Environmental Analysis of Using Recycled Asphalt Shingles in Pavement Applications

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Abstract

Recycled asphalt shingles have been used in paving applications for more than two decades and have growing acceptance in the industry. The cost of asphalt binder has steadily increased, fueling pressure to find suitable recycled materials to supplement virgin materials. The Minnesota Department of Transportation has dedicated several studies for using asphalt shingle scrap in asphalt pavements. There are two types of shingles that can be used in pavement: manufacturer waste shingle scrap and tear off shingle scrap. As a result of the studies performed, the Minnesota Department of Transportation currently allows up to 5% of manufacturer waste shingle scrap in paving applications. Research on tear off shingle scrap is continuously developing, and a draft specification from the Minnesota Department of Transportation indicates that up to 5% can be used in asphalt pavement.

In this thesis, both types of shingles were used in asphalt mixtures that were tested for performance to determine if the addition of shingles affects the physical properties. In addition, an environmental analysis was performed. The objective of this research was to determine if it physically makes sense to use shingles in pavement and to understand the environmental implications—which include reducing virgin materials which can yield energy savings.

The analysis suggests up to 3% tear off shingle scrap in asphalt mixtures results in an effect on low temperature properties similar to the addition of up to 5% manufacturer waste shingle scrap, if combined with recycled asphalt pavement addition of more than 20%. The results of our research do support previous research efforts regarding the use of recycled asphalt shingles in pavement; however, based on these results, the Minnesota Department of Transportation draft specification for the use of tear off shingle scrap in asphalt pavement should state that up to 3%, not 5%, shingles can be used.

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Chapter 1

Introduction

1.1 Background

The use of recycled asphalt shingles in asphalt paving applications has been developing for more than two decades and has growing acceptance in the industry. The cost of asphalt binder has increased steadily and there is growing pressure to find suitable recycled materials to supplement virgin materials. In the last 20 years, The Minnesota Department of Transportation (MnDOT) has dedicated several studies to the use of manufacturer waste shingle scrap (MWSS) in asphalt pavements [1]. As a result of the studies performed, MnDOT currently allows up to 5% MWSS in asphalt paving applications. Three main asphalt shingle manufacturers in Minnesota generate approximately 30,500 tons per year of shingle scrap. In 2003, 9,000 tons of scrap were recycled.

The situation is quite different for the post consumer or tear-off shingle scrap (TOSS). Because the asphalt binder in TOSS is significantly aged, adding even small quantities in asphalt mixtures can negatively affect pavement performance.

A recent research project sponsored by the Solid Waste Management Coordinating Board (SWMCB), comprised of commissioners from Anoka, Carver, Dakota, Hennepin, Ramsey and Washington counties plus representation from the Minnesota Pollution Control Agency, focused on increasing the usage of MWSS within the six counties[1]. The study also focused on the use of TOSS. Annually, about 300,000 tons, or up to 20%, of the six counties' construction and demolition (C&D) waste stream is comprised of TOSS [1]. Some informal observations indicate that nearly 90% of TOSS has the potential to be recycled similar to the MWSS for paving applications. Although small quantities of TOSS were used in a few research projects, the majority is landfilled [1]. With field and laboratory tests underway on TOSS use in asphalt pavements, the potential for the C&D and asphalt paving industries to develop recycling operations is growing.

1.2 Purpose and Scope

With over a decade of research completed, MnDOT currently allows the use of MWSS in asphalt pavement. Research studies have showed that using 5% or less of the total binder content from MWSS does not significantly change pavement performance. Based on a limited number of studies, a draft specification was released at the beginning of 2010, by MnDOT proposing a similar limit of up to 5% TOSS that can be added to asphalt mixtures. The objective of this thesis is to perform additional experimental work focused on low temperature properties of asphalt mixtures to help fine tune this draft specification. In addition, a life cycle analysis will be performed to evaluate the environmental benefits and consequences of using shingles. First, a literature review will summarize previous research performed on the use of shingles in pavements and will introduce current methods and technologies in the industry. Next, low temperature experimental work will be performed on asphalt mixtures containing different percentages of shingles using the Bending Beam Rheometer (BBR) laboratory test. Analysis of Variance (ANOVA) will be used to analyze the behavior of the different mixtures. In Chapter 4, a program called PaLATE will be used to run a preliminary life cycle analysis to compare environmental data for each of the mixtures. In Chapter 5, based on laboratory and environmental results, conclusions will be drawn and recommendations will be proposed regarding the specifications for TOSS.

Chapter 2

Literature Review

In this review, basic background information on the composition and production of asphalt roofing shingles will be briefly discussed. The history behind the research and development of recycling of manufacturer waste shingle scrap (MWSS) is then presented followed by a review of past and current research on using tear off shingle scrap (TOSS).

2.1 Introduction to Shingles

Shingles are composed of four materials: asphalt binder, a paper backing, mineral filler, and sand, as shown schematically in Figure 2.1.

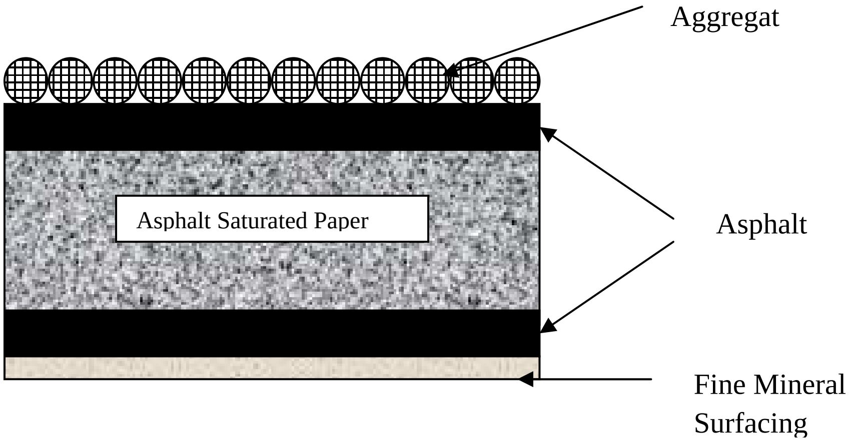


Figure 2.1 - Profile View of a Typical Asphalt Shingle

There are two main types of shingles: glass and organic. ASTM D225 [2] specifies that the paper backing of organic shingles is composed of organic fibers. In manufacturing, the paper, often made from wood fibers, is coated with asphalt to treat and prepare the paper. Next, the shingle is coated with more asphalt as an adhesive to be surfaced with mineral granules. This mineral aggregate's function is to protect the shingle [2].

ASTM D 3462 specifies that the backing of a glass shingle is composed of woven glass fibers [3]. Similar to organic shingles, the glass shingles are coated with asphalt and covered with mineral aggregate. Because specifications in the past allowed asbestos as a backing for glass shingles, some cannot be recycled and used in asphalt pavements [3].

The asphalt binder used in shingles, both saturant and coating, is stiffer than typical asphalt binders used in paving applications. At 77°F, the penetration values for asphalt in shingles ranges from 20 tenths of a mm (dmm) to 70 dmm, while traditional paving binders range from 50 dmm to 300 dmm [4]. This stiffer asphalt binder is used in shingles to prevent the flow of material during high temperatures. Asphalt shingles are composed of the paper backing, granular material, and asphalt binder. The percentage, by weight, of the granular material is the highest out of all the materials. There are several types of aggregate in each shingle: ceramic, headlap sand, and an asphalt stabilizer, often limestone. Ceramic coated aggregate is crushed rock coated with metal oxides. Ceramic granules play the largest role in shingle performance. Headlap granules are ground coal slag and make up the largest component of all the aggregate. Backsurfacer sand is washed sand, included to prevent shingles from sticking together in packaging [4].

The basic manufacturing process is similar for organic and glass shingles. In the first step, the shingle paper is unrolled onto a conveyor belt where it becomes saturated with asphalt. Next, the saturated paper is coated with adhesive asphalt and then is coated with granules and aggregate. After coating, the roll of coated paper is given time to cool before cutting. Cooling is performed to prevent agglomeration of shingles. Next, the paper is cut into individual shingles and then packed for shipping [5]. Manufacturer scrap includes tab punch outs and damaged, unusable whole shingles. Scrap material contains all valuable ingredients, but does not pass aesthetic qualifications.

2.2 Background on Manufacturer Waste Recycled Asphalt Shingles Use

Research on the use of MWSS in asphalt pavement began over twenty years ago and occurred in three phases. The Minnesota Department of Transportation a leader in the development of recycled asphalt shingles in pavement, began its first phase of research in the 1990's. The first phase of research focused on investigating the possibility of using MWSS in paving applications by performing laboratory tests and in developing a specification detailing the approved use of MWSS in asphalt pavement mixtures. The second phase, beginning in 2000, focused on promoting the use of MWSS to the asphalt industry. In the third phase, which started in 2001, research and development was proposed to better understand the effects of using TOSS in pavement applications [1].

2.2.1 Phase One

Munger Recreational Trail was one of the first pavement sections built using recycled asphalt binder and its performance was investigated in a study conducted by Turgeon et al., in 1993 The trail, constructed in 1990, used both tire rubber and manufacturer waste shingle scrap. The two mile section of the 12 foot wide trail was paved in one 2.5 in. thick pass on 4 in. of crushed concrete base. Turgeon used five mixture designs: 1) a control section with traditional quantities of aggregate and asphalt binder; 2) 3%, by weight, shredded rubber tires and an increased quantity of asphalt binder; 3)6% shredded rubber tires and an increased quantity of asphalt binder; 4)3% tires and 6% manufacturer waste shingle scrap and a slightly increased quantity of asphalt binder; and 5) 9% manufacturer waste shingle scrap and a decreased quantity of asphalt binder. When rubber is used in paving applications, more virgin binder must be used. Because binder is the most expensive material used in hot mix asphalt, used rubber tires can lead to a significant rise in construction cost. Turgeon made conclusions based on the quality of the pavement after service. After several years of use, the rubber sections failed, while the section of pavement constructed with shingles remains in use [6].

In another Minnesota study, conducted by Newcomb et. al. in 1996, three sources of roofing waste were used: felt backed manufacturer waste shingle scrap, fiberglass backed manufacturer waste shingle scrap, and tear off shingle scrap [4]. Table 2.1 lists all of the physical properties of the shingles used in the study. The manufacturer waste shingle scrap material was received from CertainTeed Corporation, a shingle manufacturer in Minnesota. The shingles were processed by a Minnesota contractor, Omann Brothers. Both types of shingles were ground by two tandem hammermills and then water cooled to prevent agglomeration. After cooling, the shingles were separately stockpiled. Because water was used to cool the shingles after grinding, they had to be fan dried prior to use . Both shingles were ground to a size of 5 to 30 mm. Newcomb et. al. used several mixtures with varying proportions of shingles; however, no mixture contained less than 5% shingle scrap.

Table 2.1 - Properties of Shingles in Newcomb et al. Study

Properties1	Felt	Fiberglass	Re-Roof
Binder Content, %	approx. 28%	approx 28%	30 - 40%
Binder Properties:			
Softening Point, °C (°F)	52-102 (125-215)	52-102 (125-215)	66-82 (150-180)
Penetration, dmm (25 °C)	23-70	23-70	20 minimum
Ductility, cm (5cm/min, 25 °C)	NA	NA	25 minimum
Flash Point, °C (°F) COC	>260 (500)	>260 (500)	232 (450) minimum
Moisture Content, %	NA	NA	5.0 maximum
Gradation, Percent Passing2			Coarse Fine
4.75 mm	100	100	95-100 100
2.36 mm	69	89	65-75 100
1.0 mm	45	65	15-35 100
0.3 mm	5	11	0-15 10 max
0.15 mm	0	1	0-10 5 max

Temperature susceptibility was determined by measuring the resilient modulus over a range of temperatures (1, 25, and 40 °C) for each mixture. The authors measured moisture sensitivity by partially saturating mixtures before performing Indirect Tensile Strength and Resilient Modulus Tests. Low temperature behavior of the various mixtures was assessed by running Indirect Tensile Strength Tests at -18 °C. Deformation was determined by performing a Static Creep Test, which applies a 100 kPa (14.5 psi) load for an hour while measuring axial deformation of the cylindrical specimens. The creep test was done at 25 °C (77°F) and 40 °C (104 °F). Based on these tests, the authors concluded that pavement mixtures with shingles required less compaction, and that moisture sensitivity was not affected by adding shingles. However, they found that thermal properties were affected: a mixture with 5% or more of shingle scrap resulted in a decrease in performance with lower tensile strengths observed. Newcomb also noted that mixtures that included felt backed shingles would deform before cracking in low temperatures. In the creep compliance analysis, Newcomb also determined that deformation was reduced when a softer virgin binder was added in addition to the shingles. The opposite held true when the stiffer virgin binder was used [4].

One important conclusion of these studies was that by using more than 5% MWSS in asphalt mixtures negatively affects their performance. By 1995, The Minnesota Department of Transportation had gathered enough information supporting the fact that adding small amounts (about 5%) of MWSS, performance was not negatively affected. In 1996, the first draft of restrictive specifications was developed and introduced to contractors and agencies [1]. At the time of adoption, shingles could only be used with permission, on a job-by-job basis. In 2003, after more research and use, the specifications were amended such that shingles could be used on a less permissive basis, allowing use unless explicitly prohibited. In 2006, after Highway 10 near St. Cloud prematurely cracked, specifications were further amended to require at least 70% new asphalt binder when asphalt shingles were used as a percentage of the total allowable recycled asphalt pavement (RAP). The specification for using MWSS is in Appendix A [7].

2.2.2 Phase Two

Phase two was conducted after phase one, and began in 2000, to accelerate industry and contractor acceptance of recycled asphalt shingles in asphalt paving applications. At the time of initiation of phase two, only two HMA producers were using recycled asphalt shingles in pavements. One of the main goals of the phase two research was to address the technology concerns of contractors. In addition, MnDOT hoped to educate various agencies about the benefits of using shingles in asphalt pavements and increase the demand. Together, MnDOT and the Office of Environmental Assistance (OEA), which is now part of the Minnesota Pollution Control Agency (MPCA), published "A Guide to the use of Roofing Shingles in Road Construction: It's All Part of the Mix [1]." This guide was distributed to agencies, HMA producers, contractors, and local engineers. In this phase, MnDOT also began to recognize the potential market for post consumer shingle waste or tear off shingle scrap (TOSS) [1].

MnDOT and OEA conducted interviews with various members of the HMA community and learned the main barrier to recycled asphalt shingles market growth was the lack of available MWSS [1]. A large portion of the MW shingles had been committed to only a few contractors. In 2005, only four contractors in Minnesota, Bituminous Roadways, Inc., Omann Brothers, Allied Blacktop, Corp., and Bauerly Companies, were processing manufacturer waste shingle scrap [1].

Bituminous Roadways, Inc., (BRI) began recycling shingles in HMA in 1995 and was contracted to receive MW shingle scrap from CertainTeed Corporation. BRI processes its own shingles and uses them in accordance with all existing MnDOT specifications. Omann Brothers began recycling in 1991 and has received scrap from CertainTeed Corporation and Owens Corning, Inc.. Unlike BRI, Omann Brothers has also been successful at producing HMA mixtures with higher percentages (i.e. 20 to 30 percent) of recycled asphalt shingles. This is possible because many of Omann Brother's clients are private and local and need not to be governed by MnDOT [1]. Allied Blacktop, in Eau Claire, Wisconsin, also received MWSS from Minnesota producers. Bauerly Companies began recycling shingles in 2004. Each of the four contractors has unique methods to processing and recycling shingle scrap, although each must screen waste for contaminants and grind before use. BRI uses a Rotochopper asphalt shingles grinder, while Omann Brothers has designed its own equipment. Allied Blacktop uses the Bandit Beast Grinder, but has a different screening process [8,9].

2.3 Phase Three and the Integration of Tear off Shingles in Paving Applications

Phase three of research was co-sponsored by MnDOT and The Recycled Materials Resource Center (RMRC) [1]. The key focus was to continue field testing, market development, and discuss technology, but this time, for tear off shingle scrap (TOSS).   At this point, market demand and research history had been established for MWSS, but a few barriers held back the development of post consumer TOSS. In the early phase of this research, alternative uses of TOSS waste other than in HMA applications were important because MnDOT did not allow post consumer shingles in pavement, citing that quality control/quality assurance was an issue.   In addition, concerns about inconsistent and sporadic quantities of shingles caused skepticism among the HMA community. Phase three also identified various end market uses of TOSS. Three of the uses included; 1) a dust control agent; 2) an unbound base aggregate supplement; and 3) A 5% blend in asphalt pavement [1].

In the United States, approximately 7 - 9 million tons of old asphalt shingles roofing (“tear-offs”) are removed from existing building, and there are 300,000 tons of tear-off shingles in landfills each year. It is the third largest source of land filled materials each year with nearly two million tons of asphalt available, which is 9% of the national need [1].   Like MWSS, the materials found in TOSS are valuable, as they are produced with high quality surface granules. With specifications already in place for the usage of MWSS in pavement, TOSS have not been used in the past because some believe the asphalt in the shingles become aged and oxidize over time. In addition, the shingles can easily be contaminated and the source of shingles can be variable.

As a method to educate the asphalt industry about using TOSS in asphalt pavement, Bituminous Roadways Incorporated (BRI) performed TOSS processing demonstration in 2003. BRI received tear off shingle waste from Sela Roofing which generated scrap from residential projects in St. Paul. The shingle waste was sorted by hand to remove waste such as metal, wood, paper, plastic, and other debris. BRI used 200 tons of the TOSS and processed it further at the asphalt plant. The shingles made multiple passes through the grinding and screening equipment to ensure adequate removal of contaminants. BRI, already with a strong history of processing MWSS, reported that TOSS were much easier to grind, due to the higher oxidation of TOSS. Although using multiple passes to de-contaminate the shingles worked well, the equipment was later improved so that one pass was sufficient to yield a high quality product [10].

Because TOSS experience a loss of aggregate over time, they can contain a higher percentage of asphalt than MWSS. The asphalt in the TOSS is stiffer due to the volatilization of organic compounds in sunlight and weathering. Due to the hardened asphalt binder in the shingles, TOSS are easier to shred and are less likely to stick together during processing. Although BRI demonstrated the feasibility of processing TOSS, the effects and consequences of using TOSS had to be further investigated.

2.3.1 Tear off shingles background

The largest quantity of TOSS is generated from residential re-roof projects. A smaller percentage is due to commercial and industrial projects and abatements. It is possible to use shingles from all sources, however, caution must be taken when using shingles from abatement projects because of the probability of hazardous waste contamination.   In addition, all three generators must sort and store the shingle scrap properly to prevent excessive debris contamination.

In the past, tear off shingles have not been allowed in government monitored (under MnDOT jurisdiction) paving projects. In January 2010, however, a specification draft dictated that up to 5% of TOSS may be used in hot mix paving applications. The provision for TOSS dictates that "tear off scrap shingles, as an asphalt binder source, may be included in plant mixed mixtures produced under specification 2360." This specification can be viewed in Appendix B [11].

The benefits of using shingles in hot mix asphalt pavements include decreased costs for shingle disposal and conserved landfill space, a reduced need for virgin material, and improved high temperature resistance [1, 4]. Because the materials used in asphalt are high quality and the asphalt binder in the shingles is stiffer, the pavement could possibly have an increased shear resistance which could reduce failure mechanisms such as rutting and shoving.   There has been some concern about the low temperature cracking behavior with the stiffer asphalt. One of the objectives of this thesis is to observe this potential effect.

2.3.2 Tear off Shingle Processing

Processing TOSS is especially important given that roofing waste can be easily contaminated. The basic steps include grinding, magnetic debris removal, and air blower debris removal. Similar to manufacturer waste shingles, the scrap must be properly ground. Grinding is often performed twice; however, some newer equipment can process the shingles in one pass. Next, because tear off shingles are contaminated with various waste items such as nails, wood, paper, and other debris, a magnet and blower must be used. The magnet attracts metallic waste, while the blower eliminates lightweight waste such as paper. Some contaminants cannot be removed with the magnet and blower, so often, manual sorting is required. In the last step, the shingles must be stockpiled properly. They must be stored separately from manufacturer waste shingles and must be isolated from excessive precipitation and weathering [12].

From 1940 to 1973 asbestos containing materials (ACM) were used in shingle production as a fiberglass paper backing. Due to the toxic nature of this material, any shingles with ACM are prohibited from use in paving mixes. This is problematic because extra effort must be taken to identify and control the materials. In addition to ACM, hazardous waste can contaminate shingles beyond potential usage. Other, less problematic, contaminants include adhesives, nails, and paper. Agencies must develop some criteria for rejecting shingles based on its contaminants. Iowa Department of Transportation has developed a method of identifying asbestos materials in shingles. A small sample of shingles is placed in a furnace at 500 degrees Centigrade for 2 hours. After cooling, the sample is viewed under a microscope and it is manually examined for the presence of asbestos fibers [13].

Chapter 3

Experimental Work and Analysis

In this chapter, background information will be presented about low temperature cracking and the experimental tests performed in this thesis. As discussed previously, research will be performed in this thesis to understand the low temperature cracking effects of adding recycled asphalt shingles in asphalt pavement. This knowledge will help fine-tune the Minnesota Department of Transportation draft specification. One distress affecting Minnesota asphalt pavements is low temperature thermal cracking. When the temperature drops significantly, the asphalt mixture contracts, and high stresses develop since the asphalt layer is restrained by the aggregate layers below it. The stresses in the pavement are released by the formation of transverse cracks perpendicular to the centerline of the pavement, as depicted in Figure 3.1. The presence of thermal cracks accelerates the destruction of asphalt pavements, since water can easily infiltrate in the pavement system and freeze-thaw cycles continuously deteriorate the pavement structure. The asphalt binder in TOSS has aged considerably due to prolonged exposure to UV radiation and heat and therefore, it is significantly stiffer and has diminished relaxation properties than the binder in MWSS.

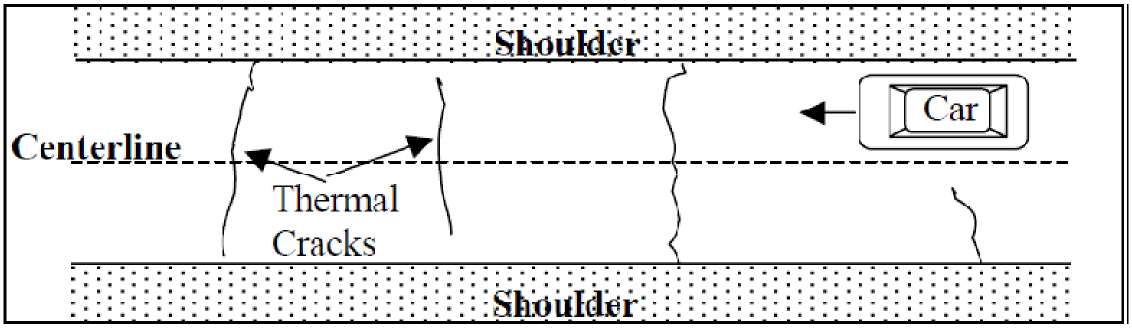


Figure 3.1 – Thermal Cracking [14]

3.1 Bending Beam Rheometer

A number of experimental methods have been developed over the years to characterize asphalt binders and asphalt mixtures behavior at low temperatures. One fundamental test used to characterize viscoelastic materials is the creep test. In this test, a stress is applied instantaneously to the specimen and it is maintained constant for the duration of the test. At the end of the test, the stress is removed and the recovery of the specimen can be monitored if recovery properties are desired. The creep compliance obtained from the experimental data can be used to calculate thermal stresses that develop in a restrained specimen that can be further used to estimate the magnitude of pavement stresses at low temperatures.

For asphalt binder, the results from a creep test performed with the Bending Beam Rheometer (BBR) have been used as part of the current American Association of State Highway and Transportation Officials (AASHTO) specifications for the past two decades [15]. For asphalt mixtures, the results from a creep test performed using the Indirect Tension (IDT) method have been used as part of a current AASHTO method for the past two decades [16]. The IDT requires expensive testing equipment and very few laboratories can perform it. Recently, it was shown that creep tests can be performed on thin mixture beams using the same BBR equipment that is currently used for asphalt binders. This test is very easy to perform and many laboratories have the equipment and training to perform it [14].

In the BBR test, asphalt mixture specimens are prepared using standard gyratory specimen. Six rounded slices are cut to 12 mm thick, and each rounded slice is sliced vertically to obtain seven rectangular beams. The ends of the beam are then cut into 101 mm long rectangular beams ranging from 6 – 8 mm thick. Three rectangular beams from each mixture, the first, fourth, and sixth are taken from round slice. This procedure can be viewed in Figure 3.2 [14].

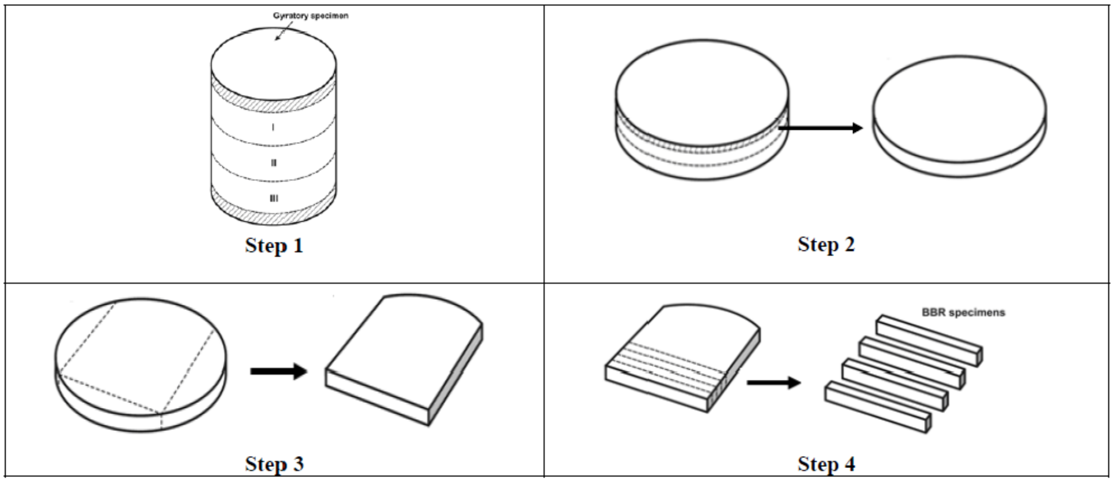


Figure 3.2 – Bending Beam Rheometer Specimen Preparation

In this research effort, a Canon Instrument BBR was used to perform the BBR test on asphalt mixtures. A 4413 mN load was applied at midspan to a simply supported beam for 1000 seconds and mid span deflections were measured. The results were used to calculate creep stiffness and rate of relaxation which represent good indicators of low temperature cracking behavior. A stiffer mixture with smaller relaxation rates will be more prone to thermal cracking. Figure 3.3 shows the testing apparatus and mixture specimen [14].

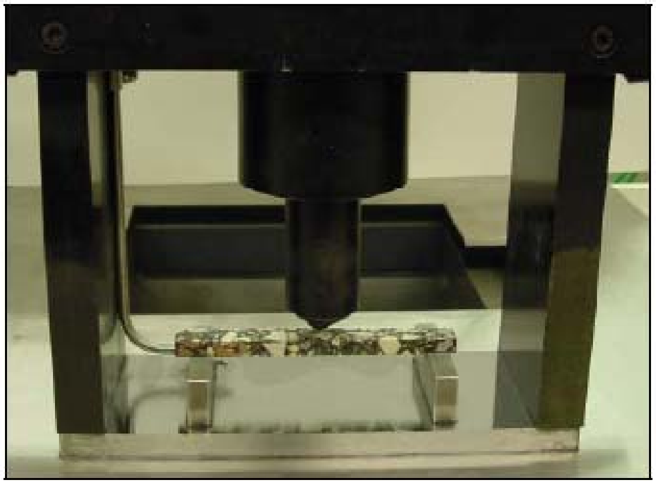


Figure 3.3 – Bending Beam Rheometer Test Setup

An example of creep stiffness curves as a function of time for mixture 1 using three replicates and two test temperatures is shown in Figure 3.4. Note that the m-value is defined as the slope of the log creep stiffness vs. log time curve.

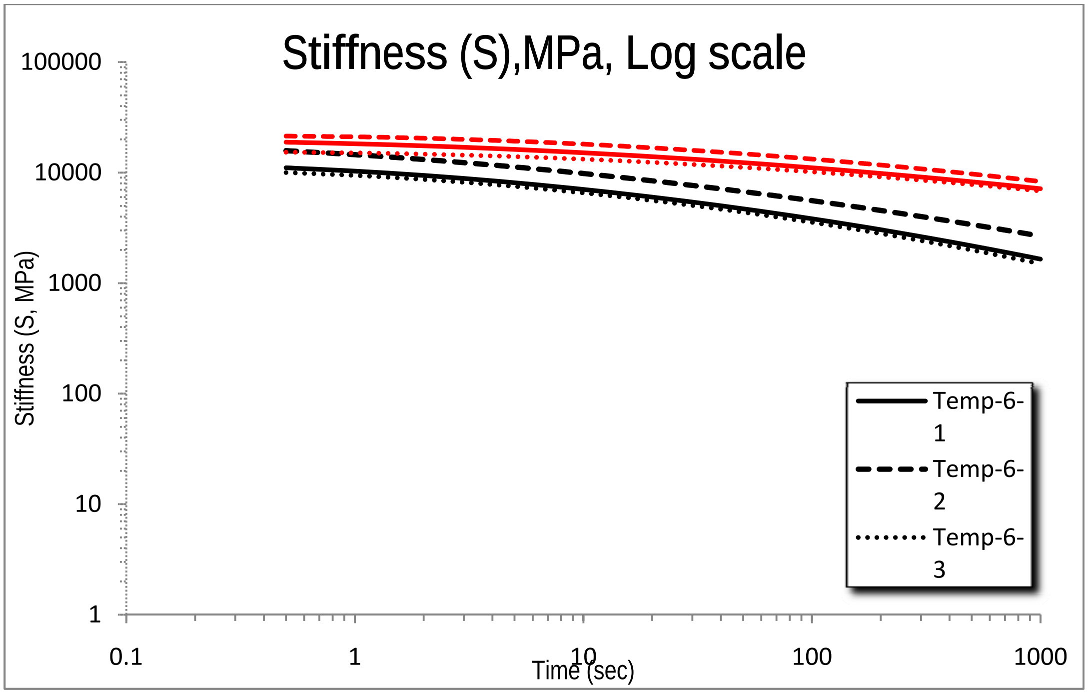


Figure 3.4 – Creep Stiffness vs. Time

3.2 Materials

The asphalt mixtures used in this study were provided by Minnesota Department of Transportation (MnDOT) and represent mixtures that were used in a separate research project performed by MnDOT and (MPCA) to determine the effects of using varying proportions of recycled asphalt shingles, reclaimed asphalt pavement (RAP), and different virgin binders on pavement performance. MnDOT developed a plan with a testing matrix of 17 different mixtures with varying amounts of recycled asphalt shingles and RAP, as shown in Table 3.1. It is important to note that the design was based on one aggregate gradation and a PG58-28 asphalt binder, and traffic of 1 to 3 million Equivalent Single Axle Loads (ESAL). MnDOT asphalt laboratory performed asphalt binder BBR tests. University of Minnesota pavement laboratory performed asphalt mixture BBR tests. The research in this study focused on the low temperature properties of asphalt mixtures and is based on the results from the BBR asphalt mixture tests [39].

Table 3.1 - Mixture Description

Mix		**Recycled Material**			**Binder**	
Mix No	**Mix ID**	**RAP (%)**	**TOSS (%)**	**MWSS (%)**	**58 - 28**	**51 - 34**
1	PG 58-28 Control	0	0	0	x	
2	15% RAP	15	0	0	x	
3	25% RAP	25	0	0	x	
4	30% RAP	30	0	0	x	
5	15% RAP 5% MWSS	15	0	5	x	
6	15% RAP 5% TOSS	15	5	0	x	
7	25% RAP 5% TOSS	25	5	0	x	
8	25% RAP 5% MWSS	25	0	5	x	
9	25% RAP 5% TOSS	25	5	0		x
10	25% RAP 5% MWSS	25	0	5		x
11	25% RAP 3% TOSS	25	3	0	x	
12	25% RAP 3% MWSS	25	0	3	x	
13	15% RAP 3% TOSS	15	3	0	x	
14	15% RAP 3% MWSS	15	0	3	x	
15	10% RAP 5% TOSS	10	5	0	x	
16	15% RAP 5% TOSS*	15*	5	0	x	
17	5% TOSS	0	5	0	x	

- Different RAP Source – millings containing 4.0% AC

3.3 Analysis of Experimental Results

Graphical comparisons and analyses of variance (ANOVA) were performed to:

1. Evaluate the effect of different amount of RAP(%) on creep stiffness, S(t) and rate of relaxation, m-value, at the specification time of 60 seconds. Evaluate the effect of different amounts of TOSS and MWSS on creep stiffness and rate of relaxation at 60s.

ANOVA is a statistical tool used to measure the relative difference between means for different data sets. The S(60) and m(60) were set as dependent variables, and temperature, percent RAP, percent TOSS, and percent MWSS, were defined as independent variables. Interactions among the various independent variables were considered in results. All test results were analyzed with a linear ANOVA model which assumes independence, normality, and equal variance among groups. In the ANOVA, initially, all independent variables were considered, however, if no statistically significant interaction was observed for a given variable, it was removed from the analysis, and the ANOVA was completed again. This was performed to isolate the critical variables in the experiment. In all analyses, the significance level, α was set as 5%.

3.3.1 Evaluate the effect of RAP (%) on Stiffness and Rate of Relaxation

In this analysis, mixtures 1, 2, 3, and 4 with 0, 15, 25, and 30% RAP, respectively, were selected for the ANOVA. Mixture 1 was set as a control group and the other three mixtures, mixtures 2, 3 and 4 were set as test groups. Table 3.2 summarizes the mixture proportions, Table 3.3 summarizes creep stiffness and rate of relaxation values, and Figures 3.5 and 3.6 illustrate the stiffness results for each of the four mixtures used in this analysis.

Table 3.2 Summary of tested mixtures

Mixture	**% RAP**	% TOSS	% MW	Binder	ETC
1	**0**	0	0	58-28	Control
2	**15**	0	0	58-28	Test
3	**25**	0	0	58-28	Test
4	**30**	0	0	58-28	Test

Table 3.3 Summary of S(60) and m(60)

Mixture	Temp, ºC	Creep Stiffness(60), Mpa				m-value(60)	
		Original	CV (%)	Log Scale	CV (%)	m-value(60)	CV (%)
1	-6	4,627	20%	3.66	2%	0.287	6%
	-18	12,886	11%	4.11	1%	0.153	8%
2	-6	6,628	19%	3.81	2%	0.177	15%
	-18	15,198	14%	4.18	2%	0.123	15%
3	-6	8,626	5%	3.94	1%	0.159	10%
	-18	16,885	21%	4.22	2%	0.119	7%
4	-6	7,524	8%	3.88	1%	0.168	4%
	-18	13,249	13%	4.12	1%	0.117	14%

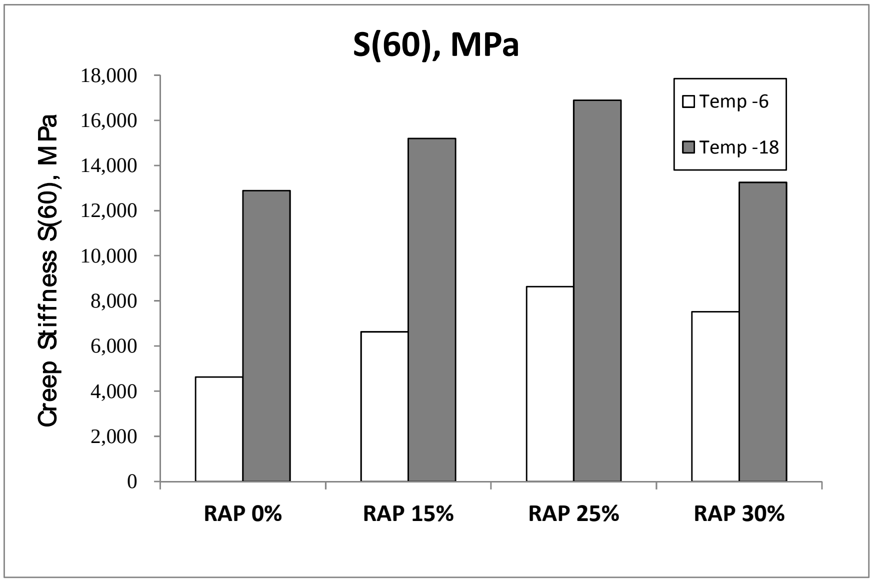


Figure 3.5 - Histogram of Creep Stiffness Values for Mixtures 1-4

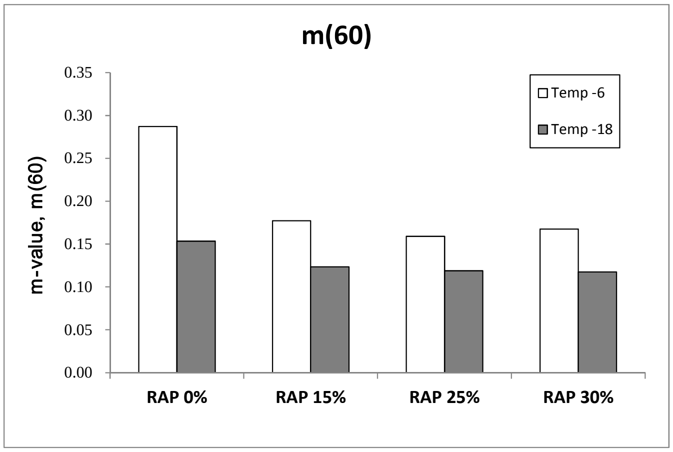


Figure 3.6 – Histogram of Rate of Relaxation Values for Mixtures 1-4

ANOVA was performed using the logarithm of the creep stiffness values. The logS- and m-values were defined as dependent variables whereas the quantity of RAP and testing temperatures were independent variables. Any possible interactions between the quantities of RAP and temperatures were considered. Also in first analysis, interaction between RAP and temperature was considered. Tables 3.4 and 3.5 summarize the results of the ANOVA using the presence of RAP and the different testing temperatures as variables only. Table 3.6 summarizes the results for different quantities of RAP and temperatures.

Table 3.4 - ANOVA Results for Creep Stiffness

Source	SS	df	MS	F	p-value
Intercept	749.05	1	749.05	175294	**0.000**
{F}RAP	0.229	3	0.076	17.8	**0.000**
{F}Temperature	1.310	1	1.310	306.5	**0.000**
{F}RAP•Temp	0.074	3	0.025	5.8	**0.002**
Error	0.167	39	0.004		
Total	750.83	47			

Table 3.5 – ANOVA Results for Rate of Relaxation

Source	SS	df	MS	F	p-value
Intercept	1.243	1	1.243	5100	**0.000**
{F}RAP	0.053	3	0.018	72.6	**0.000**
{F}Temperature	0.057	1	0.057	233.9	**0.000**
{F}RAP•Temp	0.017	3	0.006	22.9	**0.000**
Error	0.010	39	0.000		
Total	1.380	47			

Table 3.6 – ANOVA Results for Creep Stiffness and Relaxation Rate

Coefficient	Creep stiffness, S(60)				m-value, m(60)			
	Estimate	Std. error	t	p-value	Estimate	Std. error	t	p-value
Intercept	4.108	0.027	153.94	0.000	0.154	0.006	24.08	0.000
{F}RAP 15%	0.070	0.038	1.85	0.072	-0.030	0.009	-3.34	**0.002**
{F}RAP 25%	0.111	0.038	2.94	**0.006**	-0.035	0.009	-3.86	**0.000**
{F}RAP 30%	0.011	0.038	0.29	0.774	-0.036	0.009	-3.99	**0.000**
Temp	-0.449	0.038	-11.90	**0.000**	0.134	0.009	14.83	**0.000**

Using a significance level of 5%, it was observed that the different testing temperatures yielded statistically different stiffness and rate of relaxation values (at 60 seconds). Because asphalt performance is a temperature dependent, this statistical significance can be expected. By adding RAP, a statistically significant difference in stiffness and rate of relaxation can be observed, so further analysis was performed to determine what quantities of RAP yield significant differences. From Table 3.8, no statistically significant effect can be observed by adding 15% or 30% RAP; however, by adding 25%, a significant difference in stiffness was observed. This result is unexpected and further investigation is needed to determine why 25% RAP is significant and 30% is not. For all RAP mixtures statistically significant differences were observed in rate of relaxation.

Based on the p-values for the m-values in Table 3.6, it can be concluded that adding RAP significantly affects the rate of relaxation.

3.3.2 Evaluate the effect of TOSS (%) and MWSS (%) on Stiffness and Relaxation Rate

In this analysis, mixtures 2, 5, 6, 7, 8, 11, 13, and 14 were selected to evaluate the effect of using shingles in pavements.. It is important, however, to remember that a statistically significant effect was observed from using RAP in pavement without shingles. Similar to previous analysis, Log S(60) and m(60) were defined as dependent variables; however, temperature, percentage of TOSS, and percentage of MWSS were used as independent variables. Two interactions between temperature and % TOSS and temperature and %MWSS were considered. Two ANOVA testing groups were defined based on the quantity of RAP, see Tables 3.7 and 3.9.

Table 3.7 – Testing Group 1

Mixture	% RAP	**% TOSS**	**% MW**	Binder	ETC
2	15	**0**	**0**	58-28	Control
5	15	**0**	**5**	58-28	Test
6	15	**5**	**0**	58-28	Test
13	15	**3**	**0**	58-28	Test
14	15	**0**	**3**	58-28	Test

Table 3.8 – Testing Group 2

Mixture	% RAP	**% TOSS**	**% MW**	Binder	ETC
3	25	**0**	**0**	58-28	Control
7	25	**5**	**0**	58-28	Test
8	25	**0**	**5**	58-28	Test
11	25	**3**	**0**	58-28	Test
12	25	**0**	**3**	58-28	Test

The results of computed S(60) and m(60) from Group 1 and Group 2 are shown in Tables 3.9, 3.10 and Figures 3.7-3.10.

Table 3.9 – Summary of S(60) and m(60), Group 1

Mixture	Temp, ºC	Creep Stiffness(60), Mpa				m-value(60)	
		Original	CV (%)	Log Scale	CV (%)	m-value(60)	CV (%)
2	-6	6,628	19%	3.81	2%	0.177	15%
	-18	15,198	14%	4.18	2%	0.123	15%
5	-6	7,653	12%	3.88	1%	0.174	8%
	-18	16,617	11%	4.22	1%	0.129	6%
6	-6	9,612	10%	3.98	1%	0.154	13%
	-18	14,943	19%	4.17	2%	0.12	8%
13	-6	7,416	8%	3.87	1%	0.153	8%
	-18	12,513	11%	4.1	1%	0.117	16%
14	-6	6,568	14%	3.81	2%	0.172	4%
	-18	13,596	9%	4.13	1%	0.122	15%

Table 3.10 – Summary of S(60) and m(60), Group 2

Mixture	Temp, °C	Creep Stiffness(60), Mpa				m-value(60)	
		Original	CV (%)	Log Scale	CV (%)	m-value(60)	CV (%)
3	-6	8,626	5%	3.94	1%	0.159	10%
	-18	16,885	21%	4.22	2%	0.119	7%
7	-6	9,279	16%	3.96	2%	0.132	15%
	-18	15,875	20%	4.19	2%	0.104	19%
8	-6	9,596	13%	3.98	1%	0.136	12%
	-18	15,193	18%	4.18	2%	0.114	24%
11	-6	11,086	21%	4.04	2%	0.131	20%
	-18	16,996	11%	4.23	1%	0.106	15%
12	-6	9,312	17%	3.96	2%	0.143	12%
	-18	15,514	10%	4.19	1%	0.131	9%

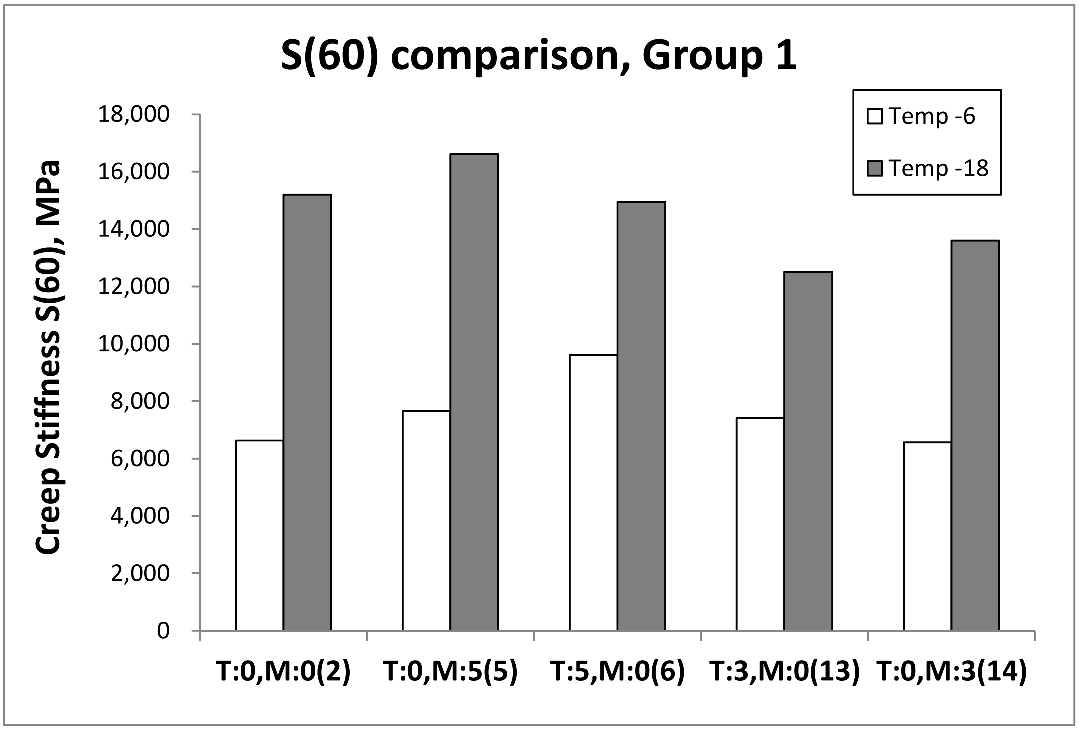


Figure 3.7 – S(60) for Group 1 Mixtures

Note that the T on the plot represents the percentage of TOSS present in the mixture, and M represents the percentage of MWSS in the mixture. In Group 1, all mixtures contain 15% RAP. In Group 2, all mixtures contain 25% RAP.

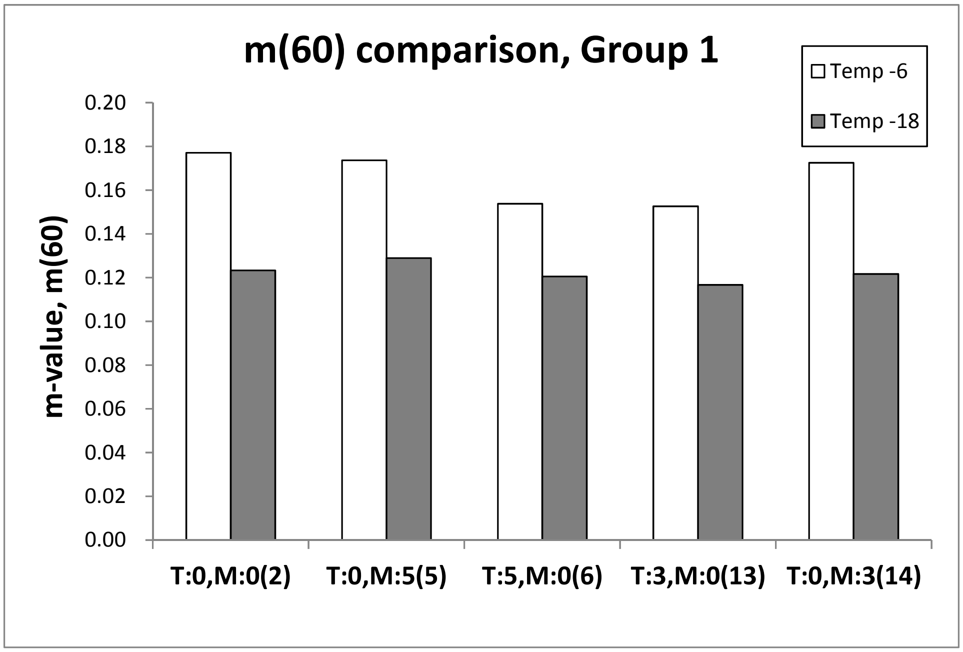


Figure 3.8 – m(60) for Group 1 Mixtures

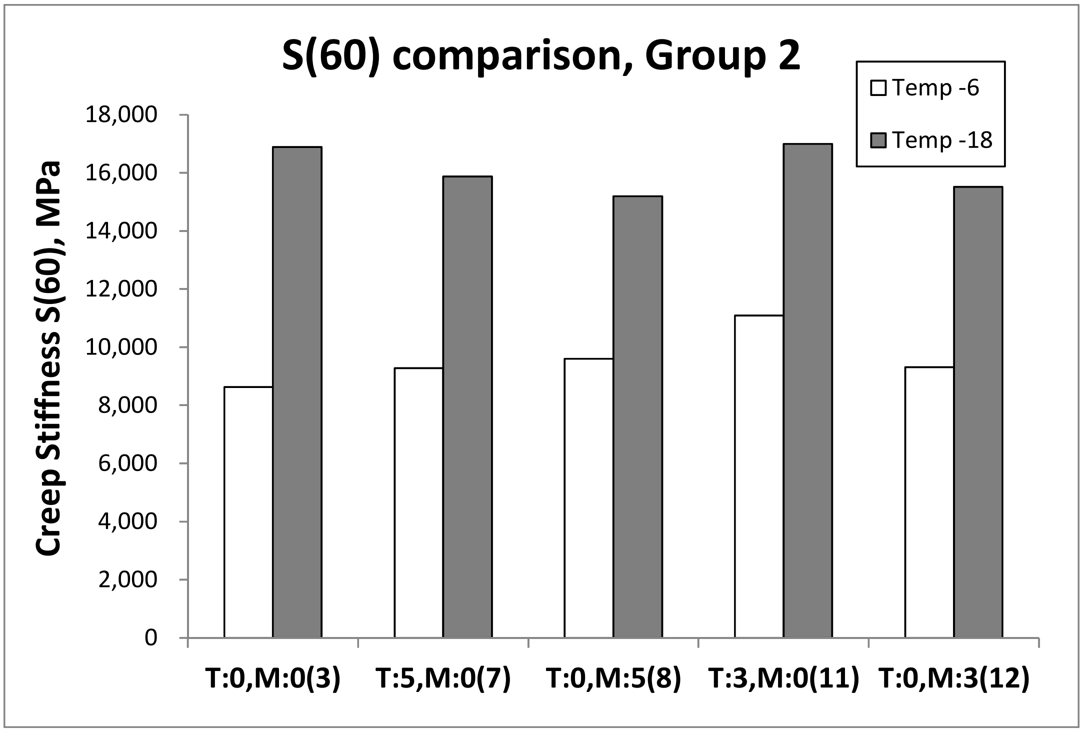


Figure 3.9 – S(60) for Group 2 Mixtures

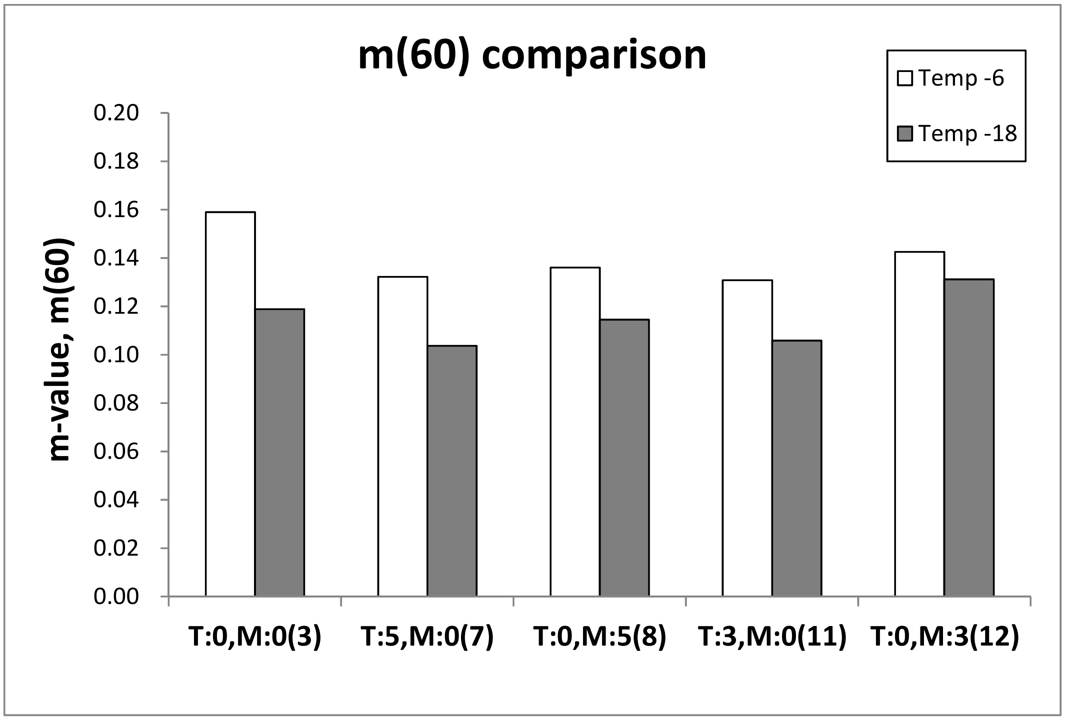


Figure 3.10 – m(60) for Group 2 Mixtures

3.3.3 ANOVA results for Group 1

Within Group 1, a statistically significant effect due to the testing temperatures was observed on both the stiffness and rate of relaxation values. Again, because asphalt is temperature sensitive, this effect is expected. However, a statistically significant effect due to the presence of both TOSS and MWSS was observed for stiffness values. Another ANOVA test was run to determine what quantities significantly affect stiffness. The ANOVA test results can be viewed in Tables 3.11-3.13.

Table 3.11 – ANOVA Results for Creep Stiffness

Source	SS	df	MS	F	p-value
Intercept	952.753	1	952.753	291792	**0.000**
Temperature	1.194	1	1.194	365.823	**0.000**
TOSS	0.057	2	0.028	8.727	**0.001**
MWSS	0.037	2	0.018	5.660	**0.006**
Temp • TOSS	0.064	2	0.032	9.856	**0.000**
Error	0.167	51	0.003		
Total	954.272	59			

Table 3.12 – ANOVA Results for Rate of Relaxation

Source	SS	df	MS	F	p-value
Intercept	1.214	1	1.214	4768.42	**0.000**
Temperature	0.028	1	0.028	109.581	**0.000**
TOSS	0.001	2	0.001	2.841	0.068
MW	0.000	2	0.000	0.218	0.805
Temp • TOSS	0.001	2	0.0005	1.370	0.264
Temp • MW	0.000	2	0.000	0.239	0.789
Error	0.012	49	0.000		
Total	1.256	59			

Table 3.13 – ANOVA Results for Creep Stiffness and Rate of Relaxation

Coefficient	Creep stiffness, S(60)				m-value, m(60)			
	Estimate	Std. error	t	p-value	Estimate	Std. error	t	p-value
Intercept	4.167	0.019	215.415	0.000	0.123	0.007	18.920	0.000
{F}TOSS 3%	-0.071	0.030	-2.351	**0.023**	-0.007	0.009	-0.713	0.479
{F}TOSS 5%	0.001	0.030	0.034	0.973	-0.003	0.009	-0.309	0.759
{F} MW 3%	-0.025	0.024	-1.028	0.309	-0.002	0.009	-0.178	0.859
{F} MW 5%	0.052	0.024	2.195	**0.033**	0.006	0.009	0.604	0.549
Temp	-0.339	0.019	-17.505	**0.000**	0.054	0.010	5.565	**0.000**

From Table 3.13, it is observed that using 3% TOSS or 5% MWSS affects stiffness. It is very important to note that adding 3% TOSS reduces the creep stiffness (Estimate = -0.071). Because a reduced stiffness is desirable, this “significant effect” will be neglected. No statistically significant effects were observed for any mixtures for rate of relaxation values.

3.3.4 ANOVA results for group 2

Within Group 2, a statistically significant effect due to the testing temperatures was observed on both the stiffness and rate of relaxation values. Again, because asphalt is temperature sensitive, this effect is expected. No significant difference was observed due to the presence of either TOSS or MWSS shingles for stiffness. A significant difference in rate of relaxation due to the presence of TOSS was observed. Another ANOVA test was run to determine what quantities of TOSS significantly affect the rate of relaxation. The ANOVA test results can be viewed in Tables 3.14-3.16.

Table 3.14 – ANOVA Results for Creep Stiffness

Source	SS	df	MS	F	p-value
Intercept	902.421	1	902.421	184946	**0.000**
Temperature	0.693	1	0.693	142.085	**0.000**
TOSS	0.022	2	0.011	2.215	0.121
MWSS	0.000	2	0.000	0.005	0.995
Temp • TOSS	0.012	2	0.006	1.226	0.303
Temp • MWSS	0.011	2	0.006	1.137	0.330
Error	0.215	44	0.005		
Total	903.374	54			

Table 3.15 – ANOVA Results for Rate of Relaxation

Source	SS	df	MS	F	p-value
Intercept	0.879	1	0.879	2652.663	**0.000**
Temperature	0.009	1	0.009	27.262	**0.000**
TOSS	0.003	2	0.002	5.004	**0.011**
MWSS	0.001	2	0.001	1.866	0.166
Error	0.016	48	0.000		
Total	0.908	54			

Table 3.16 – ANOVA Results for Creep Stiffness and Rate of Relaxation

Coefficient	Creep stiffness, S(60)				m-value, m(60)			
	Estimate	Std. error	t	p-value	Estimate	Std. error	t	p-value
Intercept	4.219	0.029	147.940	0.000	0.126	0.006	21.668	0.000
{F}TOSS 3%	0.010	0.042	0.227	0.822	-0.021	0.008	-2.644	**0.011**
{F}TOSS 5%	-0.026	0.040	-0.642	0.524	-0.021	0.008	-2.770	**0.008**
{F} MW 3%	-0.030	0.042	-0.707	0.483	-0.002	0.008	-0.260	0.796
{F} MW 5%	-0.042	0.042	-1.003	0.321	-0.014	0.008	-1.815	0.076
Temp	-0.283	0.040	-7.027	**0.000**	0.026	0.005	5.221	**0.000**

From Table 3.16, it is observed that using either 3% or 5% tear off shingles significantly affects the rate of relaxation.

Based on the analyses performed in this chapter, a number of important conclusions can be drawn:

1. Adding 15%, 25% or 30% RAP to asphalt mixtures increases the creep stiffness and decreases the relaxation rate of the mixture significantly.
2. For 15% RAP, adding 5% MWSS results in an increase in creep stiffness, however, no significant differences were observed in case of m-values. The mixtures with 3% MWSS showed a decrease in creep stiffness in comparison with the control group. Therefore it can be said that no significant difference in S(60) and m(60) can be expected at least up to 3% of adding MWSS in asphalt mixture.

3. With 25% RAP, adding 3% and 5% level of MWSS resulted in no significant differences in S(60) and m(60) values.
4. Adding up to 5% TOSS resulted in no significant difference in S(60) in either testing group. For the m(60) comparison, no significant differences were observed in Group 1, however, significant differences were observed in Group 2. With 15% RAP, no significant differences of m(60) can be expected up to 5% TOSS however, with 25% RAP, 3% or 5% of TOSS did not change creep stiffness but changed relaxation properties of asphalt mixtures significantly.

Due to the limited number of specimens and comparisons, these results have to be considered with caution.

Chapter 4

Environmental Analysis

Assuming that adding recycled asphalt shingles does not affect the performance of the pavement, the next logical step is be to determine other benefits and consequences. Understanding the other effects helps in the decision making process. Recently, industry has become increasingly aware of natural resources preservation and pollution prevention. As a result, recycling materials has increased greatly in the last few years. To help the industry measure the effects of recycling materials, Life Cycle Assessment (LCA), which considers the entire life of a product from cradle-to-grave, can be used. LCA is a method used to quantify the cumulative environmental impacts throughout the entire life of a product. It provides a general picture of the environmental benefits and consequences between various alternatives for products and processes [17].

LCA evaluates all stages in the product's life which include raw material extraction, transportation, processing, usage, and disposal. The four steps to LCA include; 1) Goal Definition and Scoping; 2) Inventory Analysis; 3) Impact Assessment; and 4) Interpretation [17]. In this thesis, steps 1) and 2) will be performed. LCA was selected as an appropriate method, because it allows the environmental analysis to be conducted only on relevant stages in the life cycle of the pavement.

In the first step, the product, process, or activities are defined and the environmental effects are reviewed and established. In the second step, the material inputs and environmental outputs are identified. The inputs are water, energy, materials; outputs include air emissions, solid waste, and waste water. In the third step, the potential ecological and human effects of the inputs and outputs are assessed. In the last step, the results from the impact assessment and inventory analysis are evaluated and are used for decision making [17].

4.1 PaLATE Model

To perform the LCA, a tool known as the Pavement Life-Cycle Assessment Tool for Environmental and Economic Effects (PaLATE) was used [18]. PaLATE was created by Dr. Arpad Horvath as a joint venture between RMRC and the University of California – Berkeley. PaLATE, which is a Microsoft Excel spreadsheet program, uses EPA data and information to quantify any environmental consequences from constructing and maintaining pavements [18]. PaLATE can also roughly estimate the trade-offs between using virgin and recycled materials. PaLATE requires user input data for initial construction material quantities, maintenance quantities, and equipment use. It then determines the environmental effects such as energy consumption, water usage, global warming potential, and various other emissions. It should be noted that this tool is simply meant to understand the general environmental effects and that the quantities provided from the program are to be used with caution. PaLATE uses EPA values in a database called Factor Information Retrieval (FIRE) to estimate all air emission/pollutants. [18]

The objective of this preliminary LCA was to evaluate the various alternatives for the management of shingle scrap. The LCA is used to quantify energy use, air emissions, and global warming potential (GWP) for various phases in the lifecycle of the pavement. The only phases in the lifecycle of a pavement with asphalt shingles differing from traditional asphalt pavement are materials extraction, processing, and construction. In the analysis, environmental output data are calculated for only these phases. Based on the experimental results and analyses detailed in Chapter 3, it is reasonable to assume that adding small amounts of MWSS or TOSS does not significantly affect low temperature performance, and therefore, for the purpose of this study, the costs of maintaining and rehabilitating pavements are not considered in the analysis.

4.1.1 Goal Definition and Scoping

The first step to the LCA is defining the objectives and scope of the project and is performed by identifying the following six decisions at the beginning of the life cycle assessment:

1. Define the Goal(s) of the Project
2. Determine What Type of Information Is Needed to Inform the Decision-Makers
3. Determine the Required Specificity
4. Determine How the Data Should Be Organized and the Results Displayed
5. Define the Scope of the Study
6. Determine the Ground Rules for Performing the Work [17]

While in the goal defining and scoping stage of the LCA, it is most important to determine what information is required and the ultimate objective. In addition, the analyst must decide whether the assessment is specific to one situation, or if it is more generic and can be applied to other situations. Because LCA's are usually used to compare alternatives, it is critical that data and results are reported identically.   In this stage, the scope is also defined. The analyst must determine what phases in the entire life cycle of the product differ for the available alternatives [17].

Using PaLATE, the goal is to determine the environmental effects of using different quantities of shingles and RAP in pavement. The LCA was performed on Mixtures 1, 5, 6, 7, 8, 11, and 13. Mixture 1 is the "control" mixture and contains no recycled materials, and Mixtures 5, 6, 7, 8, 11, and 13 all contain recycled asphalt shingles. Again, although the objective is to determine the environmental effects of using TOSS in asphalt paving, analysis will be performed on pavements containing both MWSS and TOSS. The environmental effects of mixtures with recycled materials will also be compared those for with mixture 1. Recycled asphalt shingles contribute to the total asphalt required which decreases the quantity of virgin binder required. Mixtures 5 and 8 both contain 5% MWSS, and mixtures 6 and 7 contain 5% TOSS. MWSS shingles contain about 30% asphalt binder, and TOSS contain 30 - 40% asphalt binder so, for this analysis, it is assumed that shingles contribute about 30% of their weight as asphalt [17]. Within the total asphalt mixture, about 1.5% of the weight is recycled asphalt binder from shingles. Mixtures 11 and 13 contain 3% TOSS. Within the total asphalt mixture, about 0.9% of the weight is recycled asphalt binder from the shingles. Because MWSS have already been used successfully and have been accepted by the asphalt paving industry, the environmental effects will be analyzed for MWSS pavement and compared to those for TOSS pavement. In this thesis, for simplicity, the environmental assessment is only valid for projects within the metropolitan area (30 mile radius around Minneapolis and St. Paul), and all asphalt shingles data is from BRI. During the first step of the LCA, all affected stages within the pavement's life cycle are defined. When shingles, TOSS or MWSS, are used in asphalt pavement, less virgin binder is required in the mixture. Using virgin binder is part of the "raw material extraction" stage in the life cycle of asphalt pavement. Because adding shingles decreases the amount of new binder required for the asphalt mixture, the "raw material extraction" stage in the pavement's life cycle is affected. In addition, MWSS and TOSS must be processed, so the "construction" stage of the pavement's life cycle (which includes materials transportation and equipment usage) is also affected. Assuming that the mechanical and physical performance of TOSS/RAP pavement is unaffected, the maintenance stage in the pavement's life cycle is not included in the scope of this thesis. The last stage in the pavement life-cycle is disposal. At the moment, there is no perceived difference in disposal methods for recycled asphalt pavement over traditional paving applications.

4.1.2 Life Cycle Inventory Analysis

Once the goal, scope, specificity, and required information are outlined, a list of inputs and outputs must be determined. Within each affected phase of the life cycle, all materials and energy inputs and emission, waste, and by-product outputs must be noted. This stage is illustrated in Figure 4.1.

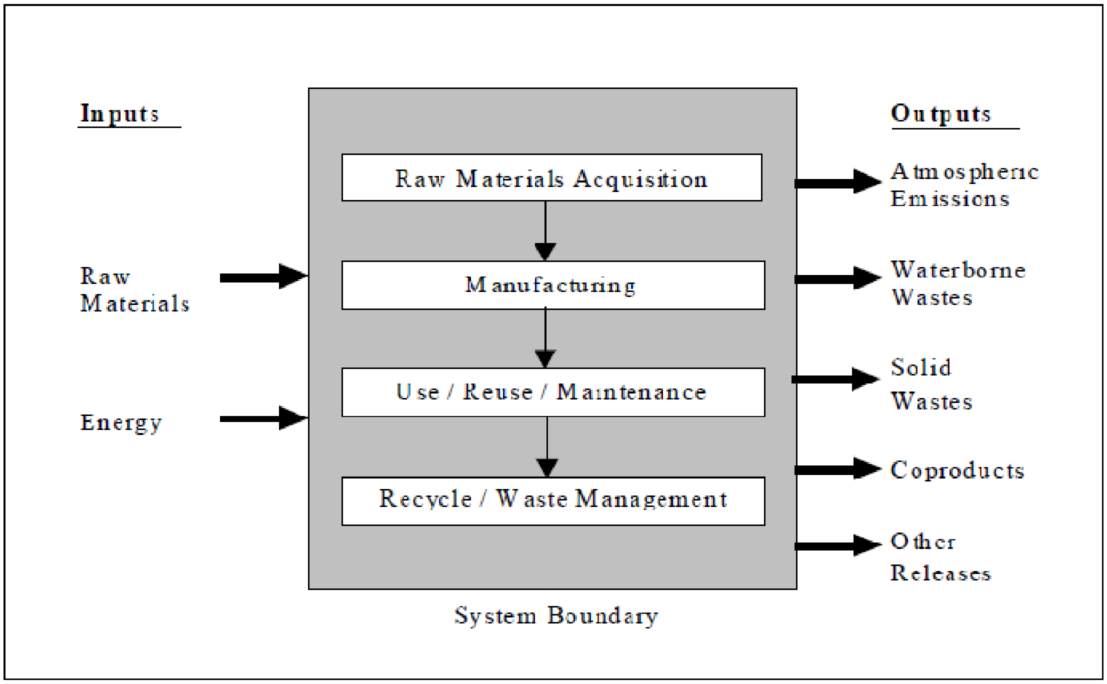


Figure 4.1 – Life Cycle Inventory Analysis [17]

PaLATE does not allow the user to input shingles data into the program, however, all environmental effects will be determined based on information from Bituminous Roadways Incorporated and from manufacturer data. Mixtures 5, 6, 7, 8, 11, and 13 all contain RAP mixtures varying from 15 to 25%, by weight. PaLATE allows the user to input the required quantities of RAP used. Also, although RAP does contribute anywhere from 5-7% asphalt binder to the mixture, in this thesis, it is assumed that RAP only contributes to the total aggregate required, thus decreasing the total virgin aggregate [4]. Because the specificity defined in the previous stage of the LCA is local, transportation of all materials never exceeds 30 miles. PaLATE uses EPA FIRE data for estimating environmental effects from materials transportation. The user specifies one-way distances required for transportation for the following materials: virgin aggregates and RAP. In addition, PaLATE determines the environmental outputs for RAP processing, aggregate storage, transportation, and screening [18].

The outputs generated from PaLATE include total energy usage, water usage, global warming potential (CO_2), criteria pollutant releases, RCRA hazardous waste releases, human toxicity potential, fumes, and leachate.

4.1.3 Life Cycle Impact Assessment

Using the PaLATE output data for environmental effects, a list of impact categories are generated which include global warming impacts, chemical smog impacts, human health morbidity and mortality, eutrophication, decreased biodiversity, loss of habitat, and loss of available water. Once output is generated, then the relevant impacts can be determined [18]. This stage will not be performed in the LCA for this thesis.

4.1.4 Life Cycle interpretation

In this final stage of the LCA, the results from the LCI and life cycle impact assessment are used to make conclusions and recommendations. Each alternative is compared against one another. In addition, any limitations and uncertainty must be reported [18]. This stage will not be performed in the LCA for this thesis.

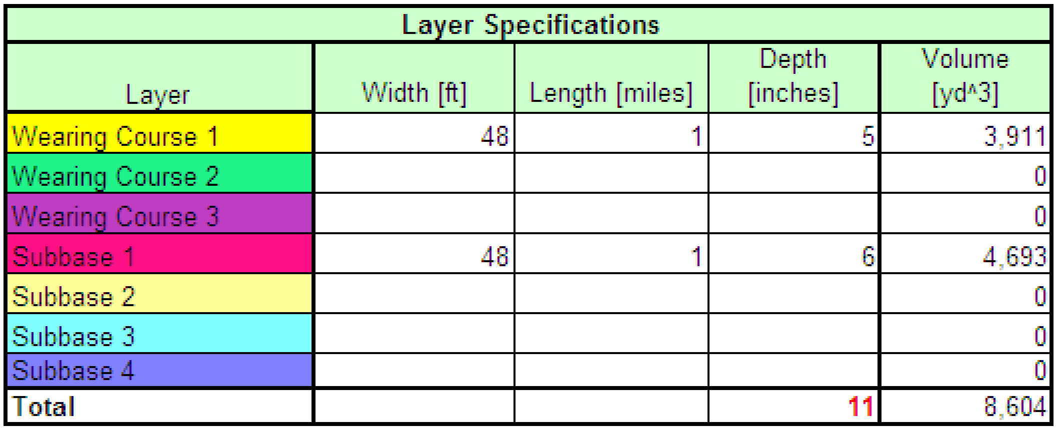
4.2 PaLATE User Input Interface

The first module in the spreadsheet is the design module where the user defines the dimensions of each layer, the density of the construction materials, and the period of analysis, as seen in Figure 4.2. The volume of the layers combined with the density of the materials calculates the mass of each material, which is used to determine duration of the operation of the construction equipment.

PaLATE was used to analyze mixtures 1 (No RAP, No RAS), 5, 6, 7, 8, 11, and 13. Mixtures were selected based on the quantities of RAP and recycled asphalt shingles. Percentages of shingles range from 3-5%, and percentages of RAP range from 15-25%. Environmental emissions were determined in the program for a 1 mile section of a 4-lane (12 ft lanes) highway consisting of 5 inches of asphalt wear course (this is the only layer that differs for each mixture), 6 inches of base, and a subgrade. (Note: the subgrade is assumed to already be present at the construction site and does not affect the analysis). Quantities of materials required were determined by using the pavement structure geometry as seen in equation (1):

Total asphalt required

$$= 1mi \times \frac{5280\,ft}{1mi} \times \frac{1yd}{3\,ft} \times 4lanes \times \frac{12\,ft}{1lane} \times \frac{1yd}{3\,ft} \times 5in \times \frac{1\,ft}{12in} \times \frac{1yd}{3\,ft} = 3911\,\text{yd3}\ (1)$$



Layer Specifications				
Layer	Width [ft]	Length [miles]	Depth [inches]	Volume [yd^3]
Wearing Course 1	48	1	5	3,911
Wearing Course 2				0
Wearing Course 3				0
Subbase 1	48	1	6	4,693
Subbase 2				0
Subbase 3				0
Subbase 4				0
Total			11	8,604

Figure 4.2 – User Input Screen for Layer Specifications

Next, the specific quantities of virgin aggregate, binder, and RAP were determined using mixture volumetrics, provided by MnDOT.

For mixture 1, 5.8%, by weight, is virgin asphalt binder, and 3.7%, by volume, is air voids.

PaLATE requires that quantities be added in volume.

To determine the quantities of required binder, the total asphalt must be converted to weight in equation (2) using the density of asphalt mix, which is assumed to be 2.16 tons per cubic yard:

$$W_{mix} = 3911yd^3 \times \frac{2.16tons}{yd^3} = 8447\,\text{tons} \qquad (2)$$

If the total virgin asphalt is 5.8%, by weight, the weight required is determined by the equation (3):

$$W_{binder} = 0.058 \times 8447tons = 489\,\text{tons} \qquad (3)$$

The total volume of binder required can be determined using the density of binder, which is assumed to be 0.84 tons per cubic yard. With the exception of the density for recycled asphalt shingles (both TOSS and MWSS), all densities used are reported from the PaLATE database and are summarized in the following table [18]:

Table 4.1- Densities

	Density (tons/cu.yd)
Aggregate	2.23
RAP	1.85
Binder	0.84
RAS	1.06
Asphalt Mixture	2.16

The density for the recycled asphalt shingles was determined in equation (4) using the densities and percent volume for both binder and aggregate, which make up over 95% shingles, by volume:

$$\rho_{RAS} = \rho_{binder}V_{binder} + \rho_{agg}V_{agg} = 0.84(0.3) + 2.23(0.65) = 1.7 \text{ tons per cubic yard} \qquad (4)$$

$$V_{binder} = 489 tons \times \frac{yd^3}{0.84 tons} = 582 \text{ yd}^3 \qquad (5)$$

Using the volumetrics provided by MnDOT, the total required volume of aggregate can be calculated in equation (5). Note, that although MnDOT has separated the total aggregate into three categories, in this thesis, only one type (crushed gravel), will be used.

For mixture 1, 84%, by volume of the entire asphalt mixture is composed of aggregate, so the volume required is calculated with the equation (6):

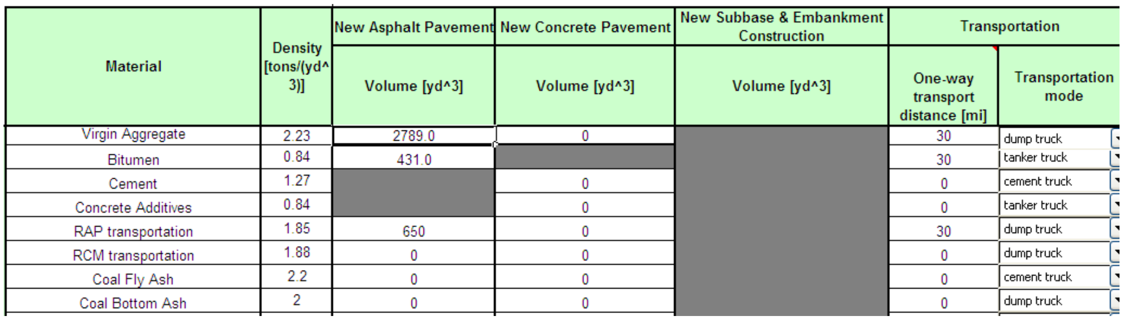
$$V_{agg} = 3911 yd^3 \times 0.84 = 3289 yd^3 \qquad (6)$$

For all mixtures with RAP and recycled shingles present, the total volumes in the mixture were determined using the MnDOT proportions along with assumed density values. Mixture 5 contains 15% RAP, by weight, and 5% MWSS, by weight. If the density of RAP and shingles, respectively, are 1.85 and 1.06, then the required volumes can be calculated as follows with equations (7) and (8):

$$V_{RAP} = 3911 yd^3 \times \frac{2.16 tons}{yd^w} \times .15 \times \frac{yd^3}{1.85 tons} = 684 yd^3 \qquad (7)$$

$$V_{RAS} = 3911 yd^3 \times \frac{2.16 tons}{yd^w} \times .05 \times \frac{yd^3}{1.7 tons} = 248 yd^3 \qquad (8)$$

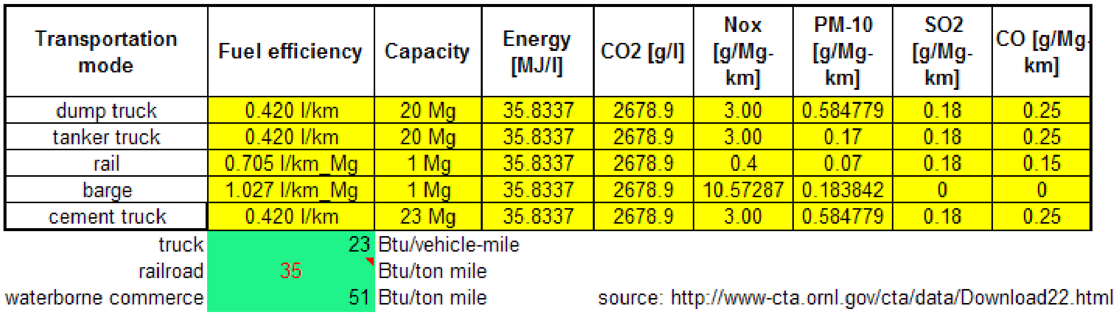
As mentioned earlier, in this thesis, it is assumed that the RAP contributes only to the required aggregate, which is a reasonable assumption, because RAP only provides 5-7% asphalt binder [19]. When entering the total required volume of virgin aggregate into PaLATE, the quantity of RAP can be subtracted. Also, since it is assumed that the total shingles in the mixture provide 30% asphalt binder, the volume of binder from the shingles can be subtracted from virgin "bitumen" required.



Material	Density [tons/(yd^3)]	New Asphalt Pavement	New Concrete Pavement	New Subbase & Embankment Construction	Transportation	
		Volume [yd^3]	Volume [yd^3]	Volume [yd^3]	One-way transport distance [mi]	Transportation mode
Virgin Aggregate	2.23	2789.0	0		30	dump truck
Bitumen	0.84	431.0			30	tanker truck
Cement	1.27		0		0	cement truck
Concrete Additives	0.84		0		0	tanker truck
RAP transportation	1.85	650	0		30	dump truck
RCM transportation	1.88	0	0		0	dump truck
Coal Fly Ash	2.2	0	0		0	cement truck
Coal Bottom Ash	2	0	0		0	dump truck

Figure 4.3 – User Input Screen for Volume Requirements

In addition to the volumes of materials entered into PaLATE, the one-way transport distance (mi) must be provided by the user. As previously mentioned, it is assumed that the project is within the metropolitan (Twin Cities) region, and transportation does not exceed 30 miles. The transportation mode is assumed to be a dump truck, with the following data:



Transportation mode	Fuel efficiency	Capacity	Energy [MJ/l]	CO2 [g/l]	Nox [g/Mg-km]	PM-10 [g/Mg-km]	SO2 [g/Mg-km]	CO [g/Mg-km]
dump truck	0.420 l/km	20 Mg	35.8337	2678.9	3.00	0.584779	0.18	0.25
tanker truck	0.420 l/km	20 Mg	35.8337	2678.9	3.00	0.17	0.18	0.25
rail	0.705 l/km_Mg	1 Mg	35.8337	2678.9	0.4	0.07	0.18	0.15
barge	1.027 l/km_Mg	1 Mg	35.8337	2678.9	10.57287	0.183842	0	0
cement truck	0.420 l/km	23 Mg	35.8337	2678.9	3.00	0.584779	0.18	0.25

truck	23	Btu/vehicle-mile
railroad	35	Btu/ton mile
waterborne commerce	51	Btu/ton mile

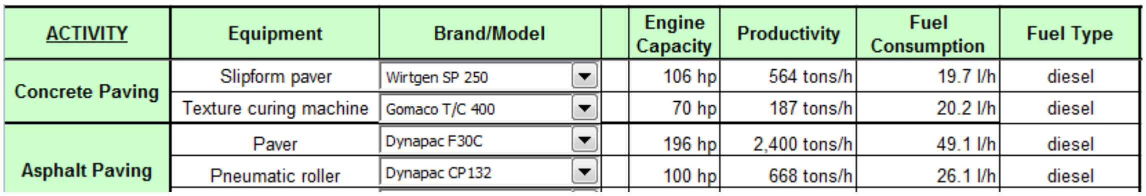
source: http://www-cta.ornl.gov/cta/data/Download22.html

Figure 4.4 – User Input Screen for Assumptions for Transportation Modes

The PaLATE inputs are summarized in the following table:

Table 4.2 – Input Data for PaLATE

	Air	Virgin Binder	Aggregate	RAP	Subbase Gravel	Transport Distance
Mixture	**yd^3**	**yd^3**	**yd^3**	**yd^3**	**yd^3**	**mi**
1	144.7	476.4	3290.1	0	3911	30
5	152.5	416.4	2910.9	390.1	3911	30
6	140.8	438.8	2900.2	390.1	3911	30
7	156.4	403.9	2659.5	650.1	3911	30
8	160.4	378.4	2681.0	650.1	3911	30
11	148.6	431.7	2655.9	650.1	3911	30
13	156.4	446.9	2893.0	390.05	3911	30



ACTIVITY	Equipment	Brand/Model	Engine Capacity	Productivity	Fuel Consumption	Fuel Type
Concrete Paving	Slipform paver	Wirtgen SP 250	106 hp	564 tons/h	19.7 l/h	diesel
	Texture curing machine	Gomaco T/C 400	70 hp	187 tons/h	20.2 l/h	diesel
Asphalt Paving	Paver	Dynapac F30C	196 hp	2,400 tons/h	49.1 l/h	diesel
	Pneumatic roller	Dynapac CP132	100 hp	668 tons/h	26.1 l/h	diesel

Figure 4.5 – User Input Screen for Equipment Energy/Productivity Values

Productivity values for the equipment, as illustrated in Figure 4.5, used in the various activities and processes modeled by PaLATE were obtained from equipment manufacturers, and it is possible that actual values differ from the ones represented in the tool [18].

4.3 PaLATE Results

After entering all of the relevant data, as summarized above, the program generated the following results:

4.3.1 Mixture 1 – 0% RAP, 0% RAS

After running the program on Mixture 1, the following outputs were generated. There are several more outputs, but only energy consumption (MJ) and global warming potential (1,000,000 g, or Mg of Carbon Dioxide emitted), will be reported. The outputs are reported for both the initial construction and maintenance stages. Within each stage, outputs are also provided for material production, transportation, and equipment use. Assuming that shingles do not significantly decrease the performance life of the asphalt pavement, no maintenance outputs will be used.

Table 4.3 – Partial Environmental Output for Mixture 1

		Energy [MJ]	**CO2 [Mg] = GWP**
Initial Construction	**Materials Production**	10,895,572	596
	Materials Transportation	505,739	38
	Processes (Equipment)	46,899	4
Maintenance	**Materials Production**	0	0
	Materials Transportation	0	0
	Processes (Equipment)	0	0
Total	**Materials Production**	10,895,572	596
	Materials Transportation	505,739	38
	Processes (Equipment)	46,899	4
	Total	**11,448,210**	**637**

According to PaLATE, the total energy used to produce 1 mile of a 4-lane pavement with mixture 1, is over 11 million MJ, and 637 Mg of CO_2 are emitted. Each of the alternatives will have the same quantities reported and will be compared with mixture 1. It is also important to note that PaLATE is simply a model, and all values must be used with caution. The following Life Cycle Assessment is used to understand the basic environmental differences between the alternatives.

4.3.2 Mixture 5 – 15% RAP, 5%MWSS

PaLATE was run for Mixture 5, and the environmental output are summarized in Table 4.4.

Table 4.4 – Partial Environmental Output for Mixture 5

		Energy [MJ]	CO2 [Mg] = GWP
Initial Construction	**Materials Production**	9,110,498	495
	Materials Transportation	493,662	37
	Processes (Equipment)	46,381	3
Maintenance	**Materials Production**	0	0
	Materials Transportation	0	0
	Processes (Equipment)	0	0
Total	**Materials Production**	9,110,498	495
	Materials Transportation	493,662	37
	Processes (Equipment)	46,381	3
	Total	**9,650,542**	**536**

According to PaLATE, the total energy used to produce 1 mile of a 4-lane pavement of 6 inches with mixture 5 is over 10 million MJ, and 573 Mg of CO2 are released.

PaLATE does not calculate any environmental effects due to the use of recycled asphalt shingles. However, using data from Bituminous Roadways Incorporated (BRI) and Rotochopper, some rough values can be calculated [8, 11]. TOSS consist of 30 – 40% asphalt, and MWSS consist of nearly 30% asphalt, so in this thesis, it is assumed that 30%, by weight, of each shingle contributes to the total asphalt binder required in the mixture.

Although RAP contributes roughly 5-7% asphalt binder, in this thesis, it is assumed that RAP does not contribute binder and simply replaces required aggregate [4].

According to Rotochopper, the asphalt grinder that BRI uses produces about 90 tons of processed shingles per hour. The asphalt grinder has 630 hp and uses diesel fuel. Mixture 5 requires roughly 240 tons of shingles, so if assuming the maximum productivity, 2.67 hours is required to process the shingles as seen in equation (9).

$$t_{grind} = 422 tons \times \frac{1hr}{90 tons} = 4.7\,\mathrm{hr} \qquad (9)$$

The fuel efficiency of the grinder is 32 gallons per hour, and according to EPA, each liter of diesel consumed is equivalent to 35,833,746 J (35.8 MJ) of energy as calculated in equations (10) - (12):

$$V_{diesel} = t_{grind} \times Eff_{grinder} = 4.7 hr \times \frac{32 gal}{hr} = 150\,\mathrm{gal} \qquad (10)$$

$$V_{diesel} = 150 gal \times \frac{1L}{.264 gal} = 568\,\mathrm{L} \qquad (11)$$

$$E_{diesel} = 568L \times \frac{35.8MJ}{1L} = 20346\,\mathrm{MJ} \quad (12)$$

Global warming potential can also be determined based on the quantity of diesel consumed. As calculated above, for mixture 5, 86 gallons of diesel fuel are consumed, and according to the EPA, per each gram of diesel fuel consumed, 3.16 grams of CO2 are emitted. The density of diesel is assumed to be 852 grams per Liter.

$$W_{diesel} = 568L \times \frac{852g}{L} = 484090\,\mathrm{g} \qquad (13)$$

$$W_{CO2} = 484090\,gDiesel \times \frac{3.17\,gCO2}{1\,gDiesel} = 1534568\,\text{g} = 1.53\ \text{Mg}\ (14)$$

Including the values calculated for the shingles in equations (13) and (14), the total energy required for mixture 5 are roughly as follows:

Energy used:9,670,888 MJ.

GWP: 537 Mg

4.3.3 Mixture 6 - 15% RAP, 5% TOSS

PaLATE was run for Mixture 6, and the environmental output are summarized in Table 4.5.

Table 4.5 – Partial Environmental Output for Mixture 6

		Energy [MJ]	**CO2 [Mg] = GWP**
Initial Construction	**Materials Production**	9,345,505	508
	Materials Transportation	494,147	37
	Processes (Equipment)	46,456	3
Maintenance	**Materials Production**	0	0
	Materials Transportation	0	0
	Processes (Equipment)	0	0
Total	**Materials Production**	9,345,505	508
	Materials Transportation	494,147	37
	Processes (Equipment)	46,456	3
	Total	**9,886,108**	**549**

According to PaLATE, the total energy used to produce 1 mile of a 4-lane pavement of 6 inches with mixture 6 is about 10,690,418 MJ, and 594 Mg of CO2 are released.

Following the calculations above for mixture 5, using the sample equipment values, and using the same assumptions for densities and energy equivalency, the total energy, water consumption, and global warming potential are as follows:

Energy used: 9,906,454 MJ

GWP:550 Mg

4.3.4 Mix 7 - 25% RAP, 5% TOSS

PaLATE was run for Mixture 7, and the environmental output are summarized in Table 4.6.

Table 4.6 – Partial Environmental Output for Mixture 7

		Energy [MJ]	CO2 [Mg] = GWP
Initial Construction	**Materials Production**	8,756,574	475
	Materials Transportation	488,181	36
	Processes (Equipment)	46,359	3
Maintenance	**Materials Production**	0	0
	Materials Transportation	0	0
	Processes (Equipment)	0	0
Total	**Materials Production**	8,756,574	475
	Materials Transportation	488,181	36
	Processes (Equipment)	46,359	3
	Total	**9,291,114**	**515**

According to PaLATE, the total energy used to produce 1 mile of a 4-lane pavement of 6 inches with mixture 7 is about 10,024,743 MJ, and 557 Mg of CO2 are released.

Following the calculations above for mixture 5, using the sample equipment values, and using the same assumptions for densities and energy equivalency, the total energy, water consumption, and global warming potential are as follows:

Energy used: 9,311,460 MJ

GWP: 516 Mg

4.3.5 Mix 8 – 25% RAP, 5% MWSS

PaLATE was run for Mixture 8, and the environmental output are summarized in Table 4.7.

Table 4.7 – Partial Environmental Output for Mixture 8

		Energy [MJ]	**CO2 [Mg] = GWP**
Initial Construction	**Materials Production**	8,342,448	452
	Materials Transportation	489,397	37
	Processes (Equipment)	46,362	3
Maintenance	**Materials Production**	0	0
	Materials Transportation	0	0
	Processes (Equipment)	0	0
Total	**Materials Production**	8,342,448	452
	Materials Transportation	489,397	37
	Processes (Equipment)	46,362	3
	Total	**8,878,207**	**492**

According to PaLATE, the total energy used to produce 1 mile of a 4-lane pavement of 6 inches with mixture 8 is about 9,599,756 million MJ, and 533 Mg of CO2 are released.

Following the calculations above for mixture 5, using the sample equipment values, and using the same assumptions for densities and energy equivalency, the total energy, water consumption, and global warming potential are as follows:

Energy used: 8,898,553 MJ

GWP: 493 Mg

4.3.6 Mixture 11- 25% RAP, 3% TOSS

PaLATE was run for Mixture 11, and the environmental output are summarized in Table 4.8.

Table 4.8 – Partial Environmental Output for Mixture 11

		Energy [MJ]	**CO2 [Mg] = GWP**
Initial Construction	**Materials Production**	9,438,150	513
	Materials Transportation	489,844	37
	Processes (Equipment)	46,593	3
Maintenance	**Materials Production**	0	0
	Materials Transportation	0	0
	Processes (Equipment)	0	0
Total	**Materials Production**	9,438,150	513
	Materials Transportation	489,844	37
	Processes (Equipment)	46,593	3
	Total	**9,974,587**	**553**

According to PaLATE, the total energy used to produce 1 mile of a 4-lane pavement of 6 inches with mixture 11 is about 10,378,626 million MJ, and 578 Mg of CO2 are released.

Mixture 11 requires roughly 144 tons of shingles, so if assuming the maximum productivity, a little over an hour and a half is required to process the shingles as determined in equations (15) and (16)

$$t_{grind} = 253 tons \times \frac{1hr}{90tons} = 2.8\,\text{hr} \qquad (15)$$

$$V_{diesel} = t_{grind} Eff_{grind} = 2.8hr \times \frac{32gal}{hr} = 90\,\text{gal} \; (16)$$

The fuel efficiency of the grinder is 32 gallons per hour, and according to EPA, each liter of diesel consumed can be calculated using equations (17) and (18), and is equivalent to 35833746 J (35.8 MJ) of energy.

$$V_{diesel} = 90gal \times \frac{1L}{.264gal} = 341\text{L} \qquad (17)$$

$$E_{diesel} = 341L \times \frac{35.8MJ}{1L} = 12219\text{ MJ} \quad (18)$$

Global warming potential can also be determined based on the quantity of diesel consumed. As calculated above, for mixture 5, 86 gallons of diesel fuel is consumed, and according to the EPA, per each gram of diesel fuel consumed, 3.16 grams of CO2 are emitted. The density of diesel is assumed to be 852 grams per Liter.

L

$$W_{diesel} = 341L \times \frac{852g}{L} = 290532\text{ g} \qquad (19)$$

$$W_{CO2} = 290532gDiesel \times \frac{3.17gCO2}{1gDiesel} = 920986\text{ g} = 0.92\text{ Mg} \quad (20)$$

The additional energy consumption and carbon dioxide emissions due to the use of shingles are determined in equations (19) and (20). Including the values calculated for the shingles, the total energy required for mixture 11 are roughly as follows:

Energy used: 9,986,806 MJ

GWP:553 Mg

4.3.7 Mixture 13 – 15% RAP, 3% MWSS

PaLATE was run for Mixture 13, and the environmental output is summarized in Table 4.9.

Table 4.9 – Partial Environmental Output for Mixture 13

		Energy [MJ]	**CO2 [Mg] = GWP**
Initial Construction	**Materials Production**	9,571,794	521
	Materials Transportation	493,318	37
	Processes (Equipment)	46,444	3
Maintenance	**Materials Production**	0	0
	Materials Transportation	0	0
	Processes (Equipment)	0	0
Total	**Materials Production**	9,571,794	521
	Materials Transportation	493,318	37
	Processes (Equipment)	46,444	3
	Total	**10,111,555**	**562**

According to PaLATE, the total energy used to produce 1 mile of a 4-lane pavement of 6 inches with mixture 8 is just about 10,820,794 MJ, and 602 Mg of CO2 are released.

Following the calculations above for mixture 5, using the sample equipment values, and using the same assumptions for densities and energy equivalency, the total energy, water consumption, and global warming potential are as follows:

Energy used: 10,123,774 MJ

GWP: 562 Mg

The environmental outputs for all of the mixtures are summarized in the following table:

Table 4.10 – Partial Environmental Output for all Mixtures

	Energy	GWP
Mixture	**MJ**	**Mg**
1 – 0% RAP, 0% RAS	11,488,210	637
5- 15% RAP, 5% MWSS	9,670,888	537.53
6 – 15% RAP, 5% TOSS	9,906,454	550.53
7 – 25% RAP, 5% TOSS	9,311,460	516.53
8 - 25% RAP, 5% MWSS	8,898,553	493.53
11- 25% RAP, 3% MWSS	9,986,806	553.92
13- 15% RAP, 3% TOSS	10,123,774	562.92

For example, Mixture 1 contains no recycled materials and based on PaLATE results, the energy consumption is over 11 million MJ and about 637 Mg of CO_2 are emitted. Figure 4.6 shows the difference between energy use for each mixture. Figure 4.7 shows the difference between global warming potential for each mixture.

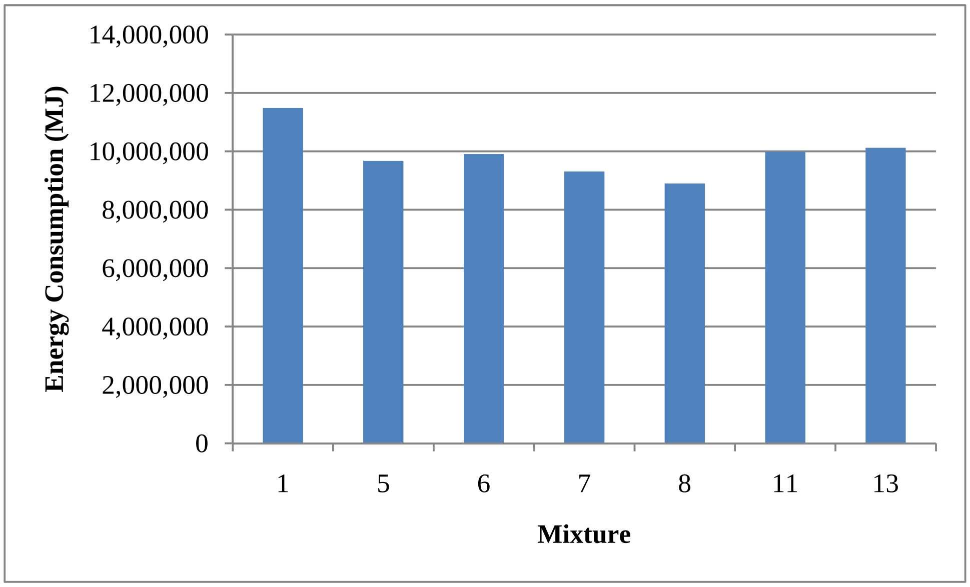


Figure 4.6 – Energy Use (MJ) For All Mixtures

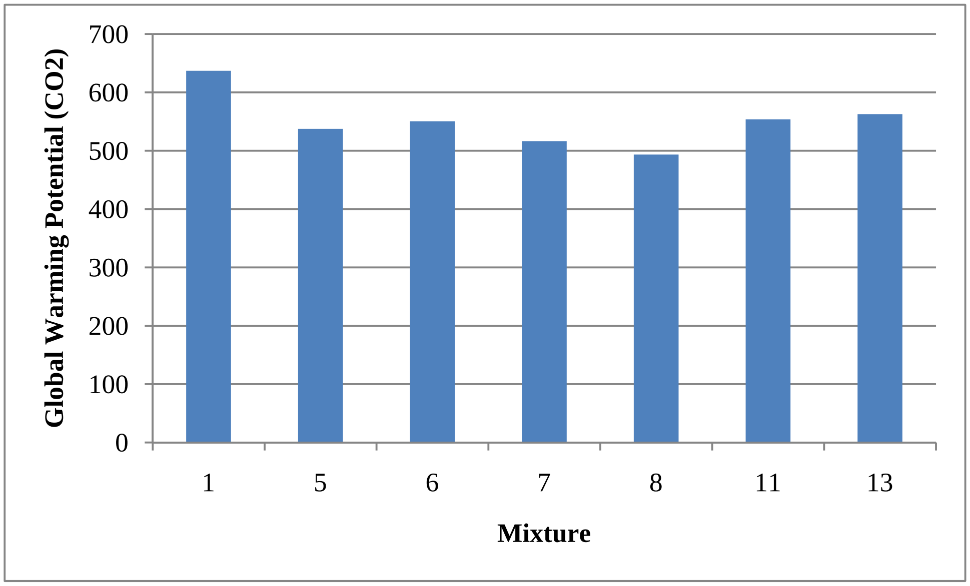


Figure 4.7 – Global Warming Potential For All Mixtures

Looking at mixtures 5, 6, 7, 8, 11, and 13 which all contain recycled shingles and RAP, the energy consumption and global warming potential, which are summarized in Table 4.10, are lower than mixture 1, which has no recycled material. Throughout the raw material extraction and construction stages of a pavement's life cycle, the energy consumption and carbon dioxide emissions are reduced for an asphalt mixture that contains recycled asphalt shingles.

Outside of PaLATE, it is also noteworthy that by using shingles in pavement, fewer will be land filled. If a mixture contains 5% shingles, roughly 137 yd^3 are required per mile of 6-in asphalt pavement and would not be disposed in a landfill. If a mixture contains 3% shingles, roughly 82 yd^3 are required per mile of 6-in asphalt pavement.

Chapter 5

Concluding Remarks and Recommendations

In this thesis, experimental work and analyses were performed to investigate how low temperature properties of asphalt mixtures are affected by the addition of small percentages of TOSS. In addition, a simple, preliminary life cycle analysis was performed to assess the environmental benefits of using recycled asphalt shingles in pavements.

Based on the results obtained in the experimental work and the environmental LCA, the following conclusions can be drawn:

- Adding 15%, 25% or 30% RAP to asphalt mixtures increases the creep stiffness and decreases the relaxation rate of the mixture significantly.
- For 15% RAP, adding 5% MWSS results in an increase in creep stiffness, however, no significant differences are observed for relaxation rate. For the mixtures with 3% MWSS, a decrease in creep stiffness was observed compared to the control group. Therefore, it can be hypothesized that no significant differences in S(60) and m(60) are expected when adding up to 3% of MWSS in asphalt mixture.
- For 25% RAP, adding 3% and 5% of MWSS results in no significant differences in S(60) and m(60) values. It is reasonable to hypothesize that the larger quantity of RAP dominates the properties of the mixtures and the addition of small quantities of MWSS has little impact.
- Adding up to 5% TOSS resulted in no significant differences in creep stiffness for

both 15% RAP and 25% RAP mixtures. For the relaxation rate, no significant differences were observed for the mixtures with 15% RAP, however, significant differences were observed for the mixtures with 25% RAP.

- The results suggest that adding MWSS and TOSS may affect asphalt mixture low temperature properties when smaller amounts of RAP are used. However, above 20%, the influence of adding small amounts (3 to 5%) of recycled shingles does not significantly affect mixture properties.
- The results of the preliminary environmental Life Cycle Analysis performed with PaLATE and assuming no change in pavement performance with addition of recycled shingles, indicate that using either MWSS or TOSS along with RAP reduces the total energy consumed and carbon dioxide emissions over the life cycle of the asphalt pavement.

It is reasonable to conclude that using up to 3% TOSS in asphalt mixtures results in an effect on low temperature properties similar to the addition of up to 5% MWSS, if combined with RAP addition of more than 20%. In addition, the use of TOSS will lead to a decrease in the quantity of TOSS land filled every year, which has additional environmental benefits that were not included in the present analysis. The results from this thesis support previous research efforts by demonstrating the possibility of using recycled asphalt shingles in pavement; however, the Minnesota Department of Transportation draft specification for the use of TOSS in asphalt pavement should state that up to 3%, not 5%, shingles can be used.

In the future, it is recommended that additional studies be implemented with respect to using tear off recycled asphalt shingles. Suggestions for additional work include:

- Predict the pavement expected life of recycled asphalt shingles pavement using modeling systems such as MEPDG.
- Perform a more complete Life Cycle Analysis based on using shingles in pavement.
- Perform a cost analysis to determine if any savings are gained by using shingles in pavement.

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(18) Horvath, Arpad. *A Life-Cycle Analysis Model and Decision-Support Tool for Selecting Recycled Versus Virgin Materials for Highway Applications*. Rep. no. Research Project No. 23. Recycled Materials Resource Center, 2004. Print.

(19) Epps, J. A., D. N. Little, R. J. O'Neal, and B. M. Gallaway. "Mixture Properties of Recycled Central Plant Materials." *Recycling of Bituminous Pavements,* American Society for Testing and Materials, Special Technical Publication No. 662, West Conshohocken, Pennsylvania, December, 1977

Appendix A - Specifications for Manufacturer Waste Shingle Scrap

Scrap Asphalt Shingles from Manufacture Waste (02/22/2010)

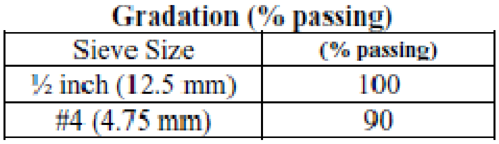
DESCRIPTION
Scrap asphalt shingles from a shingle manufacturing facility may be used in hot mixed asphalt mixtures produced under Mn/DOT Specification 2360.

MATERIALS

Scrap asphalt shingles may be included in both wear and non-wear courses to a maximum of 5 percent of the total weight of mixture. Only scrap asphalt shingles from manufacturing waste are suitable. The percentage of scrap shingles used will be considered part of the maximum allowable RAP percentage (see Table 2360.3-B2a). Refer to Section 2360.2 G1 to select a virgin asphalt binder grade. The ratio of added new asphalt binder to total asphalt binder shall be 70% or greater ((added binder/total binder) x 100 >= 70). A minimum of 1 spotcheck per day per mixture blend is required to determine new added binder.

All scrap shingle materials shall consist of organic felt, and/or fiberglass shingles, obtained from a shingle manufacturing facility.

All scrap shingle materials shall be processed to meet the following gradation requirements:



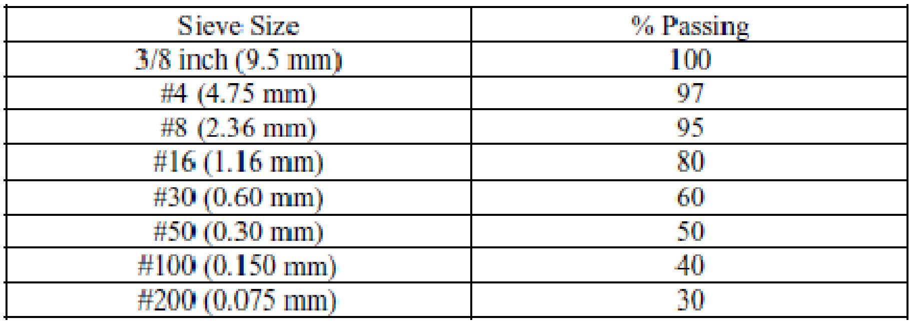
Gradation (% passing)

Sieve Size	(% passing)
½ inch (12.5 mm)	100
#4 (4.75 mm)	90

The final product shall have no particle exceeding the maximum aggregate size allowed under Specification 2360. To conduct the gradation testing, a 500-700 gram sample of processed shingle material is air dried and then dry sieved over the 1/2” and #4 sieves and weighed.

Shingle asphalt binder content is to be determined by chemical extraction, Mn/DOT Lab Procedure 1851 or 1852. To determine the percent asphalt content, use a 500-700 gram sample.

For Mix Design, the following aggregate gradation may be used as a standard gradation in lieu of determining the shingle gradation by AASHTO T30.



Sieve Size	% Passing
3/8 inch (9.5 mm)	100
#4 (4.75 mm)	97
#8 (2.36 mm)	95
#16 (1.16 mm)	80
#30 (0.60 mm)	60
#50 (0.30 mm)	50
#100 (0.150 mm)	40
#200 (0.075 mm)	30

An aggregate bulk specific gravity (Gsb) of 2.650 may be used in lieu of determining the shingle aggregate Gsb by Mn/DOT 1205 (AASHTO T84).

Deleterious Materials

Scrap asphalt shingle shall not contain extraneous waste materials. Extraneous materials including, but not limited to, metals, glass, rubber, nails, soil, brick, tars, paper, wood, and plastics shall not exceed 0.5 percent by weight as determined on material retained on the 4.75-mm (No. 4) sieve. To conduct deleterious material testing, a representative 500-700 gram sample of processed shingle material is sieved on the #4 sieve and any extraneous waste material retained on the #4 sieve is picked and weighed. The percent extraneous is based on the total sample weight.

CONSTRUCTION REQUIREMENTS

Scrap shingles from manufacture waste shall be stockpiled separate from other salvage material. Blending of scrap shingle material in a stockpile with other salvage material is prohibited. Blending of MWSS and TOSS is not allowed. Blending of a virgin sand material with the processed shingles, to minimize agglomeration of the shingle material, is allowed, but, the blended sand must be accounted for in the mixture design.

Before a Mixture Design Report for a particular mixture is authorized, the following shall be submitted, along with materials and paperwork required by Mn/DOT Specification 2360.3:

I. Certification by the processor of the shingle scrap, as to the shingle scrap content and source. Certification forms are located at the back of this provision and also available from the Bituminous
Office.

Appendix B - Specifications for Tear Off Shingle Scrap

Tear-Off Scrap Asphalt Shingles (02/22/2010)

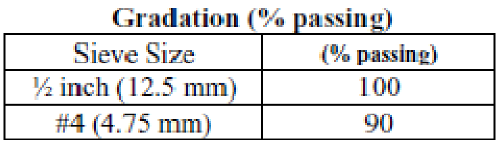
DESCRIPTION

Tear-Off Scrap shingles (TOSS), as an asphalt binder source, may be included in plant mixed asphalt mixtures produced under specification 2360 by an approved Minnesota Pollution Control Agency (MPCA) processer.

MATERIALS

Tear-Off Scrap shingles (TOSS) may be included in both mainline wear and non-wear courses to a maximum of 5 percent of the total weight of mixture. The percentage of TOSS used will be considered part of the maximum allowable RAP percentage (see Table 2360.3-B2a). Refer to Section 2360.2 G1 to select a virgin asphalt binder grade. The ratio of added new asphalt binder to total asphalt binder shall be 70% or greater ((added binder/total binder) x 100 >= 70). A minimum of 1 spotcheck per day per mixture blend is required to determine new added binder.

All TOSS materials shall be processed to meet with the following gradation requirements:



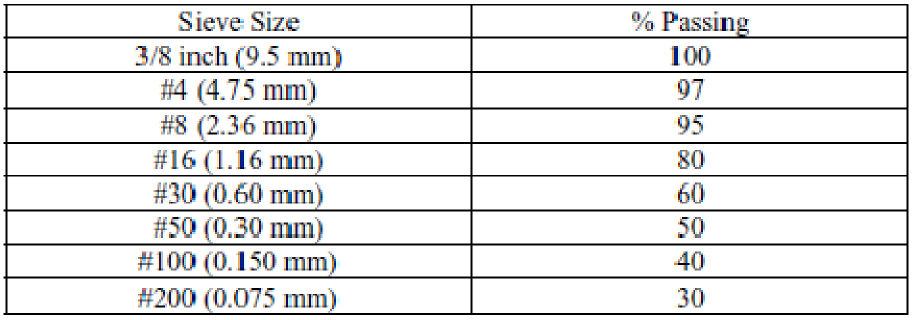
Gradation (% passing)

Sieve Size	(% passing)
½ inch (12.5 mm)	100
#4 (4.75 mm)	90

The final product shall have no particle exceeding the maximum aggregate size allowed under Specification 2360. To conduct the gradation testing, a 500-700 gram sample of processed shingle material is air dried and then dry sieved over the 1/2" and #4 sieves and weighed.

Shingle asphalt binder content is to be determined by chemical extraction, MnDOT Lab Procedure 1851 or 1852. To determine the percent asphalt content, use a 500-700 gram sample.

For Mix Design, the following aggregate gradation may be used as a standard gradation in lieu of determining the shingle gradation by AASHTO T30.



Sieve Size	% Passing
3/8 inch (9.5 mm)	100
#4 (4.75 mm)	97
#8 (2.36 mm)	95
#16 (1.16 mm)	80
#30 (0.60 mm)	60
#50 (0.30 mm)	50
#100 (0.150 mm)	40
#200 (0.075 mm)	30

An aggregate bulk specific gravity (Gsb) of 2.650 may be used in lieu of determining the shingle aggregate Gsb by Mn/DOT 1205 (AASHTO T84).

Deleterious Materials

Scrap asphalt shingle shall not contain extraneous waste materials. Extraneous materials including, but not limited to, asbestos, metals, glass, rubber, nails, soil, brick, tars, paper, wood, and plastics shall not exceed 0.5 percent by weight as determined on material retained on the 4.75-mm (No. 4) sieve. To conduct deleterious material testing, a representative 500-700 gram sample of processed shingle material is sieved on the #4 sieve and any extraneous waste material retained on the #4 sieve is picked and weighed. The percent extraneous is based on the total sample weight.

Reclaimed asphalt shingle shall contain less than the maximum percentage of asbestos fibers based on testing procedures and frequencies established by Mn/DOT, state or federal environmental regulatory agencies.

CONSTRUCTION REQUIREMENTS

TOSS shall be stockpiled separate from other salvage material. Blending of TOSS material in a stockpile with other salvage material is prohibited. Blending of Manufacture Waste Scrap Shingles (MWSS) and TOSS is not allowed. Blending of a virgin sand material with the processed shingles, to minimize agglomeration of the shingle material, is allowed, but, the blended sand must be accounted for in the mixture design.

Before a Mixture Design Report for a particular mixture is authorized, the following shall be submitted, along with materials and paperwork required by Mn/DOT Specification 2360.3:

I. Certification by the processor of the shingle scrap, as to the shingle scrap content and source. Certification forms are located at the back of this provision and also available from the Bituminous Office.

Tear-Off Scrap Shingle Certification Sheet
TEAR-OFF PROCESSOR

Project No:______________________
Project:____

Name:____

Address:____

____

Contact:____

Phone:____

We the undersigned certify that all of the asphalt shingle tear-off scrap is derived from non-regulated facilities such as private, pitched roof, residential “single family” re-roofing projects (e.g., buildings with up to four units per structure).

We certify that this shingle scrap material contains only shingles; no other material was added or introduced to this shingle scrap. We also certify the material contains no asbestos greater than the NESHAP threshold or other hazardous material[1]. Additionally, we certify the TOSS meets MnDOT gradation and deleterious material requirements for processed shingle scrap.

____
Processor of Tear-Off Shingle Scrap Material   Date

____
Name of Contractor to Whom Processed Tear-Off Shingle Scrap Material Was Supplied

Supplier of Tear-Off Shingle Scrap:
Name: ____

Address: ____

____

Contact: ____

Phone: ____

[1] Note: As determined by sampling in accordance with our MPCA approved Shingle Processing Management Plan and QA/QC Protocol

Appendix C - BBR Data

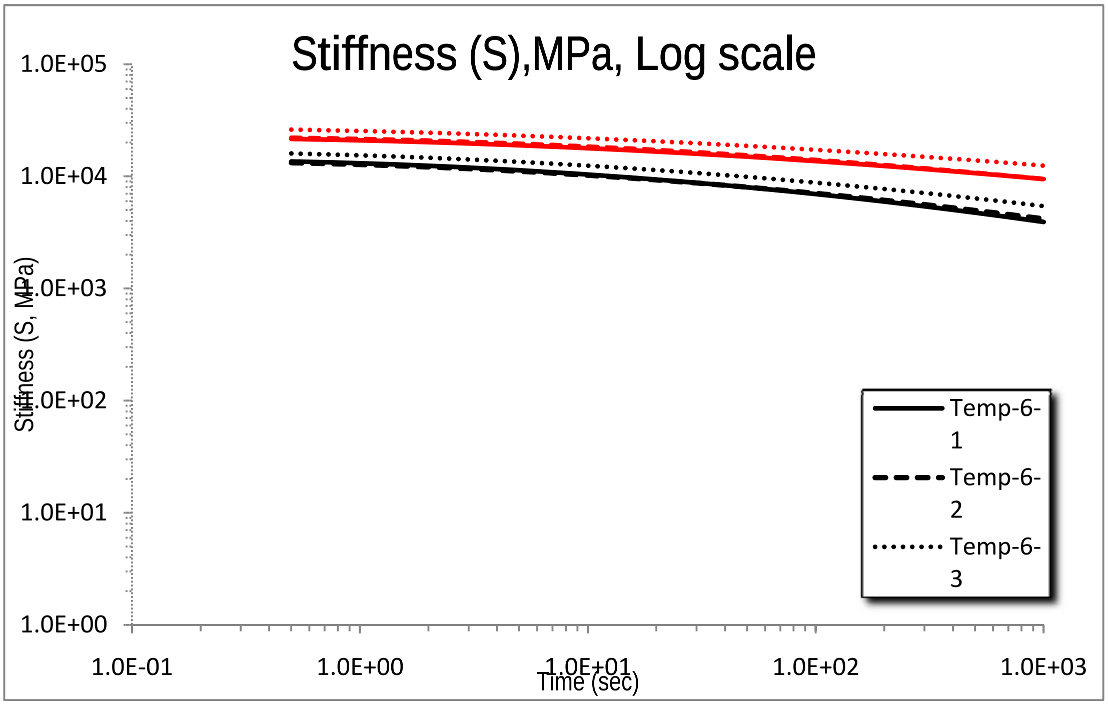


Figure C-1 - Stiffness vs. Time for Mixture 5

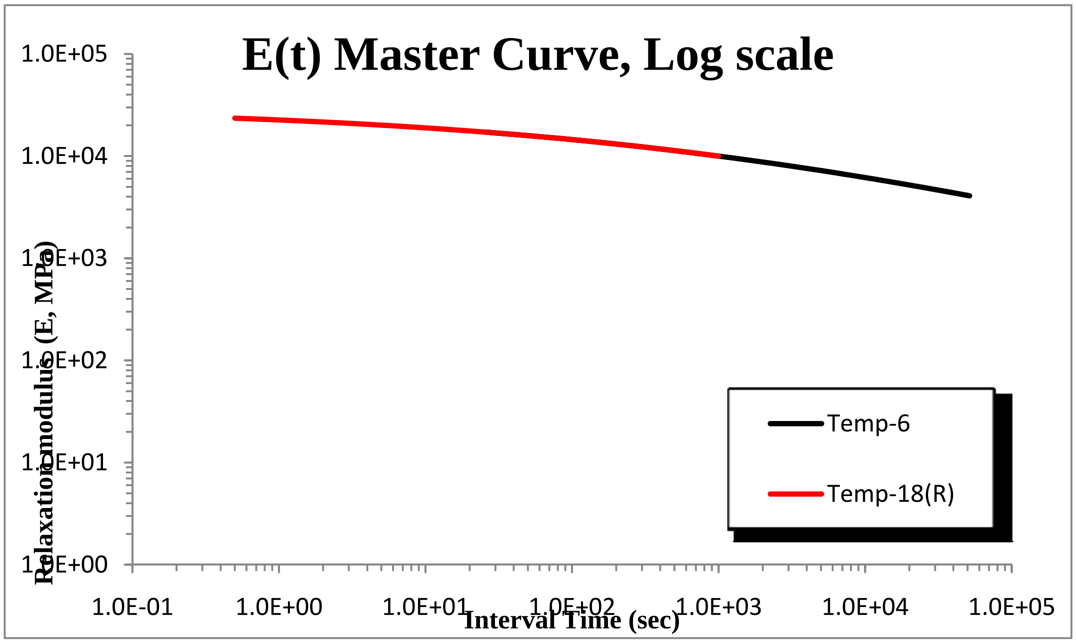


Figure C-2 - Master Curve for Mixture 5

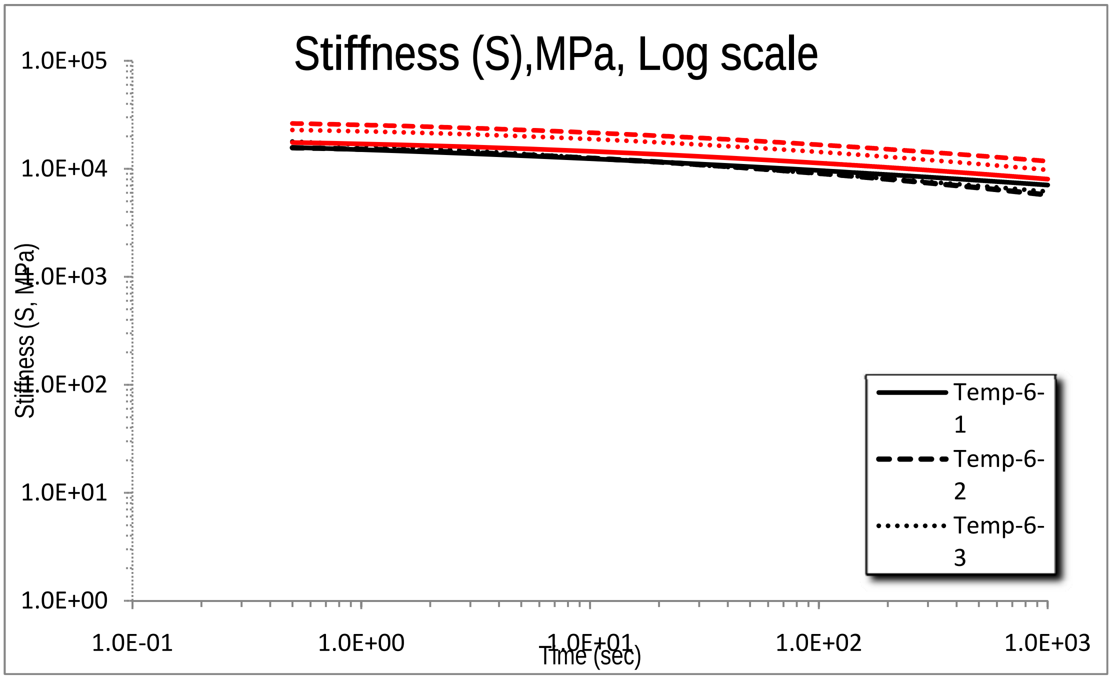


Figure C-3 - Stiffness vs. Time for Mixture 6

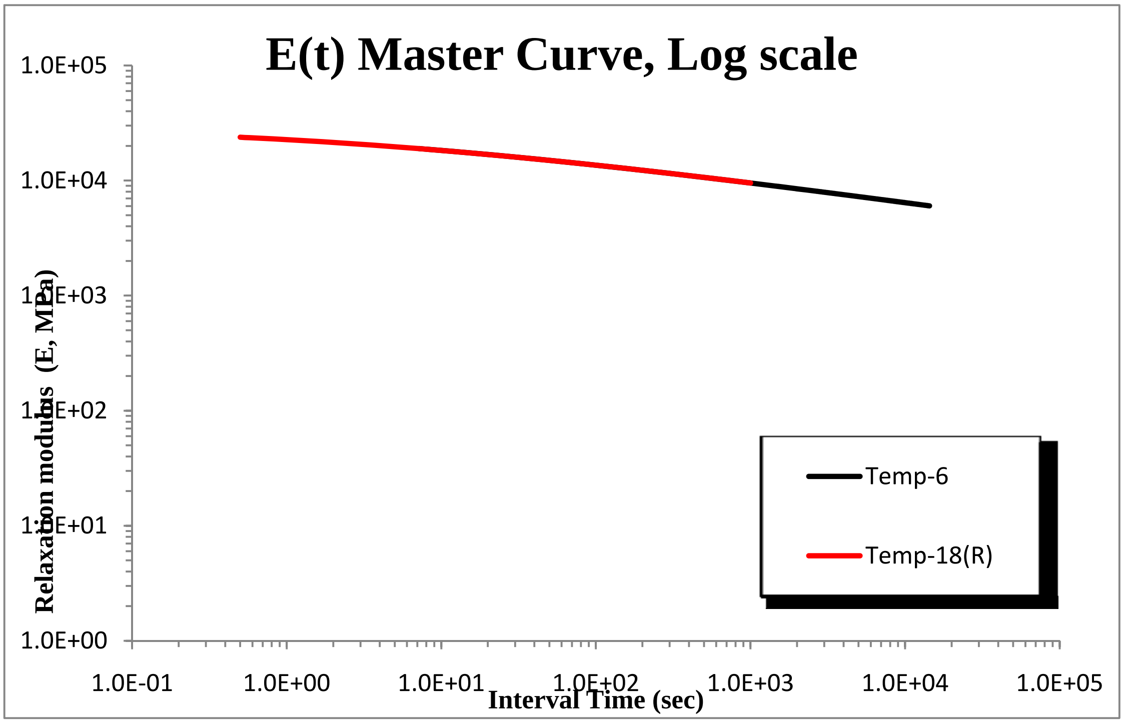


Figure C-4 - Master Curve for Mixture 6

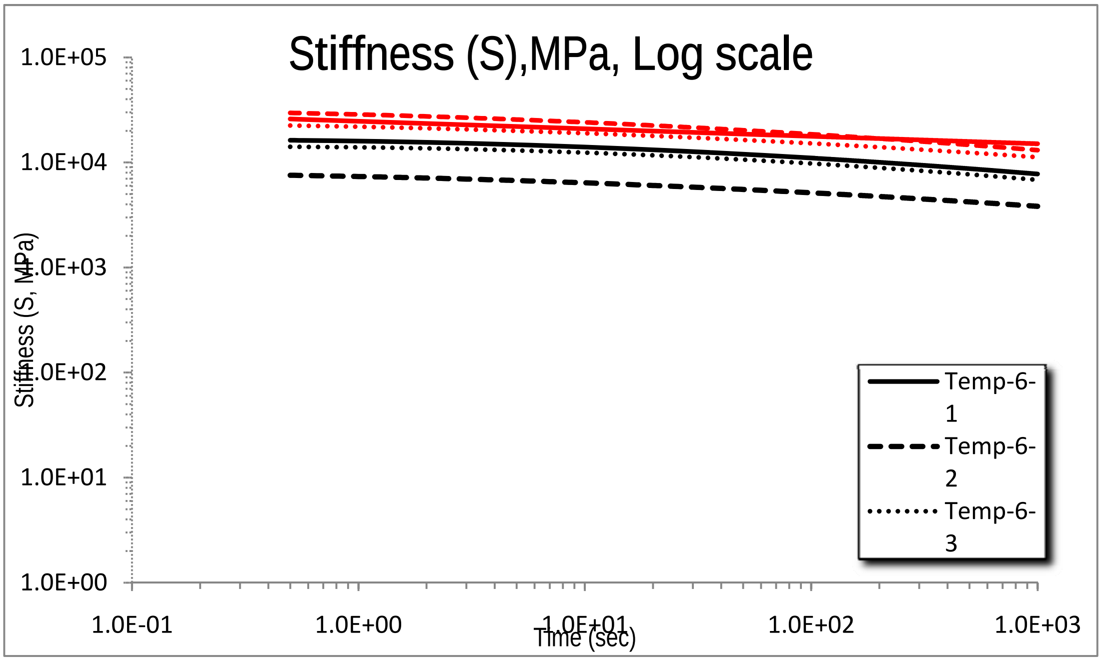


Figure C-5 - Stiffness vs. Time for Mixture 7

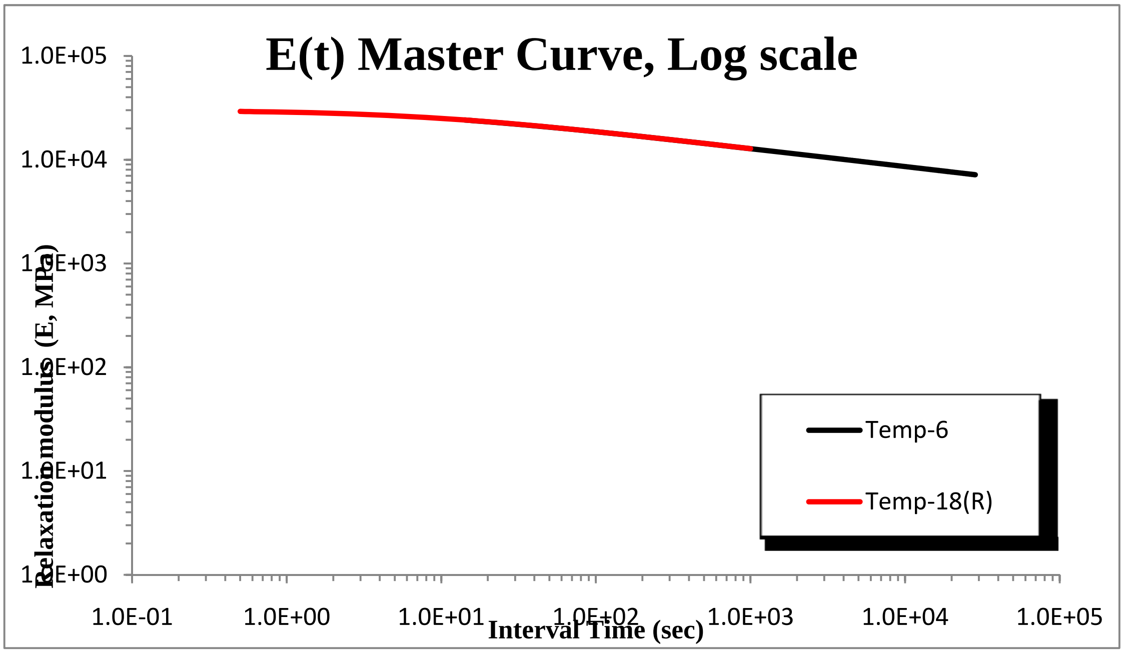


Figure C-6 - Master Curve for Mixture 7

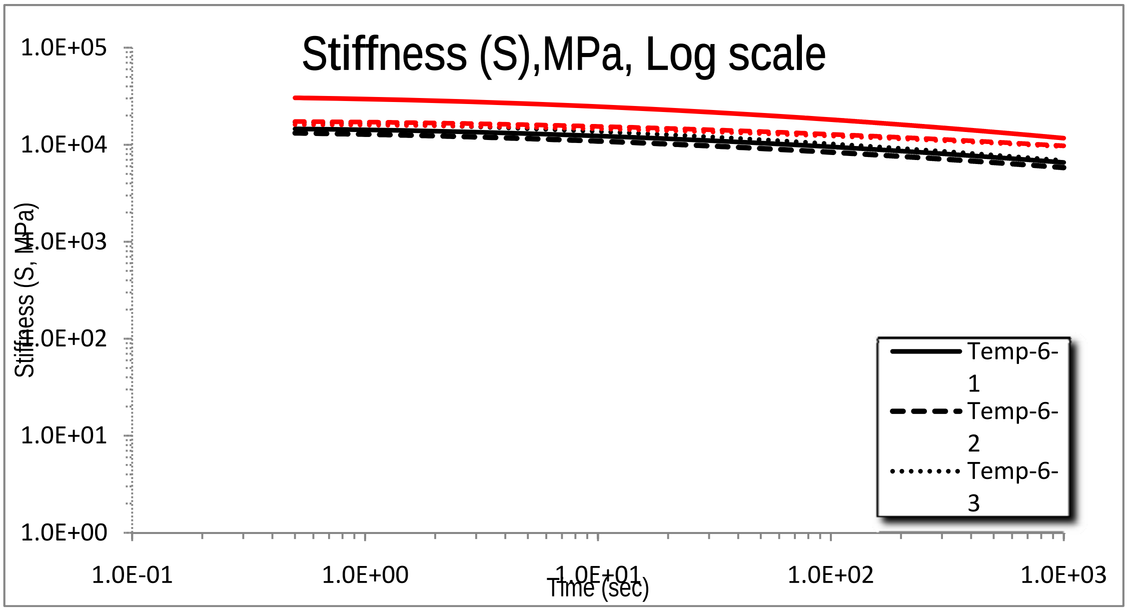


Figure C-7 - Stiffness vs. Time for Mixture 8

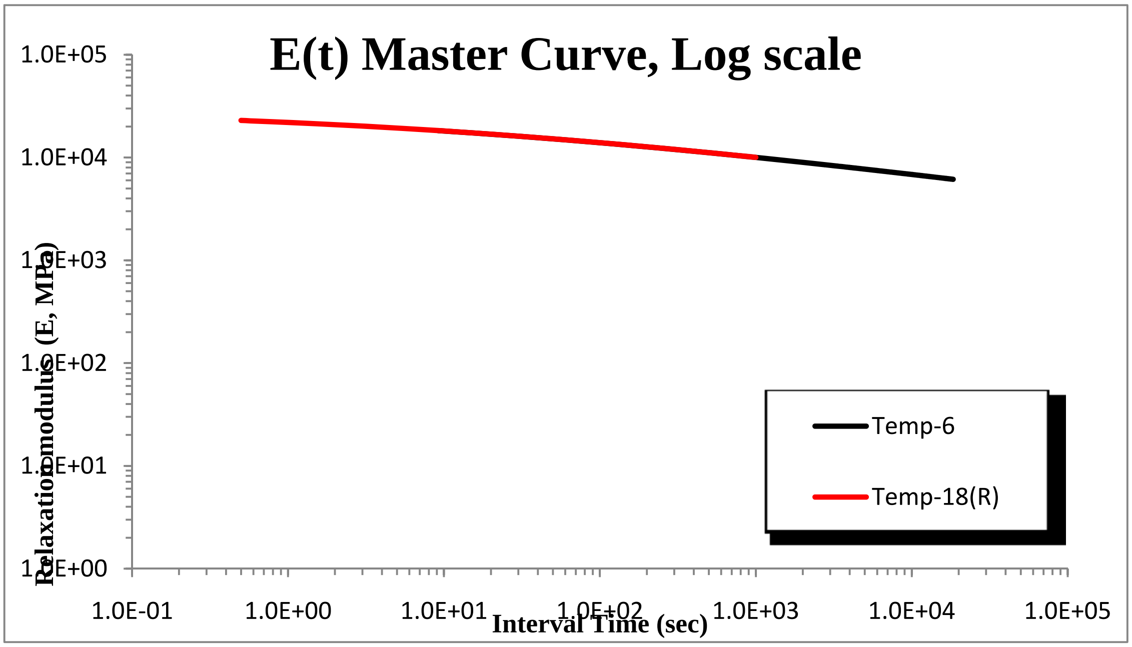


Figure C-8 - Master Curve for Mixture 8

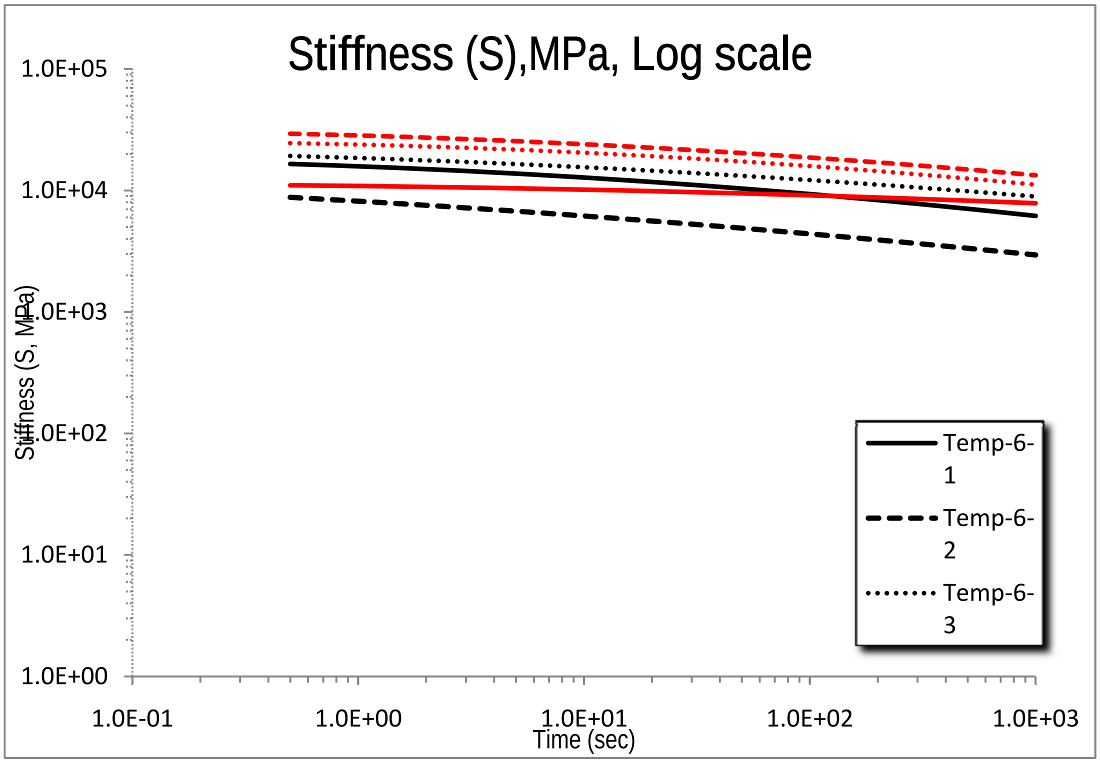


Figure C-9 - Stiffness vs. Time for Mixture 11

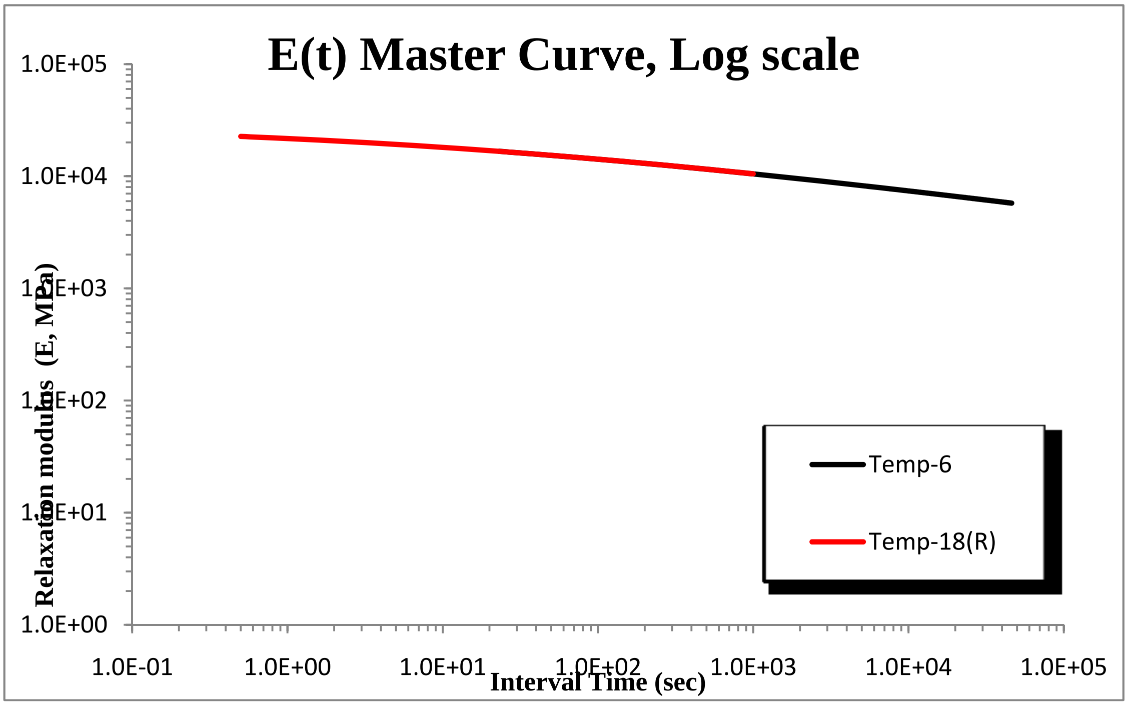


Figure C-10 - Master Curve for Mixture 11

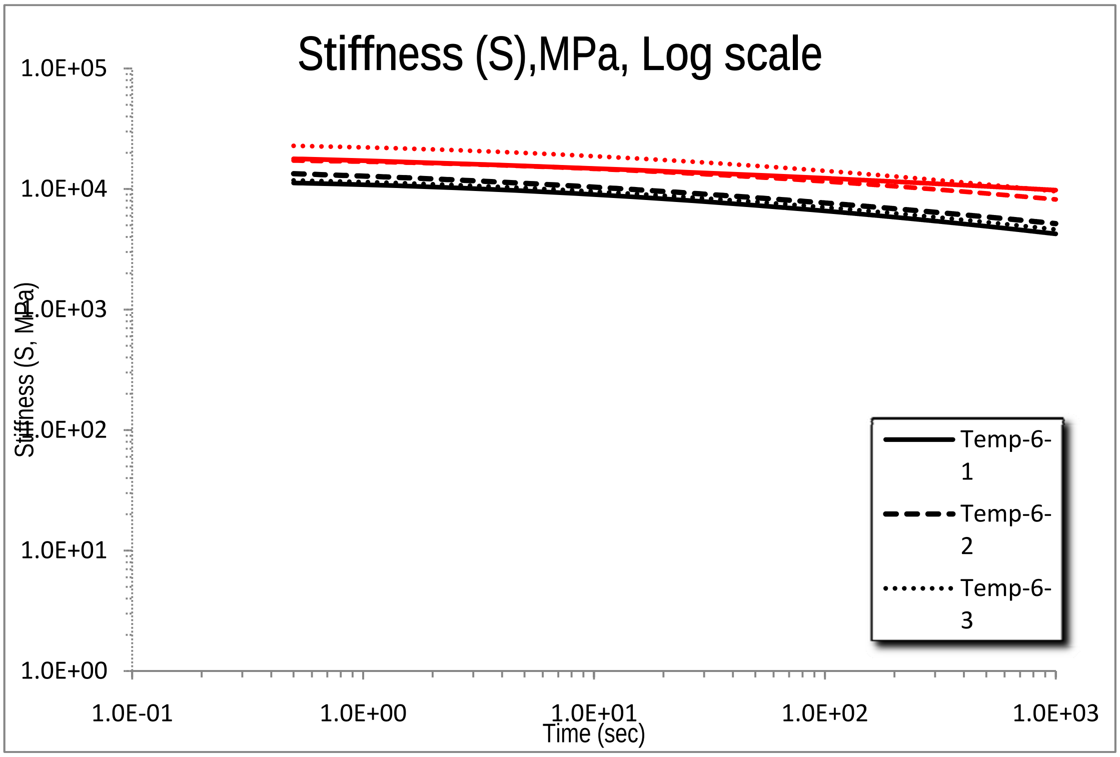


Figure C-11 - Stiffness vs. Time for Mixture 13

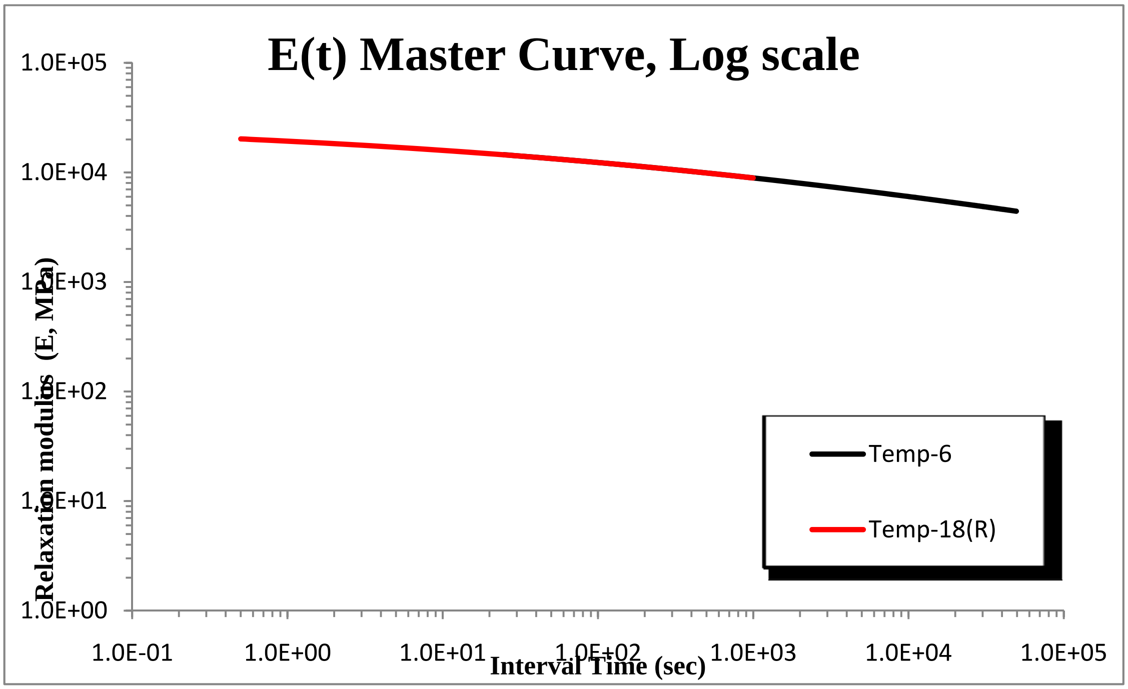


Figure C-12 - Master Curve for Mixture 1