4 Performance Evaluation

4.4.1 *Materials*

4.4.1.1 Asphalt binder

The binder grade used in this research was PG 67-22, the most commonly used asphalt binder in the state of Florida. The asphalt binder was supplied by local Asphalt Company (Bradenton, FL) and its physical properties of the asphalt binder are summarized in Table 4-1.

Table 4-1: Physical properties of the asphalt binder

Test	Test method	Specification	Test results
Rotational viscosity @ 135 ºC, 20 rpm spindle # 21	T 316	3.0 Max	0.465 Pa.s
Rotational viscosity @ 165 ºC, 20 rpm spindle # 21	T 316	3.0 Max	0.128 Pa.s
Dynamic shear (G*/sin δ, 10 rad/s)	T 315	1.0 min @ 67 ºC	1.09 kPa
Ring and ball soft point	T 53	-	54 ºC
Penetration @ 25 ºC	T 49	-	59 dmm
Flash point	T 48	230 ºC	344 ºC

(note: Pa.s = pascal-second)

4.4.1.2 Aggregates

Aggregate used in this study includes three types that are Limestone, MSWI BA and RCA Averaged test results of the basic physical properties and the corresponding test methods are listed in Table 4-2.

Table 4-2. Physical properties of the coarse aggregates

Properties	Limestone	BA	RCA	Test methods
Specific gravity (oven dry)	2.4*	N/A**	2.19	ASTM C127 [*39*]
Absorption capacity, %	3.04	12.8	6.45	ASTM C127 [*39*]
% of fractured particles in coarse aggregates (1 fractured face/2 fractured face)	81.4/74.7	N/A	88.7/83.24	ASTM D5821 [*121*]
L.A. abrasion mass loss, %	36.5	43	41.3	ASTM C131 [*122*]

*Fine aggregates specific gravity is 2.5
**Fine aggregate specific gravity is 2.2

4.4.2 *Sample Preparation*

The optimum asphalt content (OAC) was determined following Superpave mix design. For the control mixture, with conventional asphalt, the OAC was determined as 5.1% at 4% air void. The details of the Superpave Mix design details are presented in Appendix B. The Superpave mix design was used to prepare the asphalt mixtures and sand material (#30, #50 and #100) was used to meet the aggregate gradation criteria shown in Figure 4-5. To simplify addressing each sample, a code has been assign to each sample as presented in Table 4-3.

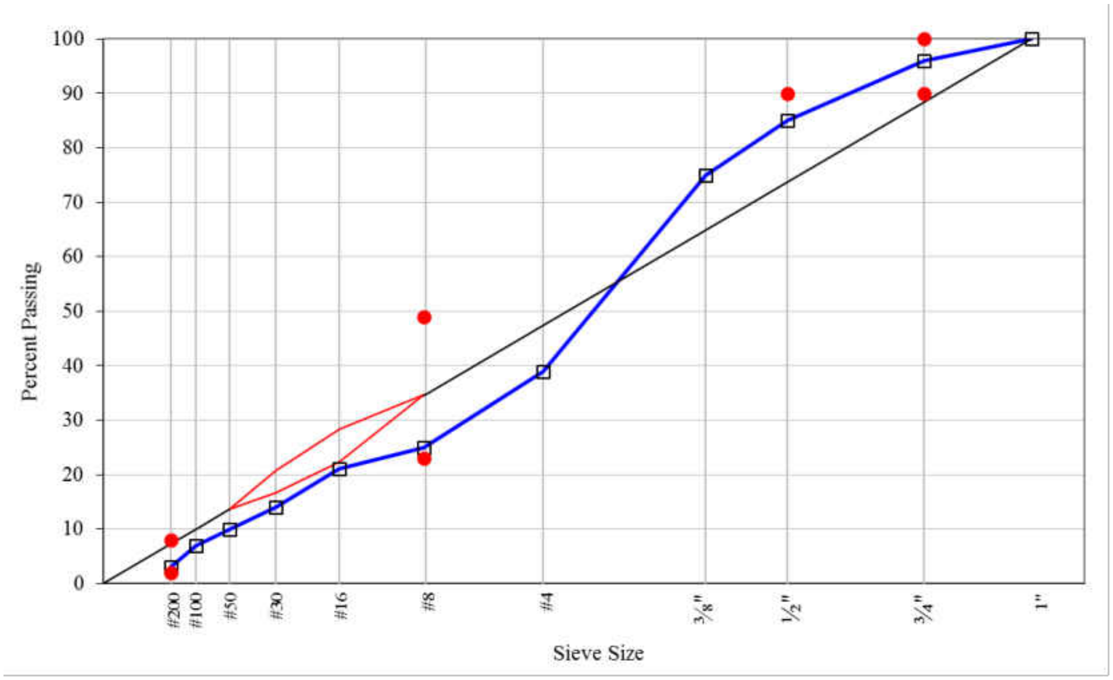


Figure 4-5. Superpave aggregate gradation curve

Table 4-3: Prepared mixtures

Sample Codes	Description
V100A5.1	100% virgin coarse and fine aggregates @ 5.1% OAC
RCA25A5.1	25% RCA coarse+100% virgin fine @ 5.1% AC
RCA50A5.1	50% RCA coarse+100% virgin fine @ 5.1% AC
RCA75A5.1	75% RCA coarse+100% virgin fine @ 5.1% AC
RCA100A5.1	100% RCA coarse+100% virgin fine @ 5.1% AC
RCA100A5.7	100% RCA coarse+100% virgin fine @ 5.7% OAC
RCA100B20A5.1	100% virgin coarse+80% virgin fine+ 20% BA fine+0% RAS@ 5.1% AC
RCA100B20A5.1R1	100% virgin coarse+80% virgin fine+ 20% BA fine+1% RAS@ 5.1% AC
RCA100B20A5.1R2	100% virgin coarse+80% virgin fine+ 20% BA fine+2% RAS@ 5.1% AC
RCA100B20A5.1R3	100% virgin coarse+80% virgin fine+ 20% BA fine+3% RAS@ 5.1% AC
RCA100B20A5.1R4	100% virgin coarse+80% virgin fine+ 20% BA fine+4% RAS@ 5.1% AC
RCA100B20A5.1R5	100% virgin coarse+80% virgin fine+ 20% BA fine+5% RAS@ 5.1% AC
RCA100B20A5.1R6	100% virgin coarse+80% virgin fine+ 20% BA fine+6% RAS@ 5.1% AC

4.4.2.1 Sample Design for the HMA containing RCA

To evaluate the effect of RCA, the coarse aggregates of the control mix (with virgin aggregates) have been replaced by RCA in the same size with 25%, 50%, 75%, and 100% (wt.%) replacement rate. All aggregates were blended at the control mix OAC.

4.4.2.2 Sample Design for the HMA containing RCA and BA

The sample design in this section includes the HMA with 100% coarse aggregate replacement by RCA and 20% fine aggregate replacement by MSWI BA. As denoted earlier, to substitute the demand for the extra binder due to MSWI BA and RCA, RAS with 1%, 2%, 3%, 4%, 5%, and 6% (by the mass of total aggregate) has been added to the selected mixture samples.

4.4.3 *Experimental Procedure*

4.4.3.1 Tensile Strength Test

Pavement crack propagation procedure has been the subject of many studies [*123-126*] Pavement performance is heavily influenced by tensile strength of asphalt concrete mixtures. Flexural stiffness measurements can be used to predict the fatigue life of asphalt pavement. A prime factor in the fatigue life of asphalt is the tensile strain at the bottom of the asphalt concrete layer. Cracking starts at the bottom of this layer and deteriorates due to the repeated stress induced by traffic loads. Eventually, these cracks propagate to the surface in the form of fatigue cracking, sometime reflective cracking if the cracks are propagated from the cracks of underlying layers.

Following the test procedure (ASTM D4867)[*127*], each set of samples was tested at the temperature of 25^0C. Dry samples were sealed and kept in water bath at 25^0C for adjusting the temperature. Indirect tensile strength of each sample was determined using the Indirect Tensile Test (IDT) device. Strain rate used in the IDT test was at 2 (in./min). Calculation formula is as follows:

$$S_t = 2000P/\pi tD \ (kPa) \qquad (4.1)$$

S_t = tensile strength, kPa
P = maximum load, N
t = specimen height immediately before tensile test, mm
D = specimen diameter, mm

4.4.3.2 Rutting Test

Rutting performance of each mixture, associated with substituted materials, was evaluated using APA testing (AASHTO T340). Since APA measurement represents mixture stiffness, this test was used to keep the results comparable. Additionally, APA testing maintains simplicity because it directly measures the sample rut depth. In this study, 75-mm dry SGC-compacted HMA cylinders with 7.0 ± 0.5 percent air voids were tested at 64 degrees Celsius to 8000 cycles.

4.4.4 *Testing Results and Discussion*

4.4.4.1 Tensile Strength Test Results and Discussion for the HMAs Containing RCA, BA, and RAS

The effect of RCA as the coarse aggregate replacement is presented in Figure 4-6, illustrating the tensile strength (in dry condition) results for the HMA containing 25, 50, 75, and 100 percent of RCA as the coarse aggregate replacement. More fractured surface and higher surface texture in RCA aggregates resulted in higher adhesion; thus, the tensile strength increased as the RCA content increases up to 75%. Figure 4-7 and Figure 4-8, illustrate 2 sets of the broken HMA samples after tensile strength test. As can be seen, HMA with RCA aggregates (Figure 4-8) shows more fractured aggregates than virgin aggregates (Figure 4-7); indicating the level of adhesion between aggregates and binder. The tensile strength decreased after 75%, which is likely due to the lack of asphalt binder and poorer asphalt coating in the mixture. This phenomenon can be verified by increasing the asphalt content to the OAC (5.7%).

The author made one additional specimen made from the increased asphalt binder of 5.7% and the same 100% RCA replacement, and the IDT result demonstrates that the tensile strength increases by 115 kPa.

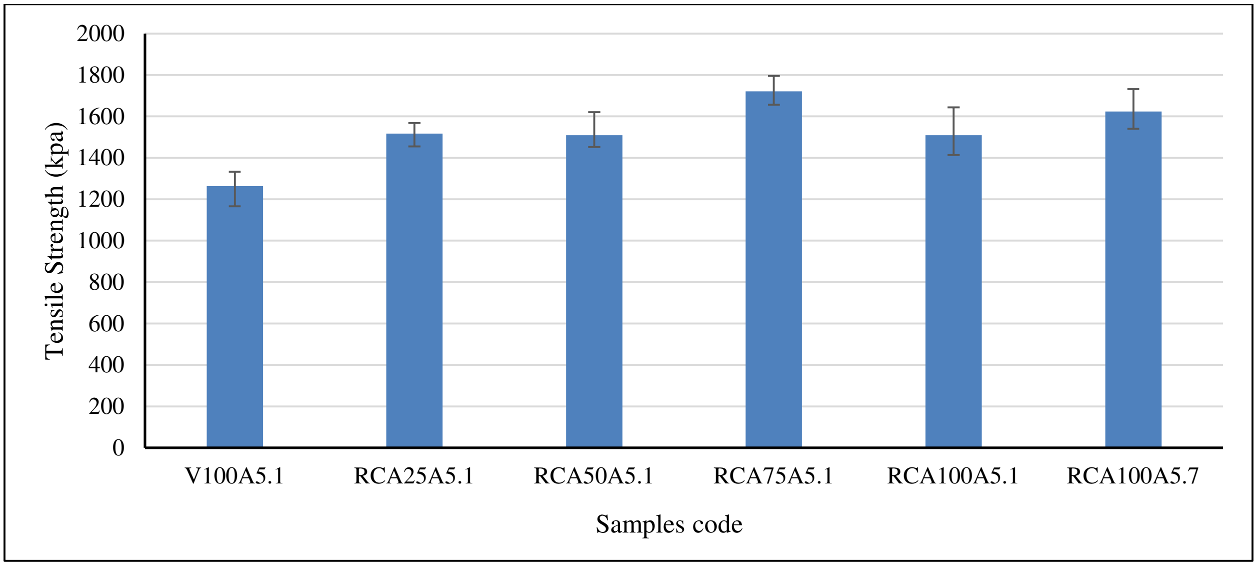


Figure 4-6. Tensile strength for the samples containing RCA

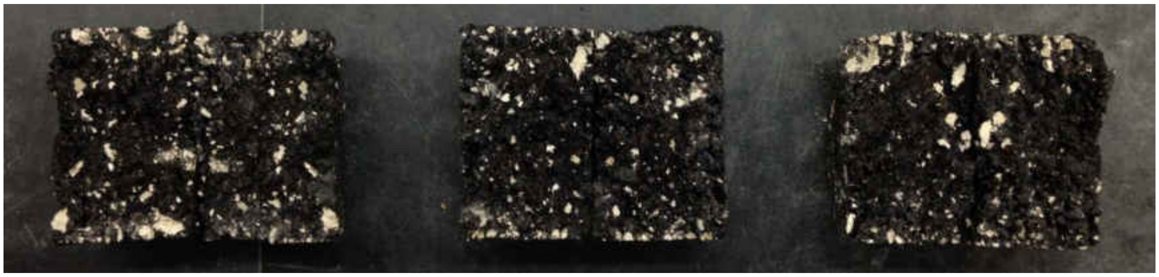


Figure 4-7: Photograph of the fractured surface for HMA ‘V100A5.1’

Figure 4-8: Photograph of the fractured surface for HMA ‘RCA100A5.1’

To achieve the maximum usage of RCA, “RCA100A5.1” has been selected to substitute the 20% of the virgin fine aggregates with BA. As the results of the combination of the two, the OAC again increases to 6.5%. 1.4% increment in the OAC may not be desirable because one of the research goals is to save natural resource; thus, RAS in different ratios has been added to the ‘RCA100B20A5.1’ and the results are summarized in Figure 4-9. As expected, increasing asphalt content up to the OAC at sample”RCA100B20A5.1R0” resulted in an increment to the tensile strength. Adding RAS to the mixture, in addition of the increasing asphalt content, increases binder viscosity; thus tensile strength goes up.

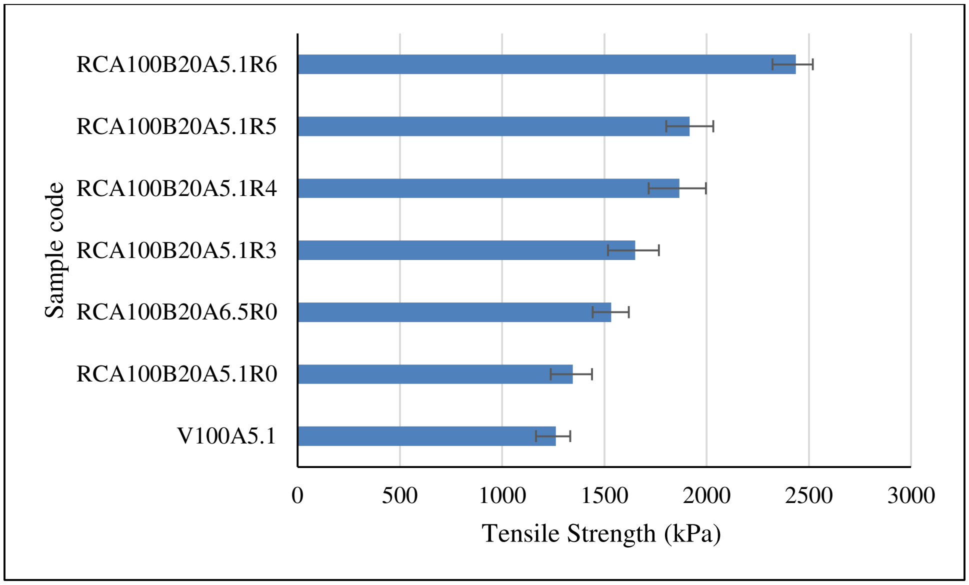


Figure 4-9. Tensile strength for the HMAs containing RCA, BA, and RAS

4.4.4.2 Rutting Test Results and Discussion for the HMAs Containing RCA, BA, and RAS

APA testing was used to evaluate the rutting resistance of the mixtures. The APA applies 8000 loading cycles and the rut depths are measured. Figure 4-10, shows the results of the rutting test for the selected HMA specimens. Unlike the trend of the tensile strength result, rutting test results do not follow the consistent trend that the tensile strength increases with increasing the RAS. This different trend may be due to the changes in effective binder content (EBC) and aggregates properties.

RCA angularity as well as highly rough surface texture can cause a strong interlocking in

HMA “RCA100B20A5.1R0”. Accordingly, increasing the binder content up to the OAC increases the EBC, thus increases resistance to permanent deformation. Adding the RAS ranging from 1 to 4 percent does not a significant change of the EBC due to the existing porous on the surface of the BA particles; hence, the extra RAS’ fillers facilitate increasing plastic deformation. EBC increased in the HMAs with 5% and 6% RAS and the influence of EBC was more than the RAS’ fillers on rutting resistance.

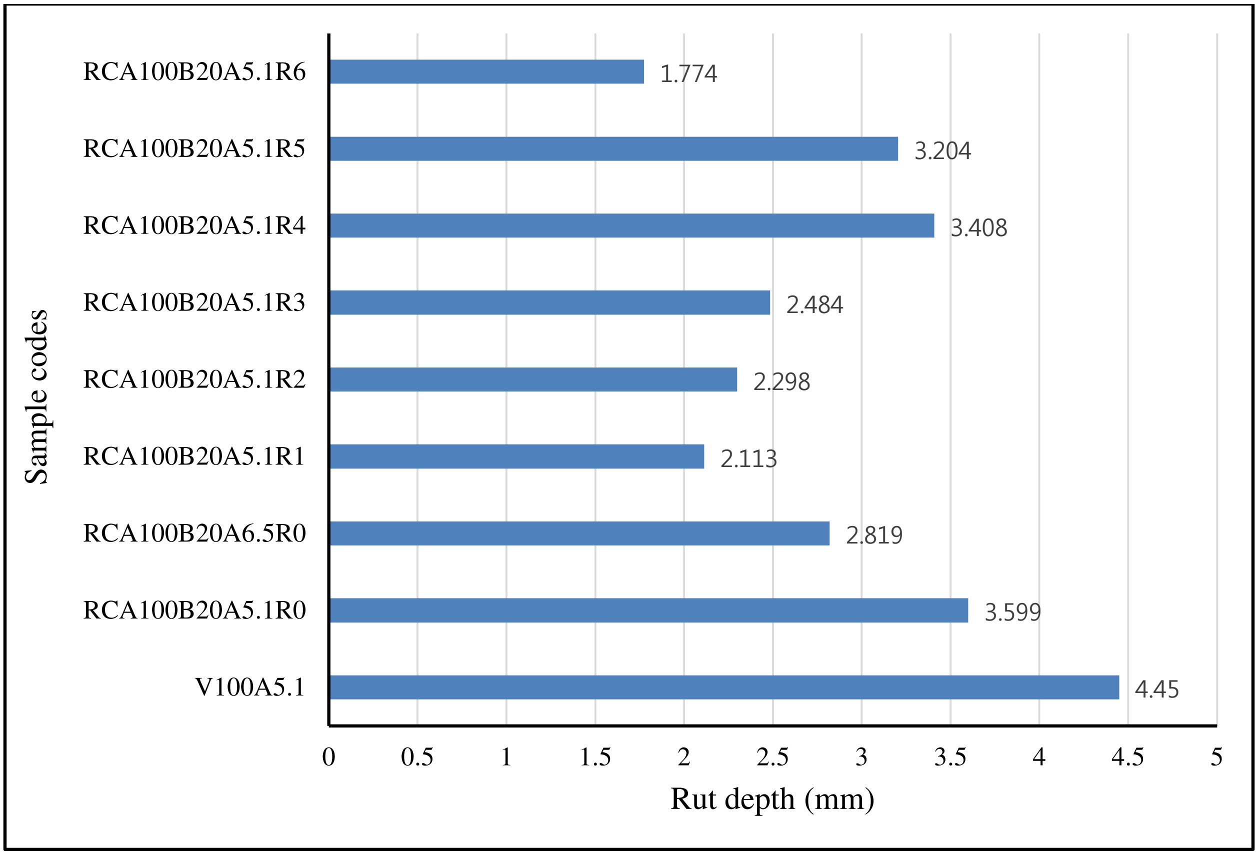


Figure 4-10: Resistant to permanent deformation results

4.4.5 *Correlation between Stiffness and Rutting Resistance*

To construct the relationship between rutting resistance and stiffness, a new stiffness index has been proposed. This index is the slope of load and displacement from IDT testing. The slope determined from the load-displacement curve can be referred to as IDT ‘stiffness’ hereafter and denoted as ‘k’ value. Steeper slopes indicate stiffer materials, generally leading to higher resistance to plastic deformation.

To better understand the correlation between rutting and “k” value, both test results have been plotted in Figure 4-11. There is a clear trend that the “k” value increases and the rut depth decreases.

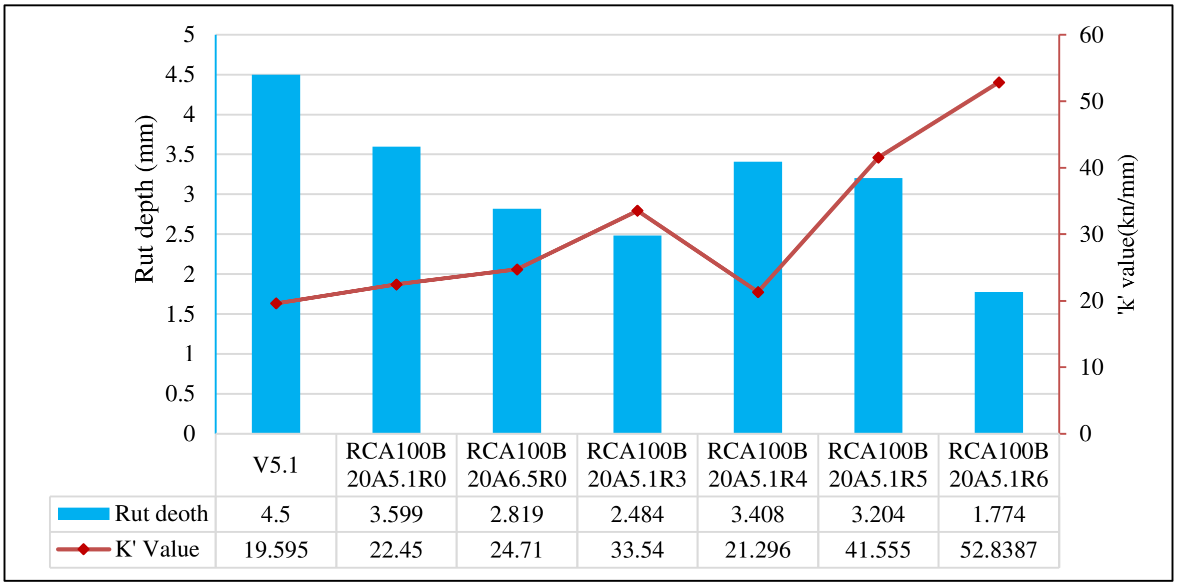


Figure 4-11. Rut depth versus ‘k’ value of the HMAs containing RCA, BA and RAS

To evaluate the correlation (linear dependence) between the “k” value and the rutting results, a statistical analysis by calculating the “Pearson product-moment correlation coefficient” (PCC) has been performed. The PCC is a measure of the linear correlation among two variables, giving a value between +1 and −1. The higher positive correlation represents the higher direct correlation, 0 is no correlation, and −1 is total negative correlation [*54*].

The calculated σ value for the data presented in Figure 4-12, is -0.78, which means there is a strong negative (reverse) correlation between two major HMA performance tests. This correlation provides researchers an idea in regards to performance estimation of the trial samples. Since rutting test-sample preparation is a time consuming work, measuring tensile strength (under dry condition) is faster and easier and can save time a lot.

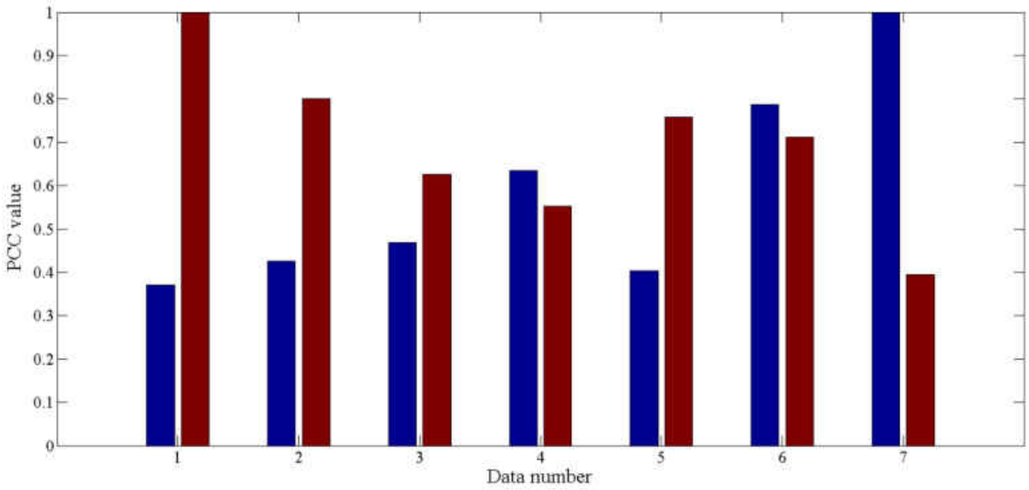


Figure 4-12. Pearson Correlation Coefficient between the rutting and “K” value

4.5 Cost-Benefit Analysis

4.5.1 *Overview*

A sustainable pavement not only meets its engineering design requirements, but also meets human needs, uses materials efficiently, and prevents further harm to the environment. By definition, “sustainability” is a broad term; its meaning connotatively changes by content, and can therefore take on a variety of interpretations. For this reason, the word 'sustainability' is not constant and can change by pavement variation. Measuring pavement sustainability is useful in quantifying, managing, and improving current practices.

Using natural resources in construction industry and the corresponding fuel consumption, can highly affect the environment ecosystem.

Fossil fuel consumption and the concentration of carbon dioxide in the air have a proportional relationship to each other. Additionally, the reduction of natural resources damages ecosystems. In the 1960s, construction and industrial material utilization considerably increased. As a result of the retrieval of raw materials not meeting the demands for resources, the environment is impacted negatively Figure 4-13 and Figure 4-14.

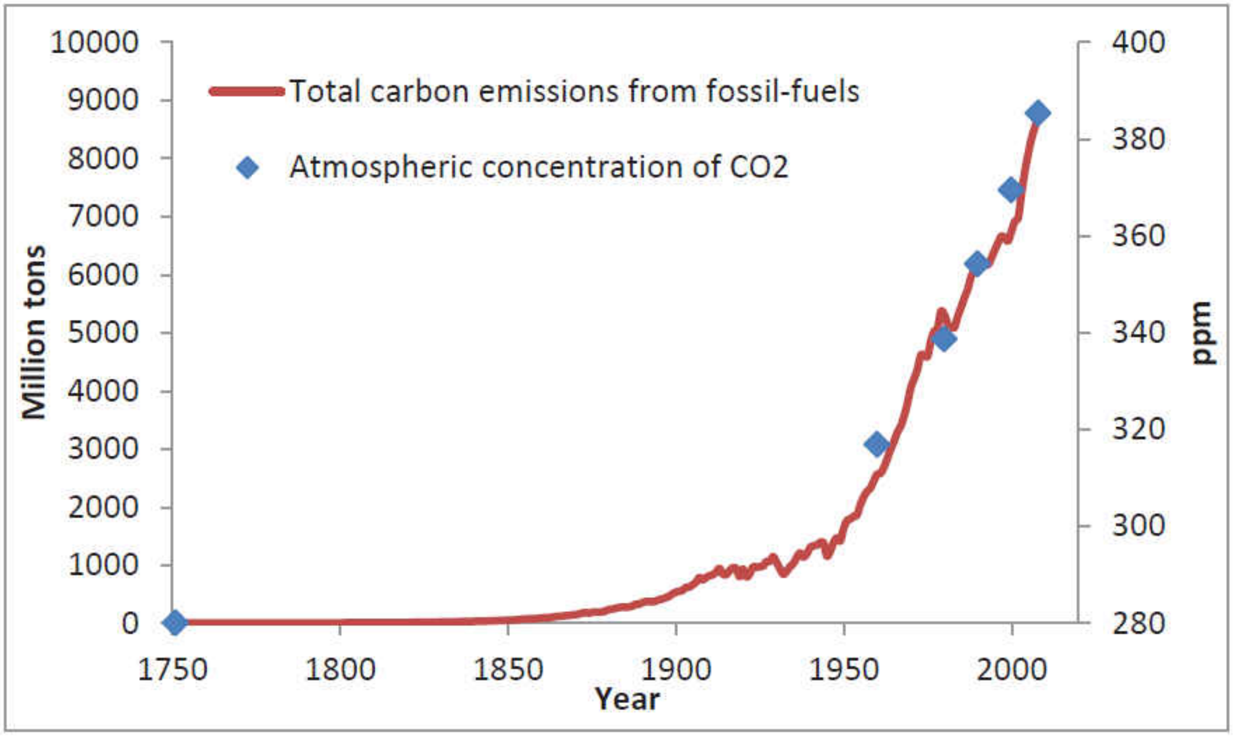


Figure 4-13. Concentration of carbon dioxide (IPCC, 2007; CDIAC, 2009)

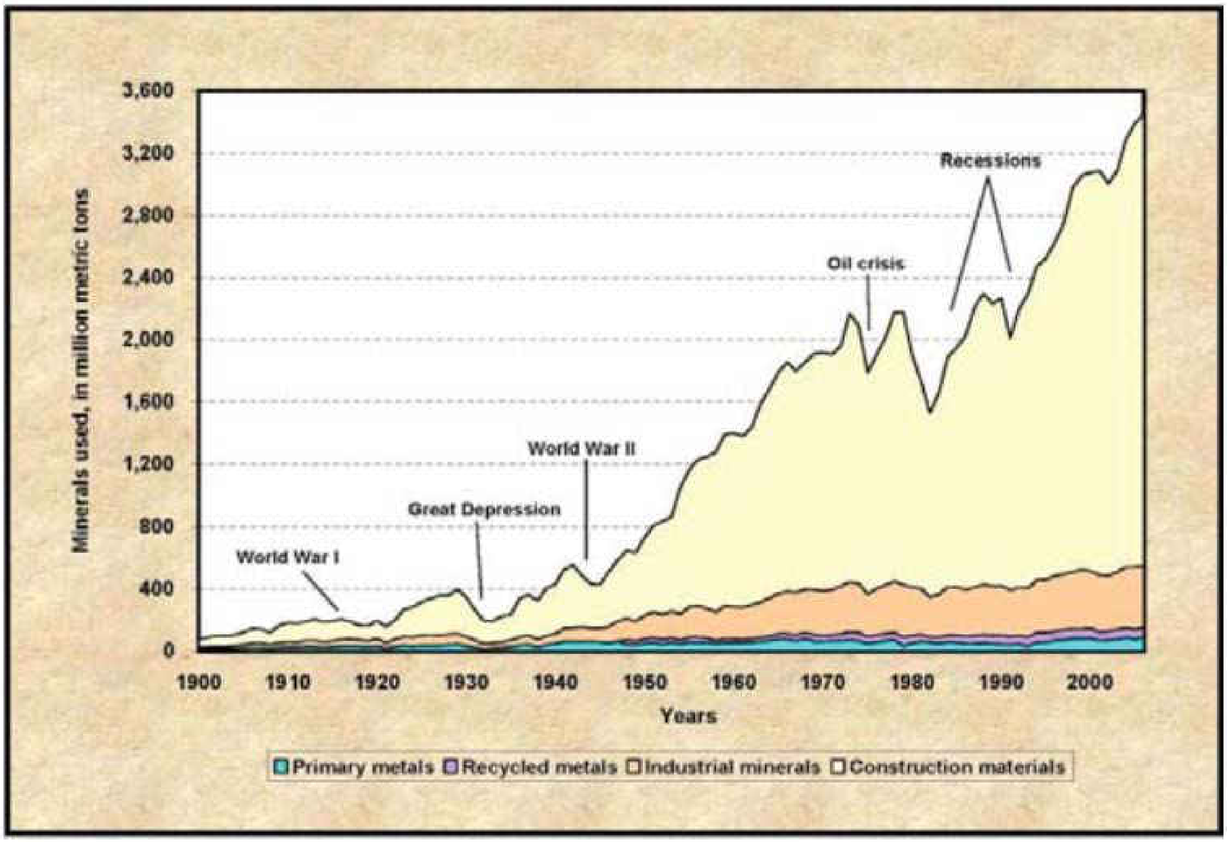


Figure 4-14. Raw materials consumed in the U.S., 1900 to 2006 (USGS, 2009)

Measuring the level of sustainability can be made by life cycle assessment (LCA) and life cycle cost analysis (LCCA). LCCA is a means to quantitatively evaluate the impact of the use of those recycling materials on economic performance. All related cost generated in the procedure from materials production through pavement construction and maintenance has been taken into account. The life cycle was determined based on the results of laboratory experiments that represent the mechanical performance (e.g strength, rutting and cracking resistance) of the selected mixture designs On the other hand, LCA was used to measure a pavement's environmental impacts over the course of its entire life, and has been widely used and accepted [*3*]. LCA allows for a quantitative analysis of the environmental impacts of construction projects, which allows for a more complete picture when making ds. LCA measures and quantifies the environmental impact of a product within specified system boundaries. A limited LCA study has been used in the field of pavement engineering, and the existing tools and methods are not fully defined in terms of data quality and source, boundaries and data interpretation. Due to the specialization and time required, it is unrealistic for LCA's practitioners to develop their own LCAs. However, by implementing an appropriate tool or software, pavement practitioners would be able to perform LCA's inexpensively, which would aid in decision making [*70*].

4.5.2 *Life Cycle Cost Analysis*

4.5.3 *LCC Analysis, Results and Discussion*

In this section, LCCA was conducted to evaluate cost effectiveness of the proposed mixtures.

LCCA is a method used to make long-term investment decisions considering cost effectiveness. During the LCCA, all of the costs associated with a project are considered, not just the initial cost but the likely future costs associated with a project over time. This tool is effective in conveying multiple scenarios of alternative investment to decision makers. The LCCA is defined in Section 303 of the National Highway System Designation Act of 1995 as " (The) process for evaluating the total economic worth of a usable project segment by analyzing initial costs and discounted future costs, such as maintenance, reconstruction, rehabilitation, restoring, and resurfacing costs, over the life of the project segment (NHS 1995)”.

The Federal Highway Association (FHWA) advocates the use of a life-cycle cost assessment to help choose a cost-effective project alternative and to help convey the benefits of the alternative chosen to the public [*75*]. The FHWA’s Life-Cycle Cost Analysis in Pavement Design – Interim Technical Bulletin details the procedure for conducting LCCA of pavement projects. LCCA incorporates discounted long-term agency cost, user cost, other cost, and performance period [65]. The discount rate used for an LCCA can have a significant influence on the final results; an acceptable discount rate for LCCA ranges from 3 - 5%. The user costs are those that are incurred by users traveling on a highway because of detours during construction of projects. Similar costs between alternatives should not be used for LCCA calculations because they will cancel out each other in LCCA calculations, but should be mentioned in the text.

In this study, an Excel based LCCA tool has been developed to convey the cost effectiveness analysis at both initial construction and 20 years maintenance period.

All costs are based on 2014 dollars. The presented prices are the average of different states. Due to a varied range in the asphalt binder cost and land filling tipping fee, Monte Carlo simulation has been employed to reflect the uncertainty on the data.

Table 4-4. Estimated service life

Sample codes	IDT strength (kPa)	Rut Depth (mm)	Fracture Energy (N.mm)	Service Life (yrs.)
Impact Assessment	30%	40%	30%	100%
V100A5.1	1263.25	4.450	43855.22	5
RCA100B20A5.1R0	1345.3	3.599	39437.89	5.54
RCA100B20A6.5R0	1533.70	2.819	48323.2	6.33
RCA100B20A5.1R6	2435.50	1.774	43296.9	6.28

Assuming the thickness of the asphalt overlay is 2 in. and the service life is 5 years, the pavement description for four proposed mixtures as alternatives are presented in Table 4-5.

Table 4-5. Pavement description

Sample code	Length (mi)	Width (ft)	Surface Depth (in)	Base Depth (in)	RAP Removal (in)	Density (ton/m^3)	Overlay Mass (tons)	Maintenance Frequency
V100A5.1	1	12	2	0	2	2.09	632.21	4
RCA100B20A5.1R0	1	12	2	0	2	2.03	614.06	3.61
RCA100B20A6.5R0	1	12	2	0	2	2.045	618.60	3.16
RCA100B20A5.1R6	1	12	2	0	2	2.06	623.13	3.18

Table 4-6. LCC components based on 2014 prices

LCC Components	Unit	Value	Reference
Virgin Aggregate	$ / ton	$50	[*77*]
Sand	$ / ton	$40	[*77*]
Asphalt Binder	$/ ton	$505 - $697	[*78-80*]
Trucking	$/ ton / mile	$0.13	(Horvath 2004)
Tipping Fee	$ /ton	$24.3 - $91	[*81*]
Shingle Grinding	$ /ton	$14.80	[*82*]
Asphalt Inflation Rate	% / year	%1.1	[*83*]
Trucking Distance [Mine to Plant]	Miles	30	
Trucking Distance [Refinery to Plant]	Miles	50	
Trucking Distance [Plant to Site]	Miles	10	

Table 4-7. Cost calculations for the proposed mixtures

HMA Code			V100A5.1	RCA100B20A5.1R0	RCA100B20A6.5R0	RCA100B20A5.1R6
Initial Construction		VA Cost	$25,797	$5,007.65	$4,701.34	$5,081.66
		Sand Cost	$3,360	$3,264.34	$3,241.45	$3,312.58
		Binder Cost	$19,057	$18,510.30	$23,765.89	$18,783.86
	Transportation	VA Trucking	$1,950	$378.58	$355.42	$384.17
		RCA Trucking	$0.00	$1,343.94	$1,353.87	$1,363.80
		Sand Trucking	$317	$308.48	$306.32	$313.04
		Binder Trucking	$203	$197.30	$253.32	$200.21
		BA+RAS Trucking	$0.00	$171.76	$170.70	$315.63
		Plant to Site Trucking	$796	$773.71	$779.43	$785.15
		RCA Tipping Credit	$0.00	$5,222.89	$5,261.48	$5,300.07
		BA Tipping Credit	$0.00	$17,448.39	$17,577.31	$17,706.24
		RAS Cost	0	$2,230.02	$2,216.14	$2,262.97
Maintenance		VA Cost	$0.00	$0.00	$0.00	$1,281.50
		Sand Cost	$117,242	$20,555.99	$16,971.96	$18,482.90
		Binder Cost	$15,274	$13,399.83	$11,701.72	$12,048.45
	Transportation	VA Trucking	$86,611	$75,983.21	$85,795.58	$68,320.25
		RCA Trucking	$8,863	$1,554.03	$1,283.08	$1,397.31
		Sand Trucking	$0.00	$5,516.77	$4,887.52	$4,960.40
		Binder Trucking	$1,443	$1,266.28	$1,105.81	$1,138.58
		BA+RAS Trucking	$923	$809.89	$914.48	$728.21
		RCA Tipping Credit	$0.00	$705.08	$1,038.28	$633.97
		BA Tipping Credit	$3,620	$3,176.03	$2,813.77	$2,855.73
		RAS Cost	$0.00	$21,439.51	$18,994.11	$19,277.32

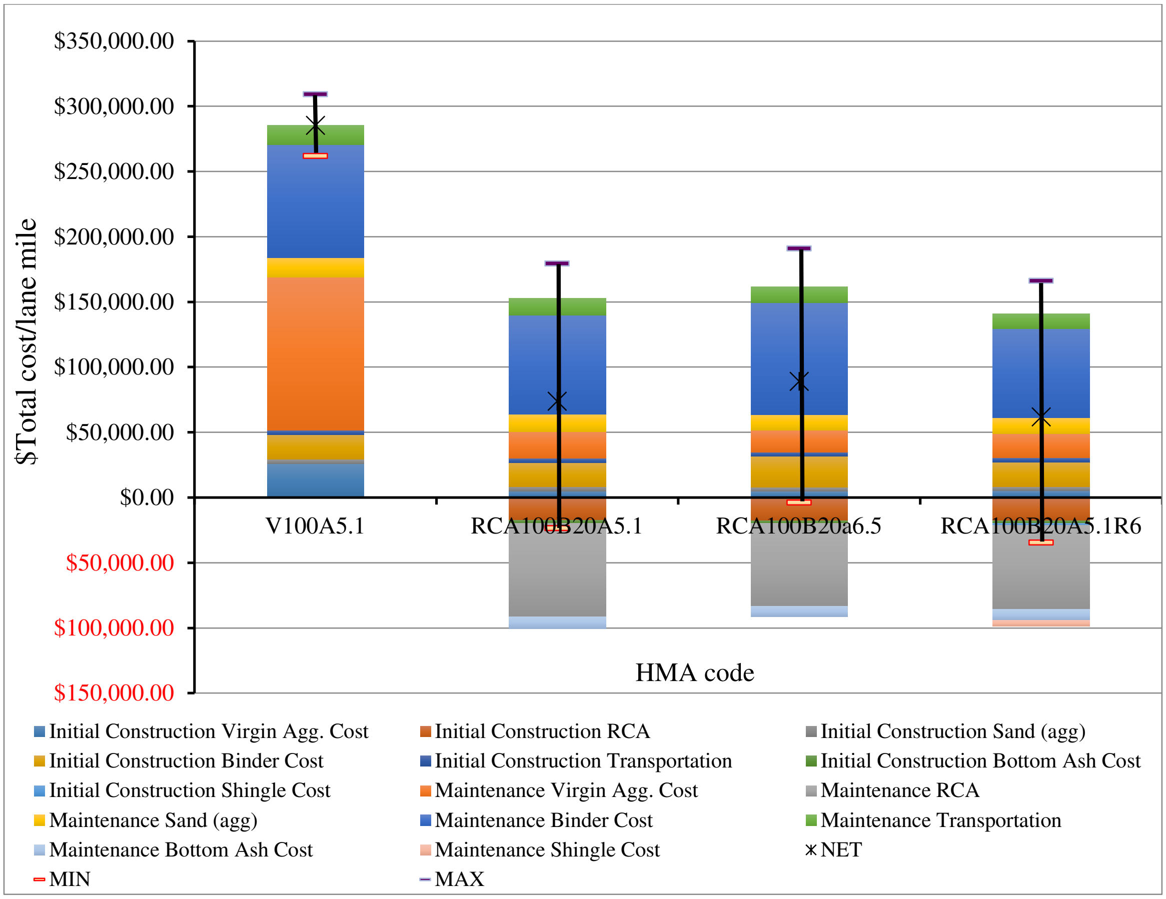


Figure 4-15. Total cost/lane mile for initial construction and maintenance in a 20 year period

The cost analysis was accomplished by calculating the savings of implemented RCA, BA and RAS in each 4 case scenarios. Taking into the difference in service life with different material, affects the amount of required material for the pavement life time.

The total cost of the virgin and recycled materials used are evaluated based on the assumption of a one-lane road in a mile as an overlaying of 2 inches in a different maintenance frequency for a period of 20 years. The total volume of the assumed pavement overlay is 302.49 (m^3). This volume accounted the same for all the scenarios. The calculated density and materials mass are presented in Table 4-5. The quantities of the recycled and virgin materials required for the asphalt pavement can be found based on the mix design.

It must be noted that, RCA, RAS and BA accounted as by products materials; thus, no cost associated with their production. However, landfilling tipping fees related to the aforementioned recycled materials, considered in the analysis. It can be found that, the aggregate tipping fee has a large impact on analysis. Overall, the net cost for the construction and maintenance of an overlay with HMA "RCA100B20A5.1R6" is 60-80% cheaper than HMA with virgin materials. This huge decrement in costs indicates the potential of saving millions of dollars annually in pavement construction.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

This research scrutinized the mechanical performance and the level of sustainability (environmental and economic outcomes) for the HMAs containing different amounts of three proposed recycled materials (RCA, MSWI BA and RAS). RCA and MSWI BA were used as virgin aggregate substitution alternatives while RAS was used as an additive that supplies asphalt binder. The performance evaluation includes Marshall Stability, indirect tensile strength, moisture susceptibility as well as rutting tests and the cost-benefit analysis which includes both LCA and LCCA. The results provide critical inputs for the decision making process regarding the type of recycled materials selected as well as optimum mix proportioning in road construction and rehabilitation. The conclusions drawn from the laboratory experiments and the LCA and LCCA are summarized as below:

- When MSWI BA are used as fine aggregate replacement in HMA, the replacement ratio of 20% is recommended because this proportion exhibited the maximum stability (or strength) and moisture resistance. However, the higher absorption capacity of MSWI BA requires higher optimum binder content compared with the control (HMA with limestone aggregate).
- MSWI BA has higher porosity and rougher surface texture compared to the control aggregate (limestone), this character increases the absorption of asphalt binder. Replacing 20% BA with virgin fine aggregates increases OBC as 1.1%. Until the 20% replacement ratio, however, adding MSWI BA increases the mixture stiffness and tensile strength likely due to an increase of aggregate interlocking in the mixture.

- MSWI BA particles during mixing or compaction may break down into smaller particles; thus, the filler portion may increase and the air void percentage likely decrease. Hence, in mix design, the possible changes in gradation curve should be considered.
- The test results from extracted asphalt binder showed that: the average amount of binder content is 34.77% which falls into a typical range of 30% to 40%. The average penetration depth is 1.5, 2, and 5 dmm at 25 °C, 45 °C, and 60 °C, respectively while the typical range of manufacturer scrap is between 23 and 70 dmm at 25 °C.
- The rutting test results indicated that there is a reverse correlation between effective asphalt binder and the rutting resistance. Samples with the asphalt binder less than the optimum asphalt content (OAC) showed higher rut depths. Although, adding RAS increases the stiffness of mixtures; meanwhile, the excess amount of RAS filler may facilitate an increase of plastic deformation and ultimately an increase of rut depth.
- The amount of energy consumption will be different depending on materials types and amount used in the asphalt concrete mixture. The energy consumption decreases from 10,500 Gj/lane mile to 8,574 Gj/lane mile for the life cycle of 20 years when 20% of MSWI BA and 5% of RAS were combined in the HMA. This energy decrease occurs mainly in the maintenance phase of binder production under the feed stock energy, and little or no change occurs in the operation and equipment. The reduction of energy consumption is not noticeable by switching from the HMA with all virgin materials at 5.7% binder content (V 100B0A5.7R0) to the HMA with the 20% replacement of MSWI BA at higher 6.7 binder

content (V100B20A6.8R0).

- Due to the large portion of aggregate in HMA, considering a life time in service period, the influence of virgin aggregate production cost is greater than that of asphalt binder in the maintenance stage. Overall, the net cost for the construction and maintenance of an overlay with HMA "V100B20A5.7R5" (the combination of 100% limestone as course aggregate, 20% MSWI BA as fine aggregate, 5% RAS, and 5.7% binder content) is 46% cheaper than the control mixture (HMA with virgin materials).
- At 6% RAS as an additive, replacing 100% coarse aggregate by RCA, 20% fine aggregate by MSWI BA can reduce the construction and maintenance costs 60-80% in a period of 20 years.

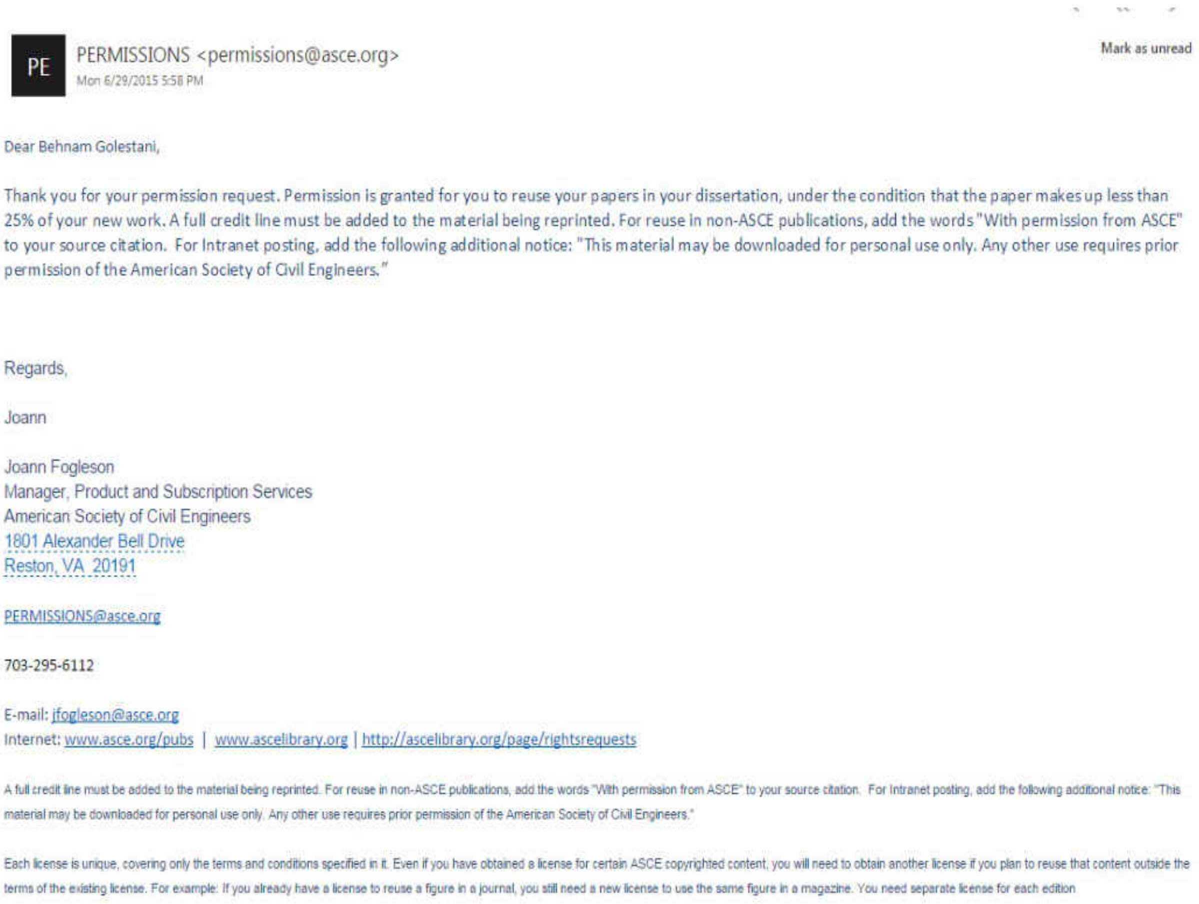
The above results validate the positive impacts of employing three different recycled materials in HMA; however, there were some limitations (as listed below) which are recommend to take into account in future studies.

- As discussed earlier, RAS contains 30-40% aged binder. In spite of positive impacts associated with implementing RAS during mixture production such as raising the stiffness and decreasing rut depth, a high percentage can also create a brittle mix; therefore, it can lower the fatigue resistance. For this reason, the application of RAS in cold climate condition should be studied more.
- Recycled waste materials, particularly BA, have toxic leaching potential. Although asphalt binder coats and seals BA particles in HMA production process, but in a long term, upon

the nature and extent of the traffic which is to pass over the pavement surface, the HMA overlay may subject to stripping; thus, no more enough binder exists to keep away BA particles from toxic leaching. In consequence, a comprehensive study is required to appraise the leaching impact based on environmental regulations while the HMA is subjected to striping or any other pavement distresses which the BA particles are directly in contact with water.

- Failure energy is recommended as one of the determinative criteria in service life estimation. In order to find proper failure energy, this hypothetic still needs to be developed more. Specimen height and diameter need to be accounted for calculation. Moreover, maximum load assumed as a threshold point; however, developing a method to determine the exact failure point, would give a more accurate comparison in different mixes.

APPENDIX A: APPROVAL LETTERS



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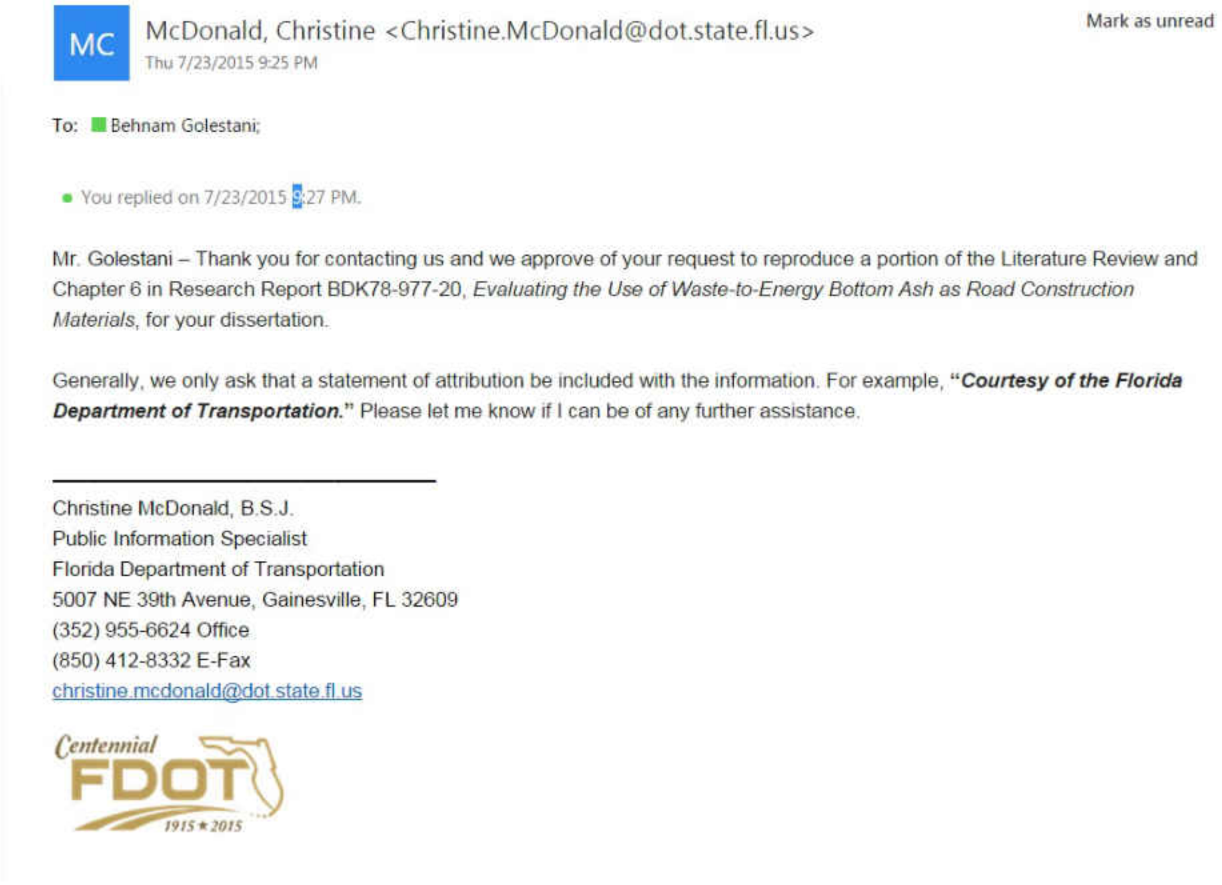

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APPENDIX B: SUPERPAVE MIX DESIGN

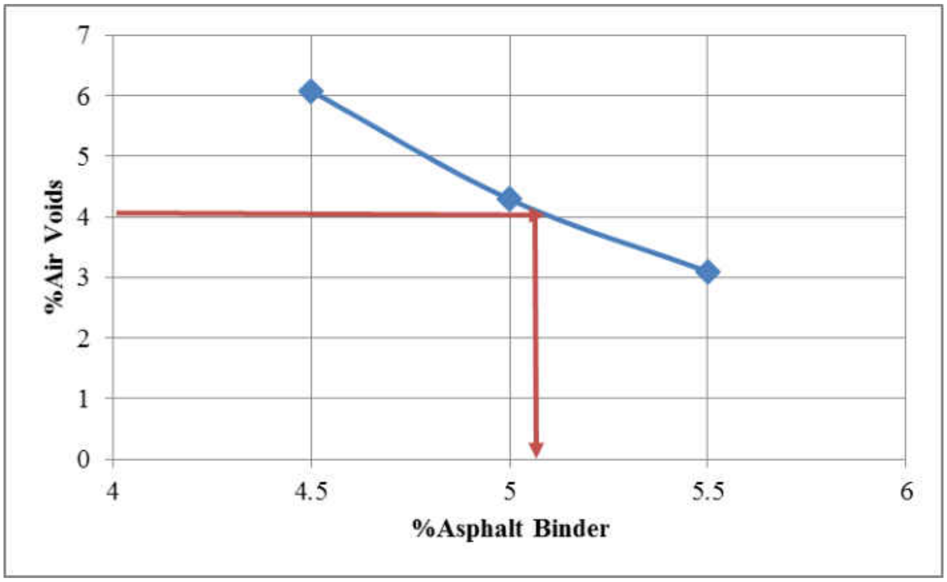

Figure B-3: Air void versus asphalt content

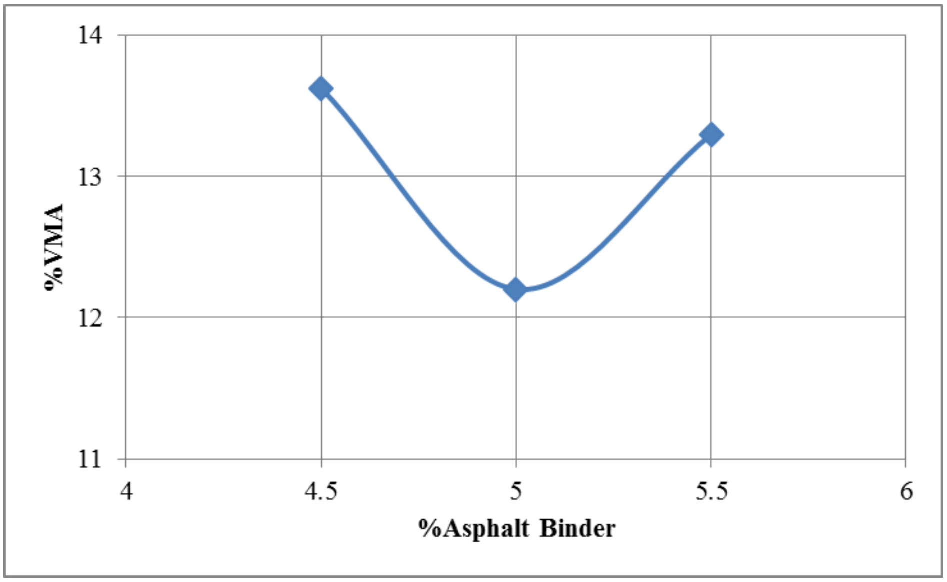

Figure B-4: Void in mineral aggregates versus asphalt content

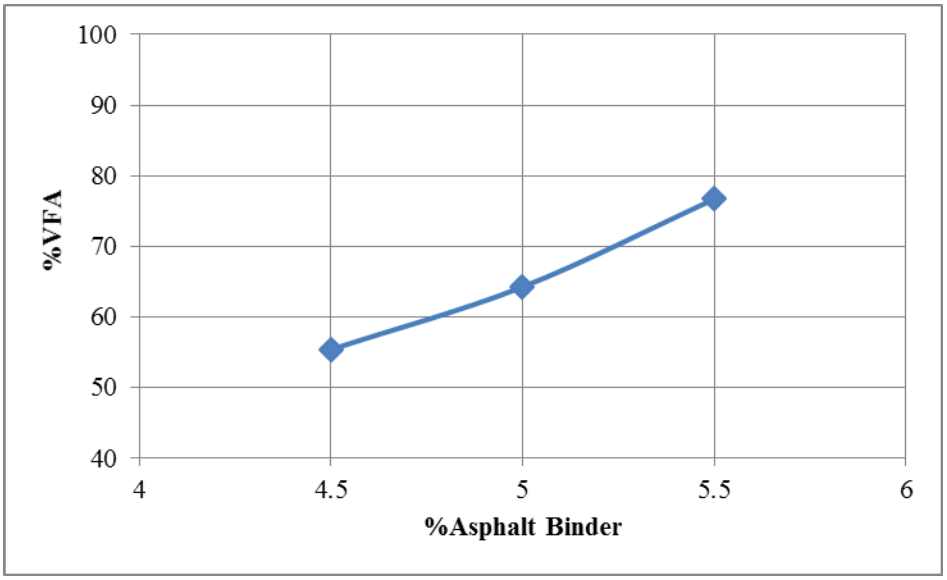

Figure B-5: Void filled with asphalt versus asphalt content

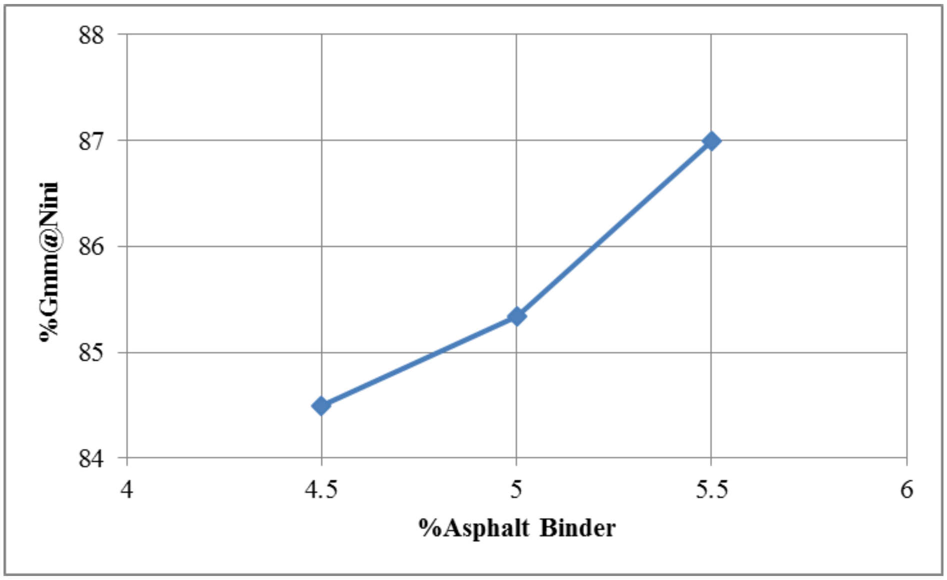

Figure B-6: $\%G_{mm}$@Nini versus asphalt content

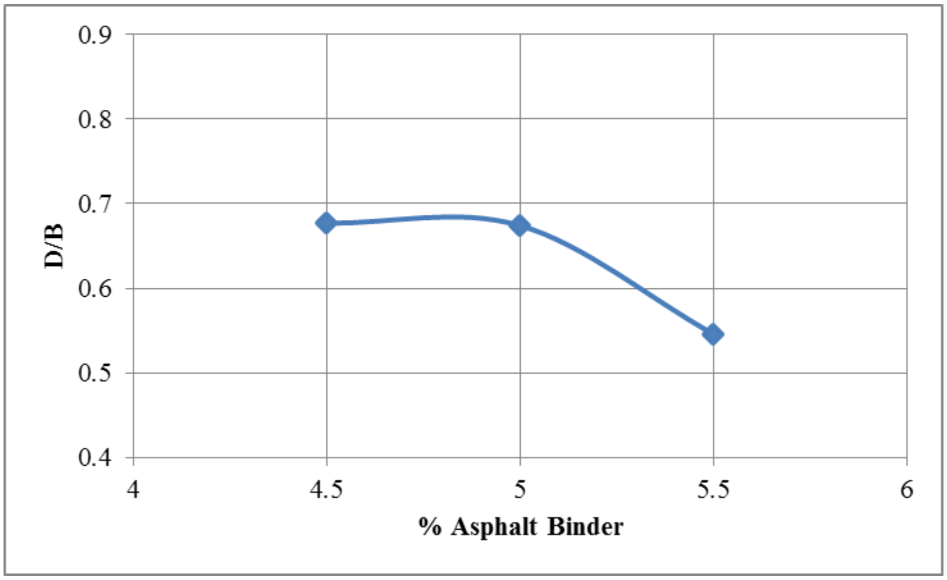

Figure B-7: Dust portion versus asphalt content

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