INVESTIGATION OF WARM MIX ASPHALT (WMA) TECHNOLOGIES AND INCREASED PERCENTAGES OF RECLAIMED ASPHALT PAVEMENT (RAP) IN ASPHALT MIXTURES

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16. Abstract

The objective of this research project was three-fold: (1).evaluate the performance of SCDOT mixtures made with WMA technologies, (2) evaluate the effect of increased RAP contents on SCDOT asphalt mixtures, and (3) evaluate the influence of WMA technologies on SCDOT asphalt mixtures made with RAP. To accomplish the research objectives, the research was divided in to three separate phases, each addressing one of the three specific objectives. Additionally, an extensive literature review was conducted to establish the state-of-the-practice related to the use of WMA and RAP in asphalt mixtures.

The effects of WMA technologies and RAP content on asphalt mixtures were evaluated for binders and mixtures. Two different WMA technologies (Evotherm™ and foaming) and five RAP contents (0, 20, 30, 40, and 50%) were selected for this study. SCDOT Surface Type B mix designs were conducted for HMA and each WMA technology using two binders and two aggregates for a total of 60 mix designs. Once the mix designs were complete, the performance of each mixture was determined by testing the indirect tensile strength, tensile strength ratio, rutting resistance, resilient modulus, and fatigue life. In addition, the effect of the WMA technologies on the relative compactibiliy of the mixtures was also quantified as the number of gyrations required to achieve the specified height of 95 mm for the ITS specimens.

This research yielded several conclusions and recommendations for the implementation of WMA and higher RAP contents in SCDOT asphalt paving operations.

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CHAPTER 1: INTRODUCTION

Hot mix asphalt (HMA) is the primary paving material in the United States, as about 94% of the paved roads are surfaced with HMA, which consists of aggregate and asphalt binder that are heated and mixed together. The primary sources of emissions in an asphalt plant are the mixers, dryers, and hot bins, which emit particulate matter, such as dust, smoke, exhaust vapor, and other gaseous pollutants. Some other sources of emissions found at an asphalt plant are the storage silos, truck loading operations, binder storage tanks, conveyers, and stockpiles.

Typically, the emissions from hot mix asphalt are classified into two major categories: visible emissions and invisible emissions (Sutton 2002). Invisible emissions are the emissions that primarily consist of non-condensable volatile organic compounds (VOCs) which precipitate in the production of ground level ozone. The visible emissions consist of fugitive dust emissions generated at the conveyers, stockpiles, and roadways and other heavier hydrocarbons that readily vaporize at temperatures around 300°F. The visible emissions condense in ambient air, adsorb to dust and water particles, and have a characteristic fuel odor. The US Environmental Protection Agency (US EPA) estimates that on average, a drum mix asphalt plant that produces about 200,000 tons of asphalt mix in a year, would emit about 13 tons of carbon monoxide (CO) emissions during that period, 5 tons of volatile organic compounds, 0.4 tons of sulfur oxides, 2.9 tons of nitrogen oxides and about 0.65 tons of total hazardous air pollutants (HAP) (US EPA 2000).

To reduce the emissions from asphalt plants, the asphalt industry is constantly trying to reduce the mixing and compaction temperatures of the mixes, without significantly affecting the properties of the mixes. The industry has been experimenting with warm and cold asphalt mixtures for decades to reduce energy requirements and for environmental benefits. However, most of the cold products are inferior to hot mix asphalt. Emulsion binders usually result in higher air voids, require longer curing times, and tend to work only with open and coarse graded mixtures. Cutback bitumen also has environmental concerns due to the volatile chemicals and requires longer curing times. Foamed asphalt does not require long curing times, but it has been reported that it only coats fine aggregate well, and is more suitable for recycling applications (Rajagopal and Croteau 2004). Another problem with these methods is that the extra costs are not offset by the savings in energy. Thus, because the cold mixes have not achieved the same overall long-term performance as hot mixes, it appears they will not be able to replace hot mixes as the primary road surfacing material.

European countries are already using warm asphalt technologies that allow reductions in mixing and compaction temperatures of 50 to 100^{o}F. The asphalt industry has developed several methods to reduce the mixing and laydown temperatures of asphalt mixtures. In principle, there are three major methods for the production of asphalt mixtures at low temperatures. These methods are based on foaming, water bearing agents, and special bitumen additives.

The foaming process generally produces tiny steam bubbles inside the asphalt binder, which causes a volume increase in the asphalt binder, leading to increased wettability of the binder and lower high shear viscosities. An example of such a process is WAM-foam, a patented process developed jointly by Shell Global Solutions and Kolo Veidekke in Norway. In the WAM-foam production process, two different bitumen grades, soft bitumen and hard bitumen, are combined with the mineral aggregate. The aggregates are first mixed with the softer binder, which is fluid enough at lower temperatures, and then the harder binder is foamed and mixed with the aggregates pre-mixed

with the softer binder. This process makes it possible to produce the asphalt mixture at temperatures between 212 and 250°F and compact it at 175 to 230°F (Koenders et al. 2000). The more recently developed Astec Double Barrel Green process allows for the production of WMA with a standard grade asphalt binder through a one-time mechanical plant modification, thereby minimizing the impact of increased material costs identified with other WMA technologies (Astec).

The method incorporating water bearing agents is based on the release of chemically bound water from the additives into the binder during the mixing process. The release of this water leads to a finely dispersed steam when it comes in contact with the heated aggregate and binder. The fine steam bubbles create micro-pores that improve the compaction properties of the binders. An example of such an additive is Asphamin®, which is a sodium-aluminum-silicate, hydro-thermally crystallized into a fine powder. It is added at a rate of 0.3% by weight of the mixture, and added at the same time as the binder. The crystals contain about 21% water, inducing a fine spray in the binder causing a volume expansion, thereby increasing the workability and compactibility of the mixture at lower temperatures. It has been reported, by the manufacturer, that a reduction of about 40 to 50°F is possible (Eurovia Services).

The third method is based on adding special additives to the binder to reduce the viscosity of the binder. Such types of additives typically consist of paraffinic hydrocarbons. The paraffins are generally soluble in the asphalt binder above temperatures of 175 to 250°F. When dissolved in the binders, they lead to a significant reduction in the viscosity. Unlike the naturally occurring saturates in the binder, the added paraffins are long chained hydrocarbons that do not adversely affect the properties of the base binder. An example of such an additive is Sasobit®, a long chain aliphatic hydrocarbon (chain lengths of 40 to 115 carbon atoms) obtained from coal gasification using the Fischer-Tropsch process.

PROBLEM STATEMENT

Warm Mix Asphalt

In recent years, the asphalt industry has investigated warm asphalt technology as a means to reduce the mixing and compaction temperatures of asphalt mixes. Warm mix asphalt (WMA) is an asphalt mixture that is mixed at temperatures lower than conventional hot mix asphalt. Typically, the mixing temperatures of warm mix asphalt range from 212 to 280°F compared to the mixing temperatures of 300 to 350°F for hot mix asphalt *(Australian Asphalt Pavement Association 2001)*. Thus, warm asphalt has been gaining increasing popularity in recent years around the country including in South Carolina. Rising energy prices, global warming, and more stringent environmental regulations have resulted in an interest in warm mix asphalt technologies as a means to decrease the energy consumption and emissions associated with conventional hot mix asphalt production.

The ‘World of Asphalt’ featured a demonstration project on WMA in 2004, and since then, the major warm asphalt additive companies have carried out several demonstration projects in the United States. The implementation of warm mix technology as a viable option for paving operations is a promising concept. However, further investigation of the effects of warm asphalt technologies on the characteristics of asphalt mixtures and pavement performance in the South Carolina was needed as the environmental conditions, equipment, standards, and work practices are different than other countries and states.

Reclaimed Asphalt Pavement

Since the mid-1970's, millions tons of reclaimed asphalt pavement (RAP) have been used to produce recycled HMA around the country. The use of RAP has become routine practice in many areas around the world. In the United States, the Federal Highway Administration reported that 73 of the 91 million metric tons of asphalt pavement removed each year during resurfacing and widening projects are reused as part of new roads, roadbeds, shoulders and embankments (*FHWA 1997*). In South Carolina, thousands of tons of RAP are generated from damaged asphalt pavements every year. Many of these RAP sources are being used in the construction of new asphalt pavements.

More than 40 states performed and documented RAP demonstration projects between 1976 and 1982, when some field trials were constructed with mixtures containing up to 80% RAP materials. The usage of RAP materials was limited due to emission controls, cracking, and the lack of a performance test to predict the behavior of high RAP mixtures. However, with current plant designs, emissions can be minimized at high-RAP contents, and with proper mix design and assessment, performance problems can be addressed.

Generally, the recycling of existing asphalt pavement materials produces new pavements with considerable savings in material, money, and energy. Aggregate and binder from old asphalt pavements are still valuable even though these pavements have reached the end of their service lives. They have been used, for decades, with virgin aggregates and binders to produce new asphalt pavements, proving to be both economical and effective in conserving natural resources. Furthermore, mixtures containing RAP have been found, for the most part, to perform as well as the virgin mixtures with respect to rutting resistance. NCHRP Report 452 report provides basic concepts and recommendations concerning the components of mixtures, including new aggregate and RAP materials (McDaniel and Anderson 2001). The Superpave Mixtures Expert Task Group of the Federal Highway Administration (FHWA) developed interim guidelines for using RAP based on past experience (FHWA 1997). In NCHRP Project 9-12, the use of the tiered approach for RAP was considered appropriate (McDaniel and Anderson 2001). Relatively low levels of RAP can be used without extensive testing of the binder, but when higher RAP contents are desirable, conventional Superpave binder tests must be used to determine how much RAP should be added or which virgin binder is recommended to be added to the mixture.

In addition, RAP processing equipment and procedures have advanced since the recommendations for incorporation of RAP in the Superpave mix design method were made in NCHRP Rreport 452 (McDaniel and Anderson 2001) and NCHRP Research Results Digest 253 (NCHRP 2001). Current crushing and screening technologies allow processing of RAP in a more consistent and uniform manner. In addition, hot mix plants are routinely able to handle higher amounts of RAP. As a result, it is now possible to consistently produce HMA mixtures containing 25% to over 50% RAP. Such high-RAP content mixes have the potential to significantly reduce the cost of HMA paving while conserving natural resources.

RESEARCH OBJECTIVES

This study was divided into three separate phases, each with its own objectives. The three phases included (1) investigation of warm mix asphalt (WMA) technologies; (2)

investigation of increased percentages of RAP in HMA mixtures; and (3) investigation of WMA technologies on mixtures made with increased RAP contents.

1. Warm Mix Asphalt

The main objective of the warm mix asphalt phase of the research was to evaluate the effects of selected warm asphalt technologies on the rheological and engineering properties of asphalt binders and mixtures. Based on recommendations from the SCDOT, only WMA-foam and Evotherm™ were included as warm asphalt technologies in this part of the study. The scope of this research phase included:

- Conducting an extensive literature review on the topic of warm mix asphalt;
- Conducting a survey to determine the experiences of various DOTs and other agencies around the country with warm mix asphalt;
- Investigating the effects of WMA made with WMA-foam and with Evotherm™ additive on mix designs;
- Evaluating performance characteristics of plant-produced (field) and laboratory-produced WMA mixtures;
- Developing recommendations for implementation of WMA in SCDOT asphalt mix designs.

2. Reclaimed Asphalt Pavement

The main objective of the RAP phase of the research was to investigate the mix performance properties of the use of high percentages of RAP in hot mix asphalt mixtures. The scope of this phase of the research included:

- Conducting an extensive literature review on the topic of RAP;
- Investigating the rheological properties of the extracted binders from selected RAP sources;
- Evaluating the effects of high RAP percentages on various asphalt mix designs;
- Evaluating performance characteristics of HMA mixes containing RAP;
- Developing recommendations for implementation of high-RAP contents in SCDOT asphalt mix designs.

3. Warm Mix Asphalt Additives Containing RAP

The main objective of the WMA/RAP phase of the research was to investigate the properties of WMA mixtures containing RAP made with WMA-foam and with Evotherm™. The scope of this phase of the research included:

- Conducting an extensive literature review on the topic of WMA mixtures containing RAP;
- Investigating the rheological properties of composite binders composed of virgin binders, extracted RAP binders, and selected Evotherm™ RAP binders;

- Determining the practical mixing and compaction temperatures for these modified mixes considering the combined effects of the RAP and WMA technologies;
- Evaluating the effects of higher RAP percentages in WMA mix designs;
- Evaluating the moisture susceptibility of plant-produced (if available) and laboratory-produced mixtures containing selected higher RAP percentages and selected WMA technologies (WMA-foam and Evotherm^{TM} additive);
- Evaluating the performance characteristics of asphalt mixtures made with WMA technologies and RAP;
- Developing recommendations for implementation of WMA mixtures containing high-RAP contents in SCDOT asphalt mix designs.

CHAPTER 2: LITERATURE REVIEW

WARM MIX ASPHALT (WMA)

The term warm mix asphalt (WMA) represents technologies that allow considerable reduction of mixing and compaction temperatures of asphalt mixes. This is done in one of two ways. The first is a process where water is introduced to hot asphalt binder, creating steam that forms a foaming effect and reduces the viscosity of the binder. The second is a process where a viscosity modifier is added to the binder that directly affects the binder's viscosity. The reduced viscosity allows asphalt to be mixed at lower temperatures with similar results. North American asphalt mixes are generally heated to 300°F or greater, depending on the binder used. Warm mix asphalt allows production at 250°F or lower, with some companies claiming up to a 100°F reduction in production temperatures.

Naturally, these WMA technologies offer the asphalt industry many promising advantages. Environmental benefits of WMA include reduced emissions and worker exposure to fumes and heat generated during production and placement. Economic benefits include reduced fuel consumption, reduced emission control spending, and longer haul distances and paving seasons. Long term physical benefits include reduced aging and cracking in WMA pavements (Prowell and Hurley 2007). Another benefit of WMA technology is a reduction in time between paving and opening a road to traffic (Hurley and Prowell 2005). The reduction in production temperature, and thereby emissions, alone means significant savings, as 30-50% of a plant's overhead cost is spent on emission control (Asphalt Pavement Association of Oregon 2003). Some WMA technologies have been studied very thoroughly, whereas others have little to no comprehensive data (Vitkus et al. 2009).

In 1956, Prof. Ladis Csanyi of Iowa State University realized the potential of foamed bitumen for use as a soil binder. Since then, foamed asphalt technology, which allows lower mixing temperatures, has been used successfully in many countries. The original process involved injecting steam into hot bitumen. In 1968, Mobil Oil Australia modified the original process by adding cold water rather than steam. Since then, multiple products have been produced that lower the mixing temperature of asphalt mixtures (Button et al. 2007).

The benefits of using WMA can be customized based on the application and the desired effects. While WMA is usually used to lower the mixing temperature as much as possible, limiting the temperature reduction can increase the compactibility of the mix, and can lead to a reduction in density and lower optimum binder content. The benefits of a lower binder content might outweigh the benefits of lower fuel consumption and mixing temperatures (Estakhri et al. 2010).

From an environmental perspective, the potentially greatest benefit of WMA technology is the potential to reduce emissions due to lower production temperatures. Additionally, asphalt produces more emissions as the production temperature increases, and the greater the reduction in temperature due to the use of WMA technologies, the greater the emission reduction. Expected emissions reduction from the production of WMA mixtures when compared to conventional HMA mixtures is as follows: reduction of CO_2 by 30-40%, reduction of SO_2 by 35%, reduction of volatile organic compounds (VOCs) by 50%, reduction of CO by 10-30%, reduction of NO_2 by 60-70%, and reduction of dust by 20-25%. Measurements of WMA mixtures have shown up to 40% lower fuel costs when compared to comparable HMA mixtures,

but it should be noted that this reduction is directly dependent upon the WMA production temperature (Vaitkus et al. 2009).

Much of WMA research currently underway is in the form of case studies, with one or more WMA pavements being compared directly to a DOT's traditional HMA mix. While WMA technology is increasing in both use and availability, many of the field performance studies are only one or two years old. Most perceived disadvantages of the use of WMA are related to insufficient investigation and its relatively short duration of use (Vaitkus et al. 2009). While the goal of most WMA products is to achieve properties comparable to HMA, the long term goal of WMA should be to improve upon conventional HMA as the technologies continue to evolve. Further advances in WMA technology will hopefully lead to both lower production and placement temperatures and stronger final products (Diefenderfer and Hearon 2010).

Studies have shown that binders containing Sasobit® had higher G*/sinδ values compared with unmodified binder, indicating increased rutting resistance (Gandhi et al. 2009). Binders with Sasobit® also showed lower permanent deformation when compared to base binders, further indicating improved rutting resistance (Biro et al. 2009). Virgin binder grade plays an important role in determining high failure temperature values of recycled WMA binders (Park et al. 2009). Midrange temperature performance using Sasobit® has also been measured. Research indicates that binders containing Sasobit are stiffer and more resistant to penetration at midrange temperatures. WMA binders containing RAP binder were observed to have significantly lower resistance to low temperature cracking. To satisfy current Superpave binder specifications, it is recommended to reduce the virgin binder grade (Park et al. 2009).

Gandhi et al. evaluated the effects of warm mix additives on aged and unaged samples. It was found that the addition of Sasobit® improved the moisture susceptibility of unaged asphalt mixes, increasing the tensile strength ratios (TSR). They also concluded that WMA aged the same as traditional HMA, and that warm mix additives do not seem to have any significant effect on aged TSR values or how rutting resistance changed as the mixes age (Gandhi et al. 2010).

Aging the binders in the RTFO at a lower temperature reduces the aging index of binders. Thus, by reducing the mixing temperatures of WMA binders, the aging of the binders can be reduced. However, changing the temperature of the RTFO had no effect on the G*/sinδ value, indicating that reducing the mixing temperature does not adversely affect the rutting resistance of binders (Gandhi et al. 2009).

Evotherm™

MeadWestvaco's Evotherm™ is an asphalt emulsion. Evotherm™ is a chemistry package that includes materials to improve workability, adhesion promoters and emulsifying agents. During field use of Evotherm™, it is pumped directly to an asphalt line using heated valves. For large scale projects, the Evotherm™ modified binder can be stored at the plant in a tank similar to other emulsions. Around seventy percent of the emulsion is asphalt residue, so the mix should be proportioned appropriately. When the emulsion is mixed with hot aggregate, the water in the emulsion forms steam, resulting in a warm mix asphalt (Hurley and Prowell 2006). While Evotherm™ behaves much like asphalt emulsions, there are key differences that make Evotherm™ feasible as a warm mix additive. The warm mix formulation allows complete coating of dense graded aggregate at temperatures as low as 60°C, where conventional emulsions are unable to do this without high chemical loadings or high doses of water. Evotherm™ also allows mix workability and compactibility to be maintained without sacrificing either cure rate

or density. Adhesion promoters are used in Evotherm™ to control moisture resistance properties (Prowell et al 2007).

Evotherm™ can be delivered in three different forms. Evotherm ET (Emulsion Technology) is a water based asphalt emulsion and requires no plant modifications; it simply replaces the liquid asphalt in an HMA design. Evotherm DAT (Dispersed Asphalt Technology) is a concentrated solution of Evotherm™ additives that is in-line injected at the mix plant. Evotherm DAT allows for flexibility in switching between warm mix and hot mix production. Evotherm 3G (Third Generation) is a newer additive introduced at the mix plant or asphalt terminal. Each version contains the same Evotherm™ additives.

Evotherm™ uses a chemical additive technology and a "Dispersed Asphalt Technology" delivery system. The producer states that by using this technology a unique chemistry customized for aggregate compatibility is delivered into a dispersed asphalt phase (emulsion). During production, the asphalt emulsion with the Evotherm™ chemical package is used in place of the traditional asphalt binder. The emulsion is then mixed with the aggregate in the HMA plant. The manufacturer reports that this chemistry provides better aggregate coating, workability, adhesion, and improved compaction with no change in materials or job mix formula required. In addition, they report 100°F reduction in production temperatures (Gandhi and Amirkhanian 2007).

In an effort to compare laboratory rutting tests to field performance of warm mix asphalts, a section of the National Center for Asphalt Technology (NCAT) Test Track was used for a surface mix design using Evotherm™. The test section was approximately 200 feet in length, and was subjected to accelerated loading using specifically loaded trailers to provide around 10 million equivalent single axle loads (ESAL) in a 2 year period. The test concluded that rutting susceptibility tests conducted in the Asphalt Pavement Analyzer (APA) indicated similar performance to that of the field, and that the WMA sections showed excellent field performance over the testing period. Other findings of the study concluded that Evotherm™ based WMA could be successfully stored in a silo for 17 hours, and that it could be opened to traffic as soon as 1.75 hours after paving commenced (Prowell et al. 2007).

In Alabama, a warm mix asphalt demonstration included the use of Evotherm™. Testing included APA rut tests, indirect tensile strength, wheel tracking, dynamic modulus, and creep compliance. The WMA in this study required more binder than the equivalent hot mix, which may have had an effect on some of the results. The study found that the tensile strengths of warm mix were lower than conventional hot mix, and that the warm mix asphalt was more susceptible to rutting. Dynamic modulus results showed that hot mix was stiffer than warm mix, and creep compliance testing suggested that warm mix was more susceptible to load induced damage. When cores were taken one year after placement and tested, the study found warm mix asphalt was closer to hot mix in tensile strength, indicating that the WMA undergoes a type of curing that increases strength as time passes, and that in-place warm mix asphalt might be more similar to hot mix than its laboratory tested counterpart. The study also found that the use of WMA had no effect on the bond between pavement layers (Kvasnak et al. 2010).

A Texas DOT project evaluating the structural performance of a 10-inch thick warm mix asphalt found that it was able to be compacted uniformly. Using ground penetrating radar (GPR) data to investigate density variations at the bottom of thick lifts, the study determined that it was possible to successfully place Evotherm™ modified asphalt in total thicknesses up to fourteen

inches (Wielinski et al. 2009). A Virginia DOT project using Evotherm™ also noticed no visible distresses up to two years after placement, and plans to continue evaluation over the life of the pavement (Diefenderfer and Hearon 2010).

Foaming Injection Method

Asphalt plant manufacturers with foaming technologies include the Terex and Gencor prototypes and the Astec Double Barrel Green System. These are sometimes referred to as foamed asphalt or free-water systems (Wielinski et al. 2009). The foaming process is accomplished by adding a small amount of water to the binder (Wielinski et al. 2009). The water then turns to steam and expands. This results in a viscosity reduction.

The Double Barrel Green System from Astec Industries uses water to produce a warm mix asphalt. Unlike other warm mix methods, the Astec system does not require the addition of commercial additives. Instead, water is injected along with the liquid asphalt binder, causing the liquid asphalt to foam and expand in volume. The foaming action helps the liquid asphalt coat the aggregate at a lower temperature than traditional hot mix. Astec specifically claims that their technology has the ability to run high percentages of RAP with standard asphalt grades (Astec Industries 2010). The Terex WMA system in Texas uses a technology very similar to Astec Industries' Double-Barrel Green foaming system.

The most common WMA technology (in Texas) used today is the foaming technology. At the present time, the laboratory technology of incorporating foamed asphalt into the mix is not readily available. As a result, the mix must be designed without foam, and then the foam must be incorporated during the trial batch when establishing the job mix formula (Estakhri et al. 2010). To produce a laboratory design process for foamed asphalt mixes, a piece of equipment has been produced to model the foaming process in the lab. All of the "foamed" binder is run through this machine to achieve warm mix properties.

A California demonstration was conducted using a Hveem mix design. This mix included 15% RAP in both the WMA and HMA mixes. The demonstration showed that the area's conventional design method (Hveem) could be used to design WMA using the foaming injection method. While the study's mixture produced lower initial stiffness and higher rutting potential, all of the mixtures met minimum mechanical property requirements. The decreased stiffness and higher rutting were attributed to the lower temperatures during production and placement having a lesser effect on binder stiffening. Because the in-place densities were successfully achieved at lower temperatures, it was concluded that this warm mix method could be used in place of conventional HMA. Continuing field performance evaluation will produce long-term results about the properties of WMA (Wielinski et al. 2009).

Sasobit®

Sasobit® is a product of Sasol Wax. Sasobit® is a fine crystalline, long-chain aliphatic polymethylene hydrocarbon obtained from coal gasification using the Fischer-Tropsch process. Sasobit® mixes with the binder to form a homogeneous solution and reduces the binder's viscosity. After crystallization, at temperatures below its melting point, Sasobit® forms a lattice structure in the binder, providing structural stability (Gandhi and Amirkhanian 2007). It re-crystallizes at midrange temperatures, increasing the viscosity and the stiffness (Biro et al. 2009).

Sasobit® is described as an "asphalt flow improver," both during the asphalt mixing process and during placement operations. Sasobit® has the ability to be combined with polymers

to achieve target specifications of polymer-modified asphalts while still possessing the advantages of warm mixes. Since Sasobit® modifies the binder's properties, it has a tendency to "bump" the PG grade of a binder. For this reason, it has been suggested that "modified binder including Sasobit® needs to be engineered to meet the desired Performance Grade" (Hurley and Prowell 2006).

The addition of Sasobit® to recycled binders increases the viscosity at 60°C, suggesting better rutting resistance at critical pavement temperatures. The creep recovery tests and repeated creep recovery tests performed by Kim et al. showed lower creep compliance values for Sasobit®-modified binders than recycled binders without warm mix additives. Frequency sweep tests indicated that the recycled binders containing Sasobit® were observed to have lower phase angles and higher complex moduli than other recycled binders (Kim et al. 2011). Kim et al. recommended further investigation into WMA-RAP mixtures to help generalize their findings and verify them for other binder sources. A study using asphalt mixes and the APA rut tester also concluded that Sasobit® significantly lowers the rut depths of both aged and unaged mixtures (Gandhi et al. 2010). While Sasobit® can decrease the rutting potential of asphalt mixes, rutting potential is increased with decreasing production and placement temperatures, possibly due to the decreased aging of the binder. Mixes containing Sasobit® were less sensitive to decreased production temperatures than control mixtures (Gandhi et al. 2009).

Zeolite

Zeolites, such as Advera® and Aspha-min®, are water-bearing agents designed to release steam when added to asphalt. The first major laboratory study on zeolite was performed by Hurley and Prowell in 2005. They determined that the addition of Aspha-min® reduced air voids by 0.65%; did not affect the resilient modulus of the mix; did not increase the rutting potential of mixes in the Asphalt Pavement Analyzer (APA), though the rutting potential did increase as mixing and compaction temperature decreased (which is the point of warm asphalt); and may increase the potential for moisture susceptibility, though the addition of lime mitigated this effect (Hurley and Prowell 2005).

Gandhi continued research on zeolite and performed binder tests using zeolite (Gandhi 2008). Noting the effects of zeolite and Sasobit on the $G^*/\sin\delta$ of different binders, he determined that binder source had an impact upon the performance of the WMA modified binder. In general, zeolite did not significantly affect binder viscosities at 135°C (275°F) and 120°C (248°F) immediately, but after 60 to 90 minutes, zeolite-modified binders exhibited viscosities significantly higher than the base binders; the zeolite also significantly increased the binder viscosities at 60°C (140°F); he attributed both effects to the mineral filler effect of zeolite (Gandhi 2008). Gandhi also noted that binders containing zeolite had significantly higher viscosities than un-modified and Sasobit®-modified binders after RTFO aging. The rutting parameter ($G^*/\sin\delta$) for binders with WMA modifiers was higher than base binders, indicating increased rutting resistance. He found that the fatigue resistance ($G^*\sin\delta$) of base and WMA-modified binders were significantly similar and that reducing the aging temperature improved resistance to thermal cracking when modified with zeolite (Gandhi 2008).

Gandhi also performed mixture testing on aged and unaged specimens. He found that unaged mixes containing zeolite had lower resilient modulus (M_R) values compared to control at 25 and 40°C (77 and 104°F). He also determined that aging WMA mixtures (here zeolite and Sasobit®) increased the stiffness of the mixes to levels similar to unaged control mixes; the warm

mix additives improved the moisture susceptibility (tensile strength ratios, TSR), but seemed to affect the mix TSRs as they aged (Gandhi 2008).

Warm Mix Technology Certification

As with most any material used in roadway construction, WMA technologies must be certified by the agency before use in construction. Based on the results of a national survey, the National Center for Asphalt Technology (NCAT) has established a national WMA certification program at the NCAT Pavement Test Track. This program consists of both field and laboratory evaluation to assist state DOTs with the approval of WMA products and processes (Powell and Taylor 2011).

The WMA certification program at NCAT is used by many states including the South Carolina DOT. The WMA approval process for SCDOT consists of two options. The first is documentation of successful performance at the NCAT Pavement Test Track. The second option is documentation that the WMA additive or process is accepted by at least five state transportation agencies with each having at least one WMA section placed with successful operations (SCDOT 2011).

As part of NCHRP Project 20-07 / Task 311, the AASHTO National Transportation Product Evaluation Program (NTPEP) is developing standardized evaluation procedures for WMA material additives and processes. The WMA evaluation program will allow submittals from three WMA categories including foaming processes (injection, damp aggregate, or mineral fillers such as zeolites), chemical additives, and organic additives. During the evaluation, products or processes will be evaluated using laboratory tests and/or field performance by way of an accelerated pavement testing facility. The development of this program is still underway with a completion date of August 31, 2012 (NTPEP 2012).

RECLAIMED ASPHALT PAVEMENT (RAP)

The production of Hot Mix Asphalt (HMA) involves the use of a bitumen-based binder and mineral aggregate. As the industry has developed and grown, it has become aware of the ability to recycle used HMA into new pavements. This reclaimed asphalt pavement (RAP) retains many of the benefits of virgin pavements, and field studies have shown no significant difference between pavements containing RAP and those with only virgin materials (Kandhal et al. 1995). If the industry uses this RAP, it need not use as much virgin binder and mineral aggregate, which have, in many areas, become more scarce and expensive. This allows road construction involving RAP to be completed at potentially reduced cost and with lower usage of non-renewable resources (Su et al. 2009).

The idea of recycling older pavements into RAP to be used in new maintenance and construction has been around for quite some time. It has long been used in shoulders, as base material, or disposed of in landfills, but these uses do not take advantage of RAP's monetary value (Roberts et al. 2003). The oil embargo and development of cold-milling machines in the 1970's provided ample incentive and an increased supply of RAP to contractors; who then had to find some cost-effective way to utilize it. The northeastern United States alone has millions of tons of stockpiled RAP, and its use presents an opportunity for state Departments of Transportation (DOT) to save considerable amounts of money and energy (Mallick et al. 2008). As of 1997, "…the recycling of old pavements into new pavements is the largest single recycling

practice in the United States" (Bukowski 1997). To aid in this practice, NCHRP Report 452 was developed to provide guidelines for incorporating RAP into the Superpave system on a scientific basis (McDaniel and Anderson 2001).

Currently, 60% of state DOTs permit high RAP (more than 25% RAP by aggregate weight) in asphalt construction, but most projects do not use high RAP percentages because of the variability in the binder and aggregate gradation and lack of experience with higher RAP contents (Copeland et al. 2010). RAP in surface courses, however, is still limited. If higher percentages of RAP, between 30 and 50%, could be used while still constructing pavements which meet or exceed all current standards, the cost savings to the states, and therefore to the taxpayers, would increase (Mallick et al. 2008). Considering that the alternative to using RAP is often paying for it to go into a landfill or finding some way to waste it, the benefits in cost alone are obvious. Su et al. determined that using up to 40% RAP in airport surface courses was feasible in Japan (Su et al. 2009). Celauro et al. determined that up to 50% RAP could be used in base, intermediate, and surface courses in Italy so long as appropriate controls were utilized (Celauro et al. 2010). The Maine DOT has utilized drum plants to experimentally produce HMA mixes containing 70% RAP (Tao and Mallick 2009). These results indicate that, with care, pavements can incorporate greater percentages of RAP while still meeting or exceeding the governing specifications.

However, RAP must be treated more carefully than virgin aggregate. Firstly, the RAP stockpile must be of high enough quality and uniformity to meet project specifications. Ideally, the stockpile should be covered to reduce its overall moisture content, as excess water requires greater heat to drive off in the mixing process and will, therefore, increase cost in heating and production time (Roberts et al. 2003). Over time, RAP stockpiles develop a crust of oxidized material. This crust is useful in shedding off water, but should be blended back into the rest of the stockpile before use to ensure a more uniform product. The cold feed bins used for RAP are similar to those used for virgin aggregate with one exception: the interior sides are much steeper. This allows the RAP to slide more easily from the bin and prevents sticking in hot or wet weather, when the asphalt may otherwise bridge the opening (Roberts et al. 2003). Other plant modifications may vary from plant to plant; some plants crush and/or fractionate their RAP and may require more than one RAP cold feed bin; others simply pass the RAP over a scalping screen to remove any large chunks of material. Introduction of the RAP into the virgin mix also varies, but care must always be taken to prevent overheating the RAP and thereby volatizing the binder.

As RAP mixes generally contain more aged, and therefore stiffer binders, they have often shown greater rutting resistance (Xiao 2006), but that same stiffness also affects the resilient modulus and fatigue life of RAP mixes.

RAP Considerations

The mix design procedure for including RAP is essentially the same as the standard Superpave method, with the additional requirement for binder analysis because each RAP source is unique (Roberts et al. 2003). After years of service in pavement, binder becomes stiffer and less elastic; this is known as aging. The degree of aging depends on a number of factors, including: temperature, air void content of the mix, and the chemical make-up of the binder (Chen et al. 2007). The aggregate and gradation may also differ among RAP sources, even if they use the same aggregate source and conform to the same gradation specification.

Binder aging is primarily a result of oxidation, though photo-degradation and volatilization also contribute (Asphalt Institute 2003). Because each pavement is subjected to different conditions, it reasons that the binders from different recovered pavements will differ. Their viscosities and other rheological properties must be accounted for to ensure a quality final product. The amount of RAP included in the mix also changes the effects it has upon the final product. Typically, the virgin binder is softer (of a lower PG grade) so that the blended binder will meet the desired specifications after mixing. When this is not adequate, a rejuvenating agent may be used to soften aged binders.

Many have questioned exactly how RAP binder combines with virgin material during mixing. Since specifications call for a final PG grade binder, researchers have specifically wanted to understand how RAP binder will influence the final binder. The mixing of RAP can be presented in three cases: black rock, total blending, and real world. Black rock treats the RAP as simply another aggregate source and assumes absolutely no mixing between the RAP and virgin binders; therefore the RAP's only contribution to the mix would be through the aggregate and its gradation. Total blending assumes the two binders mix completely and uniformly; therefore the RAP contributes to both aggregate (and gradation) and binder properties of the mix. Real world scenarios depend upon the amount of RAP used. Bonaquist has developed a method to evaluate whether total blending does, in fact, occur (Bonaquist 2007). This method compares the dynamic modulus of the mix with an expected dynamic modulus obtained from the Hirsch model developed by Christensen et al (2003). The method uses the shear modulus of recovered RAP (thus totally blended) binder to estimate the dynamic modulus. If the estimated and measured dynamic moduli are a match, blending of the virgin and RAP binders is assumed.

A three tiered solution was proposed by McDaniel and Anderson to address changes to the virgin binder to account for RAP interactions and is shown in Table 2.1 (McDaniel and Anderson 2001). Lower percentages of RAP are treated as black rock, but this assumption breaks down as the percentage of RAP increases. Higher RAP percentages see the aged binder mixing completely with virgin materials in sufficient quantities to significantly affect the mix's performance properties (McDaniel and Anderson 2001). These assumptions have begun to be questioned on the micro-scale (Do et al. 2008), but more research is needed before they are overturned.

Table 2.1. Virgin binder selection guidelines for RAP mixtures

	RAP Percentage		
	Recovered RAP Grade		
Recommended Virgin Asphalt Binder Grade	**PG xx -22 or lower**	**PG xx -16**	**PG xx -10 or higher**
No change in binder selection	<20%	<15%	<10%
Select virgin binder one grade softer than normal (e.g., select a PG 58-28 if a GP 64-22 would normally be used)	20-30%	15-25%	10-15%
Follow recommendations from blending charts	>30%	>25%	>15%

Table 2.1 implies the importance of knowing the PG grade, and thereby the rheological properties, of the recovered RAP binder. This was stated by Celauro et al. when she expressed

the need to use "new bitumen with adequate rheological properties…" to produce "…high-performance mixtures" (Celauro et al. 2010). Determination of binder properties is accomplished through the standard Superpave binder tests.

The second important control when using RAP is aggregate gradation. High percentages of RAP cannot be used if they drive the gradation of the final mix out of specification. For this reason it has been proven necessary to fractionate RAP when using higher percentages (Xiao 2006; Valdés et al. 2011). This is done for two reasons. First, to control the amount and size fractions of RAP aggregate introduced into the mix. Secondly, since different size fractions of RAP have different binder percentages, fractionating allows greater control of the aged binder introduced to the mix (Valdés et al. 2011).

WARM MIX ASPHALT WITH RECLAIMED ASPHALT PAVEMENT

The most researched use of RAP with WMA has been in base layers. Mallick et al. studied the use of heated reclaimed asphalt pavement materials with emulsion and the use of hot mix asphalt with Sasobit® as base course materials (2007). They determined that Sasobit® helped to achieve similar workability and compactibility at lower temperatures compared to hot mix; no significant difference between stiffness and retained strength values was found. The addition of 1% Sasobit® (by total binder) yielded better properties than a mix with 1.5%, but the mix with 1.5% Sasobit® showed better workability (Mallick et al. 2007).

Mallick et al. successfully recycled 75% RAP into asphalt base course mixture using the WMA additive Sasobit H8 at lower than HMA temperatures (125 and 135°C) (Mallick et al. 2008). The H8 product used has slightly lower molecular weight and melting point than regular Sasobit®. They used three binder grades (PG 64 -22, PG 52 -28, and PG 42 -42), one for control and the others to rejuvenate the aged RAP binder. They performed volumetric, tensile strength, and seismic modulus tests and found that 75% RAP warm mixes can be produced with similar air voids to conventional HMA recycled mixes. The addition of Sasobit H8 helped create more uniform mixes and the addition of significantly lower PG graded binder to the high RAP mix produced results most like those of the HMA control mix (Mallick et al. 2008).

Mallick and Tao also performed a study where 100% RAP was recycled into a base course with the addition of Sasobit® H8 and Advera® zeolite at various levels (Tao and Mallick 2009). They performed volumetric, seismic modulus, ITS, and workability tests. No virgin binder was used in this study. Instead, the mix was heated to 125°C, and the warm mix modifier was added. Because zeolite acts through foaming action, slotted molds had to be created for mixes with higher dosages to release water pressure generated during compaction. The study found that 100% RAP WMA mixes were feasible from a workability standpoint. The addition of WMA modifiers helped lower the viscosity of the RAP as low as 110°C, but that both modifiers likely had a stiffening effect at low temperatures. The WMA mixes had higher ITS and seismic modulus values than the control HMA. Finally, the Sasobit H8 caused the bulk specific gravity of mixes to increase proportionally to its concentration (Tao and Mallick 2009).

Field tests have been performed using WMA additives and RAP. The Maryland State Highway Administration paved a section of road using 45% RAP in the base course, SMA in the intermediate course, and 35% RAP in the surface course; they used 1.5% Sasobit by weight of total binder. The stiffness of the WMA and HMA control mixes were statistically similar (Michael 2005). A demonstration project was constructed in Orlando, Florida using 20% RAP

and zeolite. The zeolite reduced production and compaction temperatures by 19°C (39°F) and resulted in in-place densities similar to control RAP produced at HMA temperatures (Hurley and Prowell 2005).

The Florida DOT paved a section of State Route 11 with 45% RAP using both HMA and the foaming injection WMA method in December 2007 (Copeland et al. 2010). The following tests were performed on the mixes: performance grading of the binders, dynamic modulus, and flow number. The tests indicated that the WMA mix was slightly softer than the HMA mix, both in dynamic modulus and PG binder grade (Copeland et al. 2010). Interestingly, while the HMA mix was shown to demonstrate complete blending of RAP and virgin binders using the method suggested by Bonaquist, the WMA mix may have experienced incomplete blending, as the measured modulus values exceeded the expected values. Copeland et al. suggests further study into whether blending occurs in WMA-modified high RAP mixes (2010).

With warm mix asphalt and high RAP usage becoming more commonplace in asphalt paving, understanding how each affects the pavement has become more important. Research has shown that considerable literature exists on how each technology affects asphalt pavements individually, and a handful of studies have been done to examine the two used in conjunction, but no method currently exists to predict the mechanical properties of mixtures containing warm mix modifiers at high RAP percentages, and the blending and interaction between the aged RAP binders and these warm asphalt additives is not known. These are holes in the current body of knowledge. Gandhi performed a study on virgin and aged binders with WMA, but his samples were created in the laboratory and then artificially aged, so the effect of modified virgin binder blending with aged binders at mixing was not studied (Astec Industries 2010).

CHAPTER 3: SURVEY OF THE USE OF WARM MIX ASPHALT

A survey of state DOTs and agencies was conducted at the beginning of this study in 2009 to assess the adoption of WMA technologies and current WMA specifications or supplements of HMA related to WMA. Some concerns such as life cycle costs, health, and environmental protection were also included in this survey. The complete survey is presented in Appendix A. In total, 30 of 56 state DOTs and agencies responded to this survey.

The survey revealed that 80% (24 states) of the respondents specified the utilization of WMA additives or process for producing WMA mixture. However, only 20% of the respondents have the completed reports for WMA projects. These states included Ohio, Texas, New Jersey, Nebraska, Florida, and South Carolina. In addition, only Iowa, Minnesota, Oregon and South Carolina have the information for projects where WMA was used in city, county, and private work rather than state projects.

Half of the responding states did not have a procedure for qualifying the WMA additives. However, five states have approved WMA technologies and ten states are processing them. Figure 3.1 summarizes the application of all states having the WMA specifications.

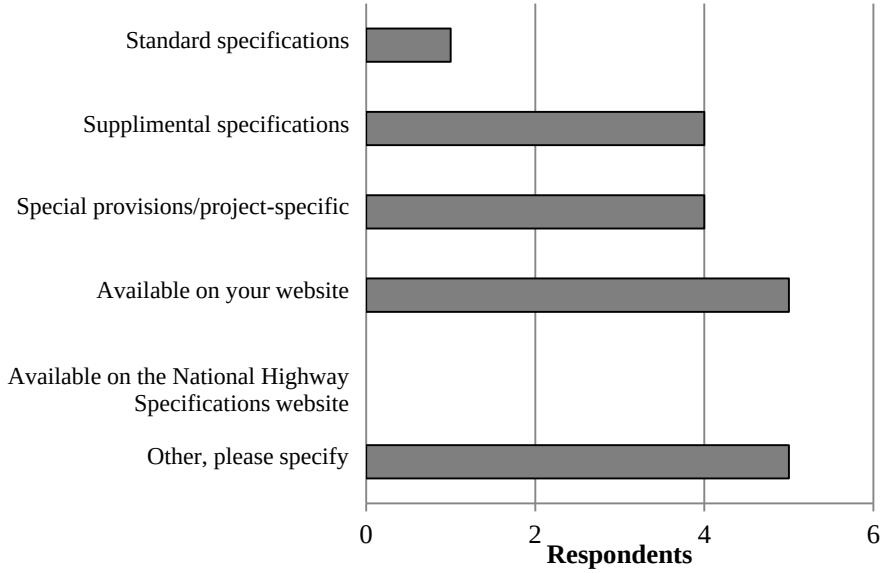


Figure 3.1 Available specifications

Only two of the responding states (Ohio and Alabama) allow for an increase in allowable RAP percentage for WMA compared to HMA in this survey. Ohio considers that it can be used only if other RAP processing can be met, and Alabama allows 10% to 25% in HMA and up to 35% in WMA mixtures.

Figure 3.2 summarizes the typical laboratory mixing and compaction temperature ranges of WMA compared to HMA. It can be noted that twelve states do not give any guidance for lab mixing and compaction temperatures. Seven states used the temperatures recommended by manufactures. One or two of them base the temperatures on the performance grade of asphalt binder, research projects, quality control of WMA, and a set range 10-30^{o}F lower than HMA.

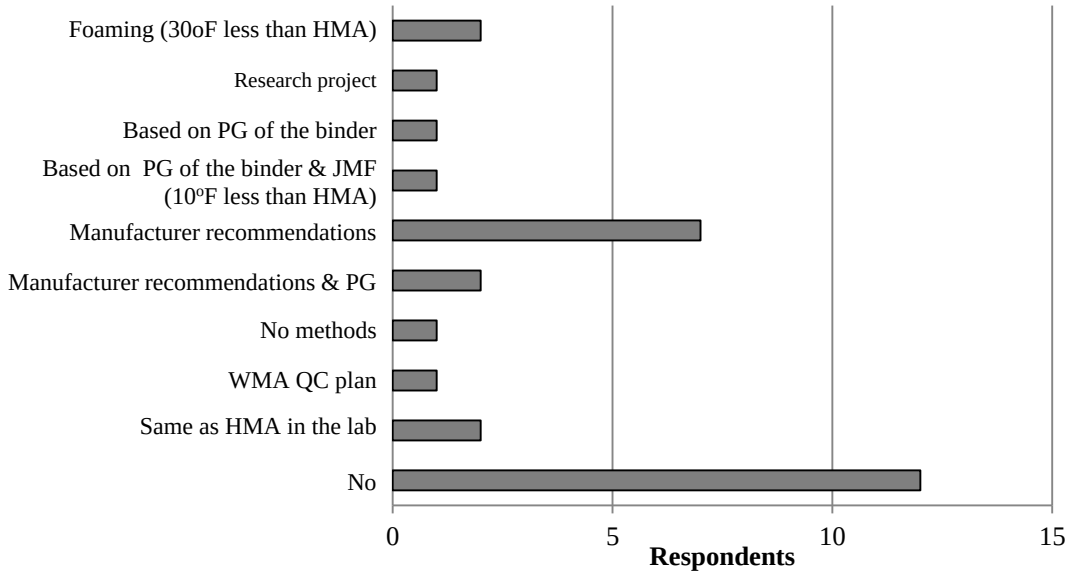


Figure 3.2 Typical laboratory mixing and compaction temperature ranges

The typical pavement mat compaction temperature ranges for WMA compared to HMA mixtures are summarized in Figure 3.3. Fourteen states do not provide any guidance for pavement mat compaction temperature. Five of the states use temperatures recommended by the manufacturer/supplier. A few of them base the temperatures on density of pavement without damaging the mat or various temperature reductions compared to HMA.

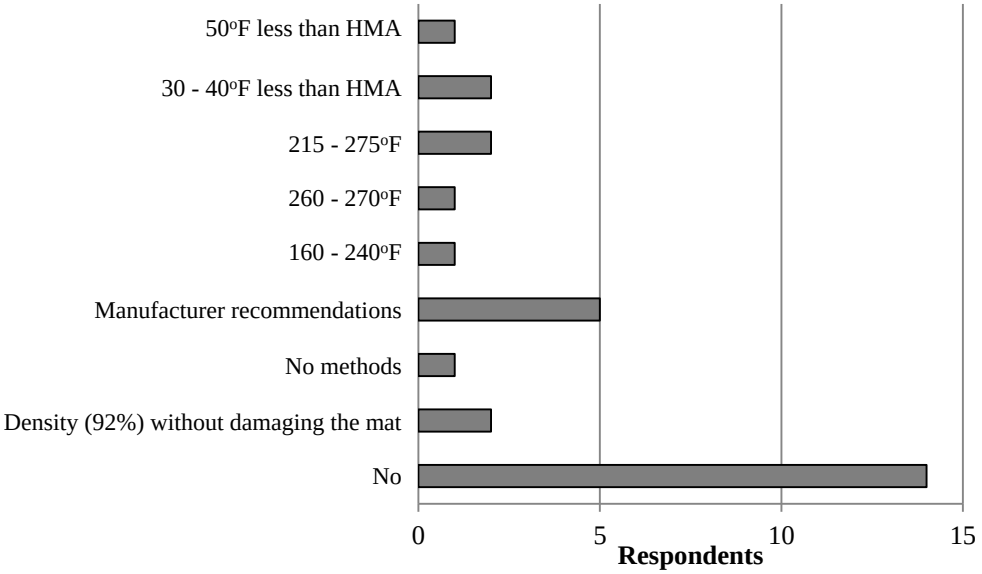


Figure 3.3 Typical pavement mat compaction temperature ranges

Some states had recently completed research studies related to WMA technologies. These studies focused on different aspects of WMA mixtures. Figure 3.4 shows the topics of various studies such as emissions, life cycle cost, energy, and engineering properties. Six states did research on moisture susceptibility, five of them suggested to test the rutting resistance, four require field and lab performance, one state has a requirement for emissions of WMA at the roadway and asphalt plant, and one state is considering the use of RAP in WMA mixtures. However, research studies focusing on the environmental and health concerns, life-cycle cost analysis, fatigue resistance and energy consumption analysis are not currently in the majority.

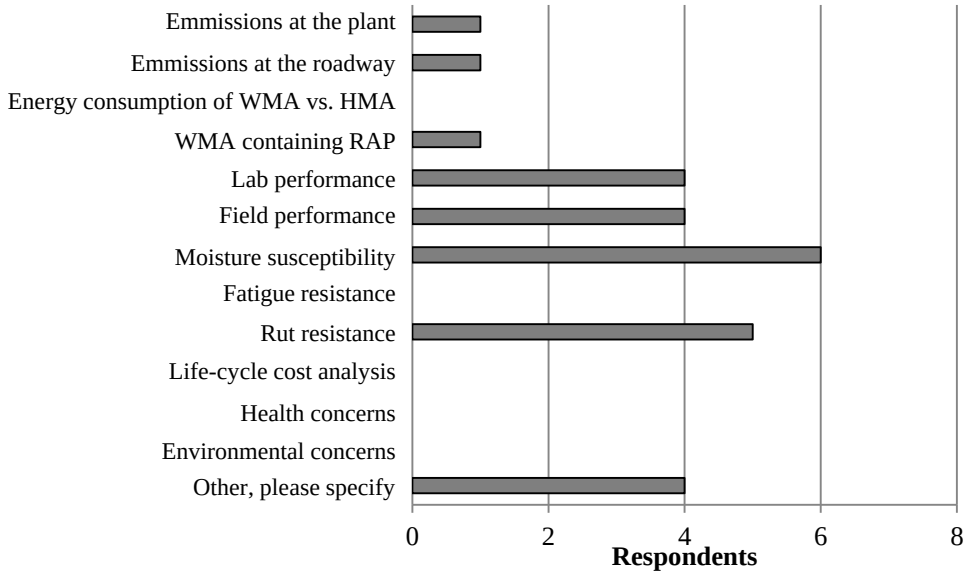


Figure 3.4 Research studies of WMA technologies

The major concerns of WMA mixtures in various states are compiled in Figure 3.5. It can be seen that ten states are still experimenting with WMA mixtures; seven of the states need a new WMA mix design procedure; five states do not know enough about the processes or products and consider that energy reduction benefits are not sufficiently qualified currently; and four states still have concerns that WMA technologies are too expensive compared to HMA mixtures.

Some states gave other concerns about WMA mixtures (Figure 3.6). For example, Ohio, Florida, and New Mexico were concerned about the long-term performance; South Dakota is focused on the ultimate quality of WMA vs. HMA; Texas was developing special provisions for WMA mixtures; Alabama, Oregon, and Iowa considered stripping a major concern; North Carolina's major concern was about WMA's potential long-term effects on the PG binder properties; Idaho questioned the proper temperature to reheat and test WMA specimens for QA and QC; South Carolina was concerned about the coating issue and changes to plant operations; and New York considers that the appropriate acceptance testing should be developed.

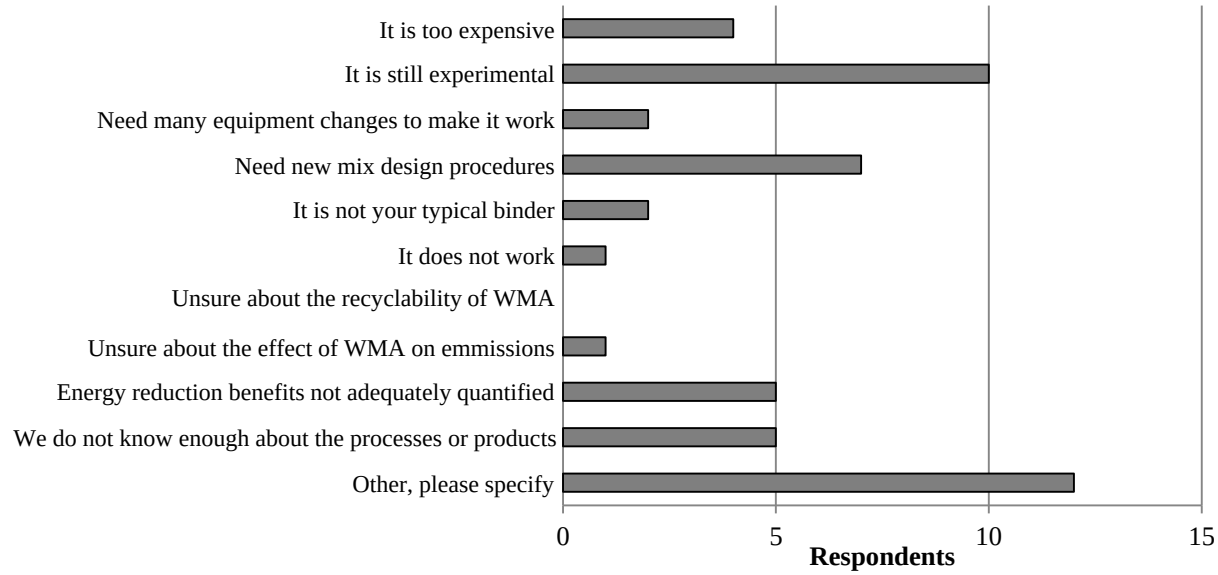


Figure 3.5 Concerns of WMA technologies

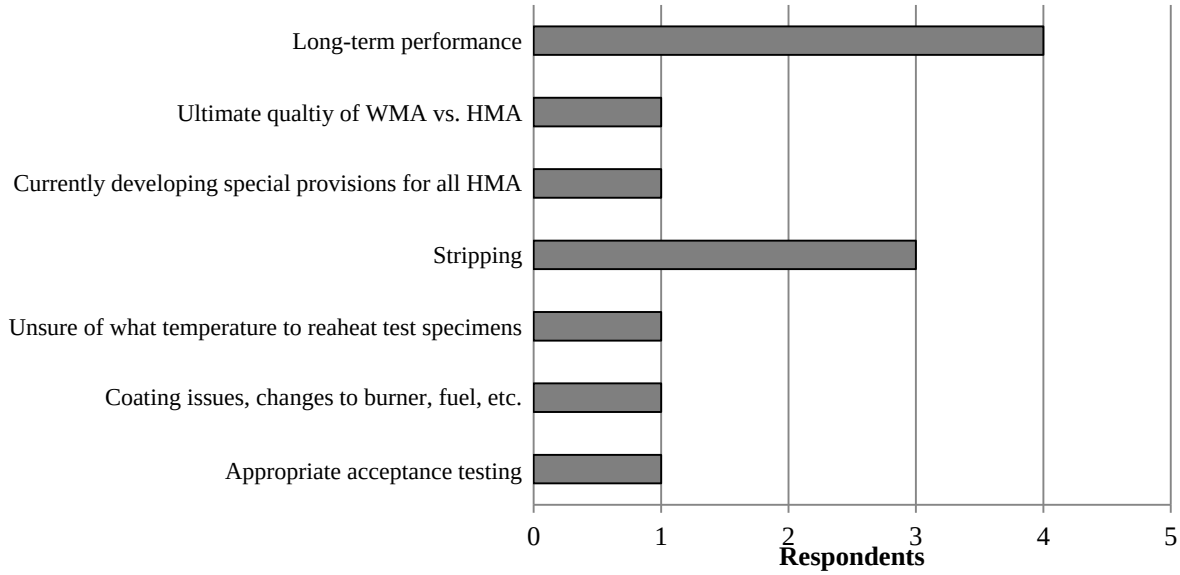


Figure 3.6 Other concerns of WMA technologies

Some states had additional comments about WMA mixtures including:

- "We do not have any immediate concerns with the use of WMA. We are currently developing special provision to allow WMA in all of our HMA mixture types."
- "We have experienced mix tenderness with WMA involving one plant retrofitted with a water-injection/asphalt foaming system. The tender mat hampered efforts to achieve good compaction and ultimately resulted in poor ride quality in certain locations."
- "We have only produced one test project at this time. Production and construction both went well."
- "We have only used WMA on a demonstration basis and do not have any specification completed. We are also in the early stages of researching WMA."
- "Would like to see the reduced oxidation through the plant quantified."
- "Workability at low temperatures, ability to perform hand work, and concerns noted above."
- "What is the impact of using any WMA technology on the mix cost (i.e., increase in $/ton for the different technologies)? At the plant, what is the fuel savings (if any) per ton of mix produced? Long-term low-temperature cracking: some WMA technologies."

CHAPTER 4: EXPERIMENTAL MATERIALS AND METHODS

EXPERIMENTAL MATERIALS

To realize the objectives of this research study, mixtures were produced using two aggregate sources, two binder sources, two WMA technologies, and two RAP sources. All of the materials for this research were selected with input from the project Steering and Implementation Committee. In total, 60 different mix designs were evaluated throughout the course of the study.

The binders selected for this research originated from two different sources (binder A and B). From each source, a PG 64-22 binder was used for the majority of the mix designs. For the mixtures having 40 and 50% RAP, a PG 58-28 binder from source B was used to evaluate the effects of using a softer binder grade for mixtures made with higher RAP contents. Additionally, a PG 76-22 binder from each source was included to study the effects of WMA technologies on the properties of polymer modified binders. The properties of each of these binders are summarized in Table 4.1. Additionally, the mixing and compaction temperatures used for each binder were recommended by the supplier based on viscosity tests.

Table 4.1. Properties of binders included in this study.

Property	Binder A		Binder B		
	PG 64-22	PG 76-22	PG 58-28	PG 64-22	PG 76-22
Unaged					
Viscosity (at 135°C), *Pa·s*	0.45	0.72	0.31	0.65	0.82
G*/sinδ, *kPa* (test temp)	1.23 (64°C)	1.47 (76°C)	1.38 (58°C)	2.13 (64°C)	1.61 (76°C)
RTFO aged					
G*/sinδ, *kPa* (test temp)	3.70 (64°C)	3.32 (76°C)	3.88 (58°C)	4.16 (64°C)	3.63 (76°C)
PAV aged					
G*sinδ, *kPa* (test temp)	3213 (25°C)	3605 (25°C)	3060 (19°C)	2157 (25°C)	1605 (25°C)
Stiffness (60s), MPa (test temp)	178 (-12°C)	198 (-12°C)	249 (-18°C)	144 (-12°C)	130 (-12°C)
m-value (60s), (test temp)	0.306 (-12°C)	0.285 (-12°C)	0.281 (-18°C)	0.349 (-12°C)	0.303 (-12°C)

The two aggregate sources selected for this study were from South Carolina sources and consisted of a marble schist (aggregate B) and granite (aggregate C). The properties of these aggregate sources are included in Table 4.2.

Table 4.2. Properties of aggregates included in this study.

Property	Aggregate B	Aggregate C
G_{sb}	2.81	2.60
G_{sa}	2.85	2.65
Absorption, *%*	0.5	0.8
LA Abrasion Loss (C grading), *%*	24	29

The RAP materials selected for this study were obtained from two sources (B and C) both satisfying the requirements of the SCDOT. The RAP from source B was used for mixtures made with aggregate B and RAP C was used for aggregate C mixtures. The aggregate material from RAP C was from the same source as aggregate C. This limited the effects of RAP on the aggregate C mixtures to only the aged binder from the RAP and not the aggregate. The aggregate from RAP B, however, was not from aggregate source B. The properties of the RAP materials are summarized in Chapter 6.

In this study, two WMA technologies were evaluated: Evotherm™ and foaming. When the Evotherm™ was added to the asphalt binder, the binder was first heated to the target mixing temperature. The Evotherm™ additive was then added to the binder at a rate of 0.5% by weight and then stirred for 5 minutes using a medium-shear radial flow impeller at a speed of 300 rpm before being placed back in the oven at the mixing temperature for 30 minutes. Once mixed, the binder was added to the heated aggregate and mixed in a mechanical bucket mixer in the same manner as the regular HMA samples.

For the foaming WMA technology, water was injected into the hot asphalt binder at a rate of 2% by weight of the asphalt binder using "The Foamer". The binder used for the foamed WMA mix designs was heated and inserted into "The Foamer" at HMA mix temperatures before water was injected into the binder and the WMA binder was emitted and mixed with the hot aggregate at WMA mix temperatures. This mixing of the water instigated the foaming action creating the WMA. This foamed WMA binder was then added to the heated aggregate and mixed in a mechanical bucket mixer in the same manner as the regular HMA specimens.

For WMA mixtures, the mixing and compaction temperatures were based on the recommendations of the Evotherm™ supplier which was a 50°F reduction for mixes without RAP. To maintain consistency, the same reduction was used foamed WMA mixes in this study.

EXPERIMENTAL METHODS

Binder Testing

All of the binders (virgin, WMA, and RAP) were tested to determine specific properties. The tests employed to characterize the binders are summarized in Table 4.3.

Table 4.3. Binder tests used to characterize binders.

Test	Property	Temperature	Binder
Viscosity (AASHTO T316)	Viscosity	105 – 165°C	Virgin, WMA, RAP
Dynamic Shear Rheometer (AASHTO T315)	G*/sinδ and G*sinδ	58 – 88°C 25 – 28°C	Virgin, WMA, RAP
Bending Beam Rheometer (AASHTO T313)	Stiffness (60s) and m-value (60s)	-18°C or -12°C depending on binder grade	Virgin, WMA
RTFO (AASHTO T240)	Short-term aging of binders	163°C and 135°C for HMA and WMA binders, respectively	Virgin, WMA, RAP
PAV (AASHTO R28)	Long-term aging of binders	100°C and 2.1 MPa for 20 hours	Virgin and WMA

RAP Testing

Each RAP source was sampled from plant RAP stockpiles and transported to Clemson in covered metal containers. To ascertain the properties of each RAP material, several test procedures were employed. First, the RAP material was dried in a 105°C oven until all moisture had evaporated, then allowed to cool to room temperature before handling. The RAP was then separated into two size fractions: Finer than the No. 4 sieve (-No. 4) and retained on the No. 4 sieve, but passing the ½ inch sieve (+No. 4) using a mechanical sieve shaker. The binder content of each RAP fraction was determined using the ignition oven procedure outline in SC-T-75. The gradation of the aggregate material remaining after the ignition oven test was then determined using the procedure outlined in AASHTO T27.

It was also important to quantify the properties of the binder present in the RAP material. To accomplish this, the binder was extracted from the RAP using the procedure outlined in AASHTO TP2 and recovering the binder using the SC-T-95 procedure. The recovered binders were then characterized using the appropriate binder test procedures. Additionally, composite binders consisting of RAP and virgin binders were blended at the appropriate ratios and tested using the same binder testing procedures.

Mix Design

Mix designs for each combination of materials were accomplished by preparing eight 150 mm diameter by 115±5 mm tall specimens using the Superpave gyratory compactor (2

specimens at each of 4 trial binder contents). The specimens were prepared by first combining the appropriate aggregate size proportions for a total of 4500 grams per specimen, including 1% hydrated lime. Water was added (5% of the total aggregate batch) to the aggregate batch to hydrate the lime and the material was thoroughly mixed before being placed in the oven at an appropriate temperature to evaporate the water and heat the aggregate prior to mixing with the binder.

When RAP was included in the mix, the oven-dried RAP material was mixed with the dried, heated virgin aggregate at the specified (target) mixing temperatures. The RAP/aggregate mixture was then heated for one hour to ensure that all of the material reached the target mixing temperature before being mixed with the binder. Binder was added to the aggregate material at the mixing temperature and the mixture was blended using a bucket mixer until the aggregate was thoroughly coated by the binder. Finally, the mixture was placed in an oven at the target compaction temperature for two hours prior to compaction.

The Superpave gyratory compactor (SGC) was used to compact the specimens. Each specimen was compacted using 75 gyrations of the SGC as specified for a Surface Type B mixture by SCDOT (2011). Following compaction, a specimen was removed from the mold and allowed to cool in front of a fan. Once cooled, the bulk specific gravity (G_{mb}) of each specimen was measured using AASHTO T166. The volumetric properties of each specimen were then calculated using the theoretical maximum specific gravity (G_{mm}) of the mixture determined using SC-T-83. The optimum binder content was determined to be the binder content that corresponded to 4.0% air voids.

Mixture Performance Testing

The susceptibility of each mixture to moisture damage was assessed by comparing the wet indirect tensile strength (ITS) to the dry ITS of a mixture using the procedure outlined in SC-T-70. Four 150 mm diameter by 95 mm tall specimens were prepared having a void content of 7 ± 1%. Two of the specimens were saturated to a level of 70-80% and conditioned in 60^{o}C water for 24 hours followed by 1 to 2 hours in a 25^{o}C water bath prior to testing. The other two specimens were tested in a dry condition at 25^{o}C.

Six cylindrical specimens (150 mm diameter by 75 mm tall), for each mix type, were compacted to 4 ± 1 % air voids by a Superpave gyratory compactor. These specimens were then conditioned in the Asphalt Pavement Analyzer (APA) chamber at 64°C (147°F) for six hours and tested at the same temperature to determine the rut depth after (8000 cycles) in accordance with AASHTO TP63-09 (currently AASHTO T340).

The resilient modulus of each mixture was measured in accordance with ASTM D4123. Four specimens (150 mm diameter by 95 mm tall) were made at the optimum binder content, and then compacted to 7 ± 1% air voids. The values of the resilient modulus determined from this test method is a measure of the elastic modulus of the HMA materials recognizing certain nonlinear characteristics. The resilient modulus value can be used with structural response analysis models to calculate the pavement structural response to wheel loads, and with pavement design procedures to design the pavement structure. During the testing process, the indirect tensile testing mode produces a highly nonlinear stress field with the least variability at the center of the specimen, and linear variable differential transducers (LVDTs) were used to measure the response. A frequency of 1Hz and test temperature of 25ºC was used in this study.

Fatigue resistance of the mixtures was evaluated using the four point flexural beam fatigue test in accordance with AASTHO T321. Two prismatic specimens (15 × 6 × inches) were compacted using a vibratory plate compactor for each mixture. Each prism was then cut into two beams measuring 15 × 2 ½ × 2 inches. The G_{mb} was measured for each beam and the volumetric properties were calculated. Prior to testing, each beam was conditioned at the test temperature (20^{o}C) for at least two hours prior to testing. Each beam was tested using a loading frequency of 5 Hz. The fatigue life was determined as the number of cycles required to reduce the stiffness of the beam by 50% of the initial stiffness.

CHAPTER 5: EFFECTS OF WARM MIX ASPHALT ON ASPHALT MIXTURES

The primary objective of this phase of the research was to investigate the influence of WMA technologies on asphalt mixtures used by SCDOT. To accomplish this objective, an SCDOT Surface Type B mixture was used as the basis of comparison. Two technologies (Evotherm™ and Foaming) were used to make WMA mixtures. HMA mixtures were also used as a basis for comparison. A total of 12 mix designs (2 WMA technologies plus HMA, two aggregate sources, and two binder sources) were evaluated in the laboratory portion of this phase and the performance of each was evaluated. The materials and methods used in this portion of the study are summarized in Chapter 4.

EFFECTS OF WMA ON BINDER PROPERTIES

Prior to mixture evaluation, the effects of Evotherm™ on different binder sources and grades were evaluated using standard binder test procedures. Binders from two different crude sources typically used in SCDOT projects were used in this evaluation. For each source, a PG 64-22 and PG 76-22 binder were tested. For binder source C, a PG 58-28 was also evaluated as it was used in the investigation of higher RAP contents reported in Chapters 6 and 7.

The results of the binder testing are presented in Figures 5.1 through 5.5 and Tables 5.1 through 5.3. Based on the results, it is evident that the addition of Evotherm™ to any of the binders had no significant effect on the binder performance. This was true for all three binder grades and two sources.

Table 5.1. Properties of unaged control binders and binders modified with Evotherm™.

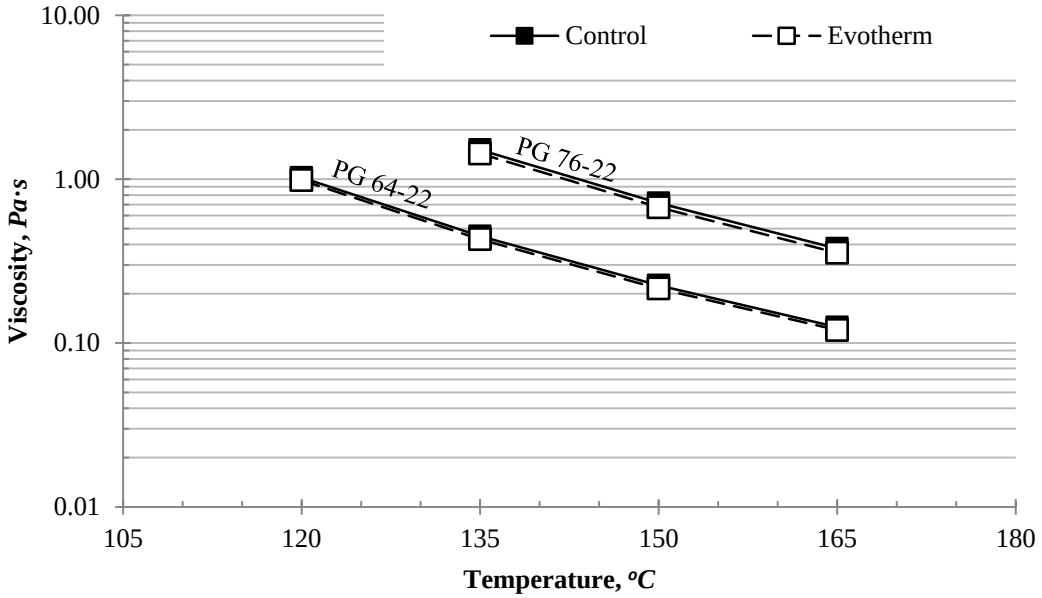
			Viscosity (135°C), *Pa·s*	**G*/sinδ (test temp), *kPa***	**Failure Temp., *°C***
Binder A	PG 64-22	HMA	0.449	1.233 (64°C)	65.8
		Evotherm	0.430	1.457 (64°C)	67.1
	PG 76-22	HMA	1.510	1.468 (76°C)	80.2
		Evotherm	1.433	1.391 (76°C)	79.6
Binder B	PG 64-22	HMA	0.648	2.127 (64°C)	70.7
		Evotherm	0.632	2.467 (64°C)	71.8
	PG 76-22	HMA	1.734	1.613 (76°C)	81.2
		Evotherm	1.708	1.595 (76°C)	82.2
	PG 58-28	HMA	0.310	1.378 (58°C)	60.6
		Evotherm	0.308	1.556 (58°C)	61.5

Table 5.2. Properties of RTFO aged control binders and binders modified with Evotherm™.

			G*/sinδ (test temp), *kPa*	Failure Temp., *°C*
Binder A	PG 64-22	HMA	3.703 (64°C)	68.1
		Evotherm	3.018 (64°C)	66.5
	PG 76-22	HMA	3.322 (76°C)	80.7
		Evotherm	2.671 (76°C)	78.0
Binder B	PG 64-22	HMA	4.692 (64°C)	70.2
		Evotherm	5.382 (64°C)	71.4
	PG 76-22	HMA	3.625 (76°C)	81.2
		Evotherm	3.456 (76°C)	81.2
	PG 58-28	HMA	3.875 (58°C)	62.6
		Evotherm	3.290 (58°C)	61.4

Table 5.3. Properties of RTFO/PAV aged control binders and binders modified with Evotherm™.

			Stiffness (60s, -12°C), *MPa*	m-value (60s, -12°C)
Binder A	PG 64-22	HMA	179	0.306
		Evotherm	155	0.307
	PG 76-22	HMA	198	0.285
		Evotherm	164	0.322
Binder B	PG 64-22	HMA	144	0.349
		Evotherm	159	0.357
	PG 76-22	HMA	130	0.258
		Evotherm	143	0.354
	PG 58-28	HMA	249	0.281
		Evotherm	236	0.295



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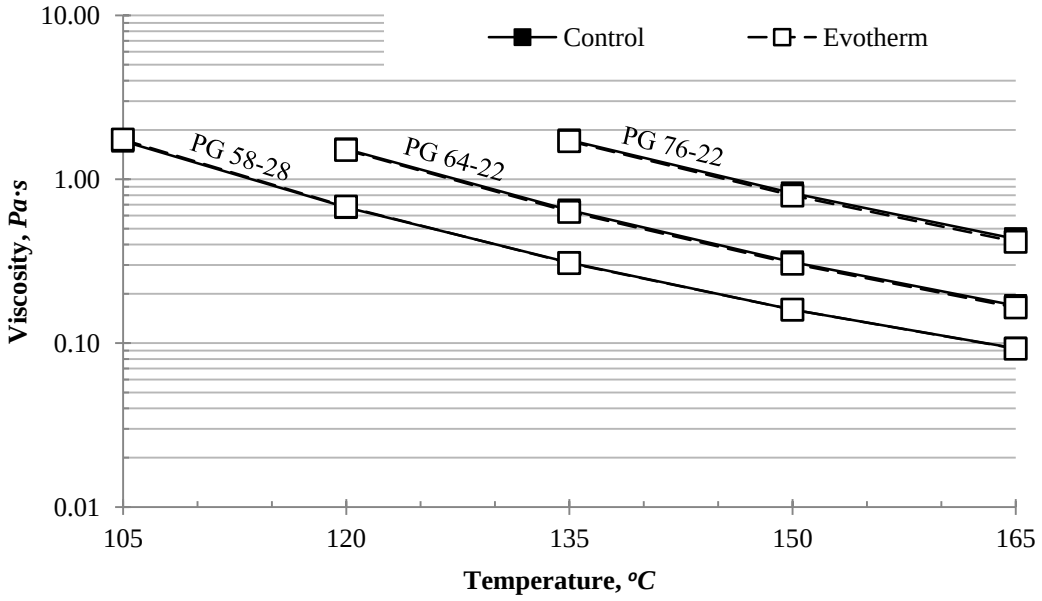

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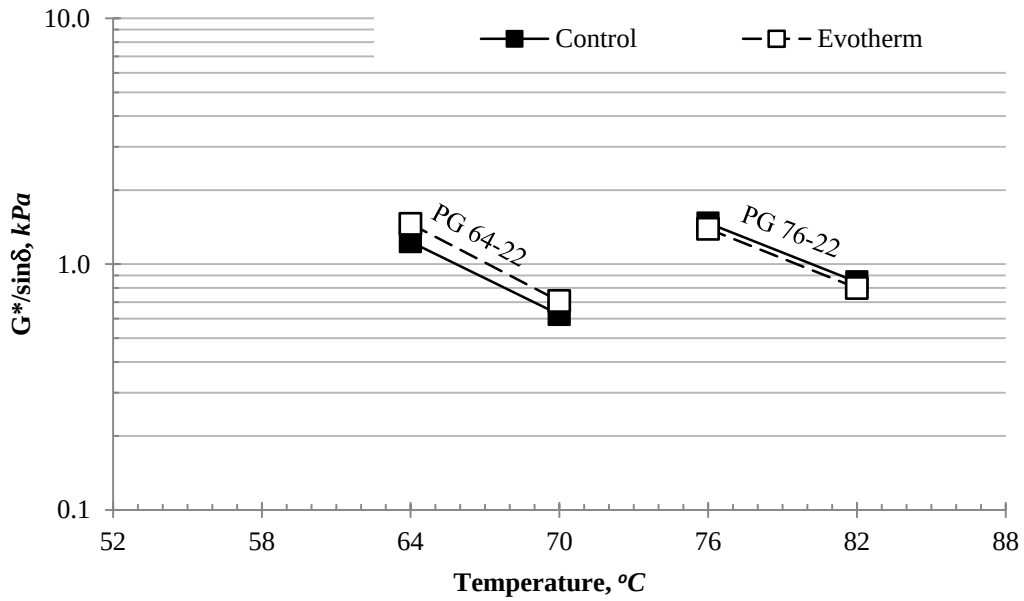
Figure 5.1. Viscosity of original binder with and without Evotherm™ for binders from (a) source A and (b) source B.



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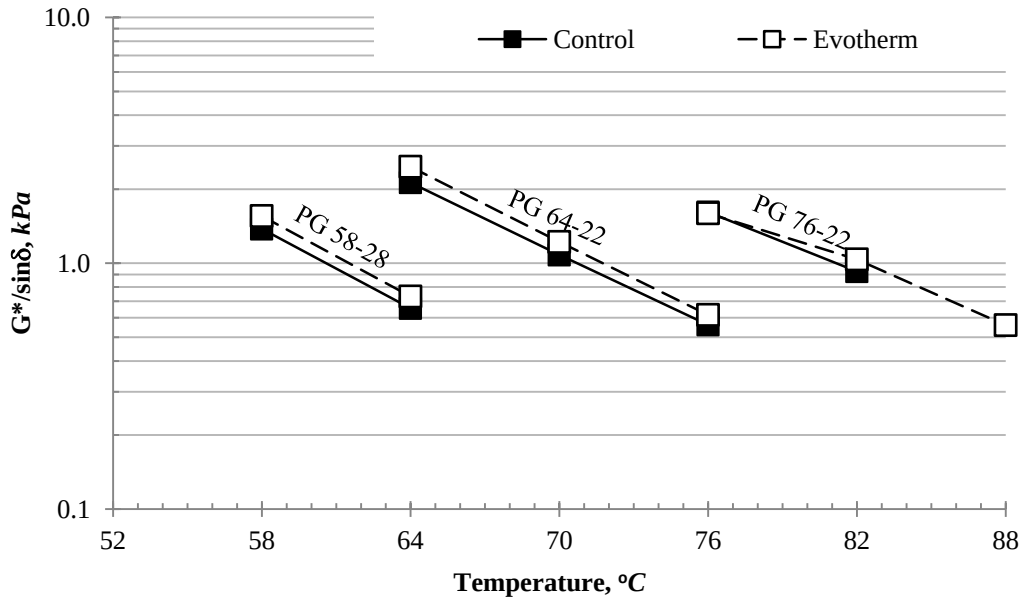

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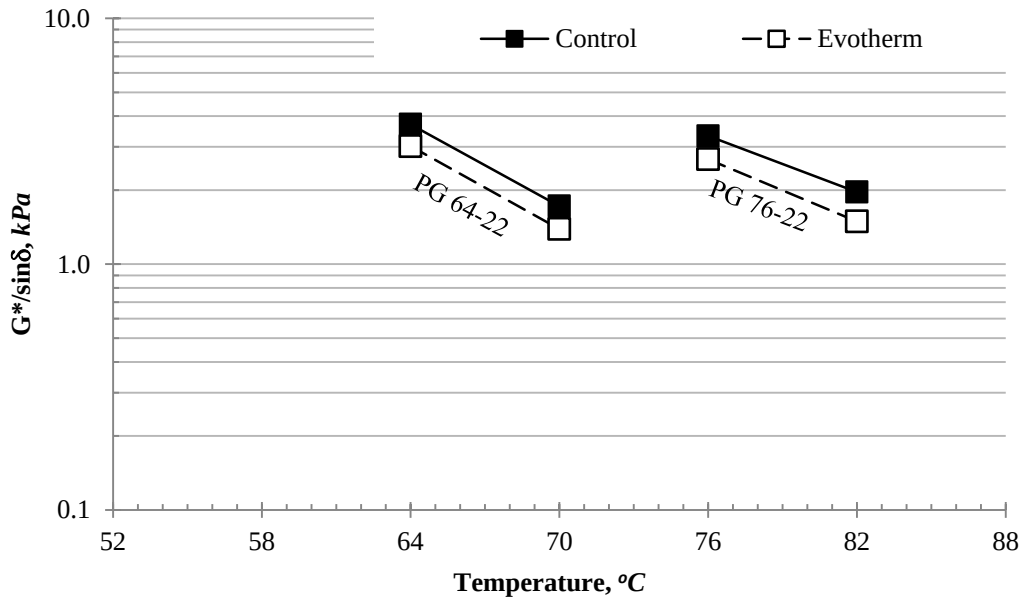
Figure 5.2. Temperature sweep results of original binder with and without Evotherm™ for binders from (a) source A and (b) source B.



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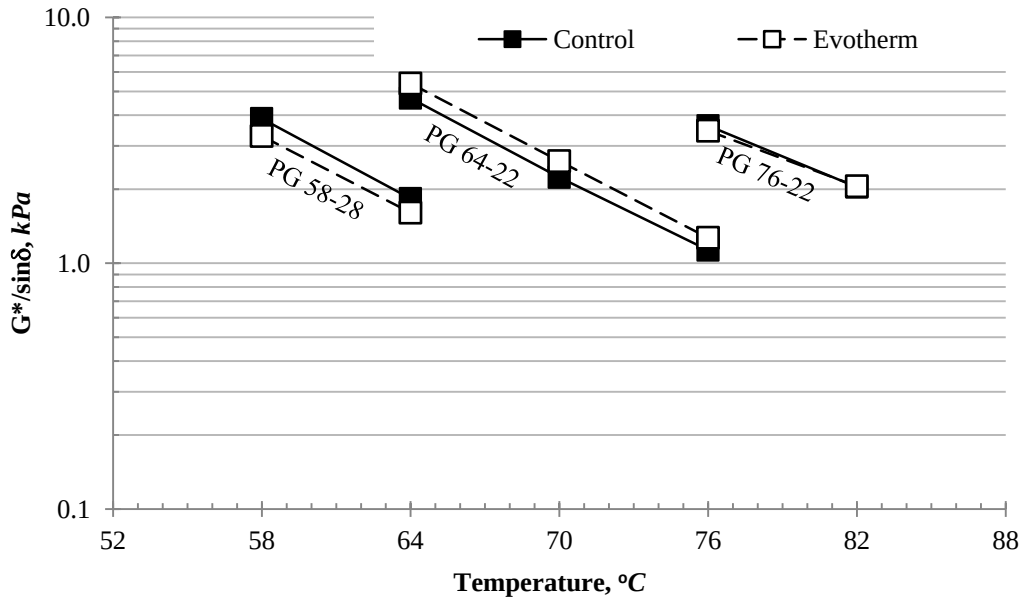

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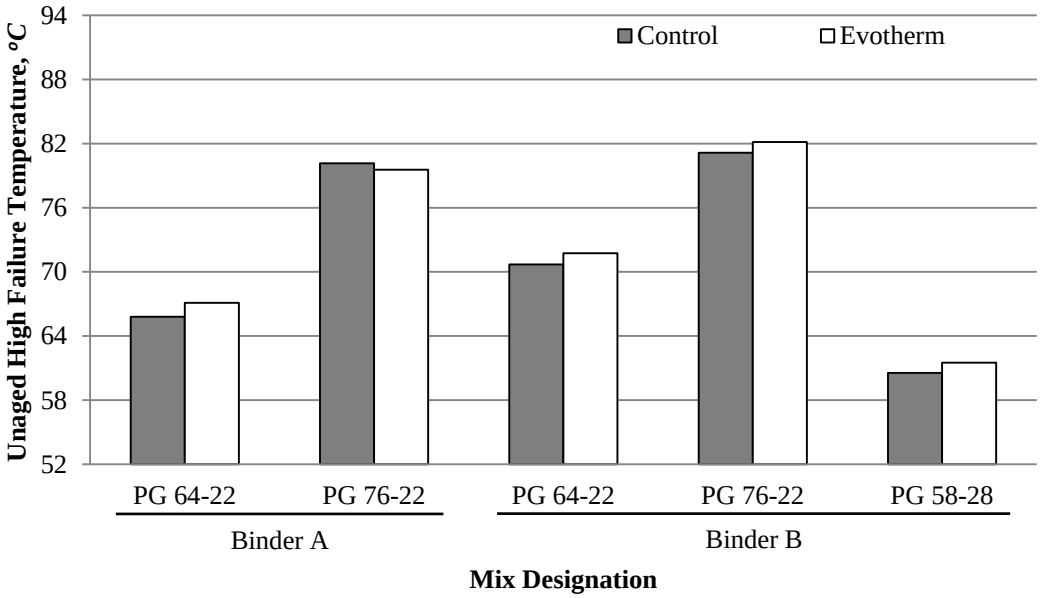
Figure 5.3. Temperature sweep results of RTFO aged binder with and without Evotherm™ for binders from (a) source A and (b) source B.



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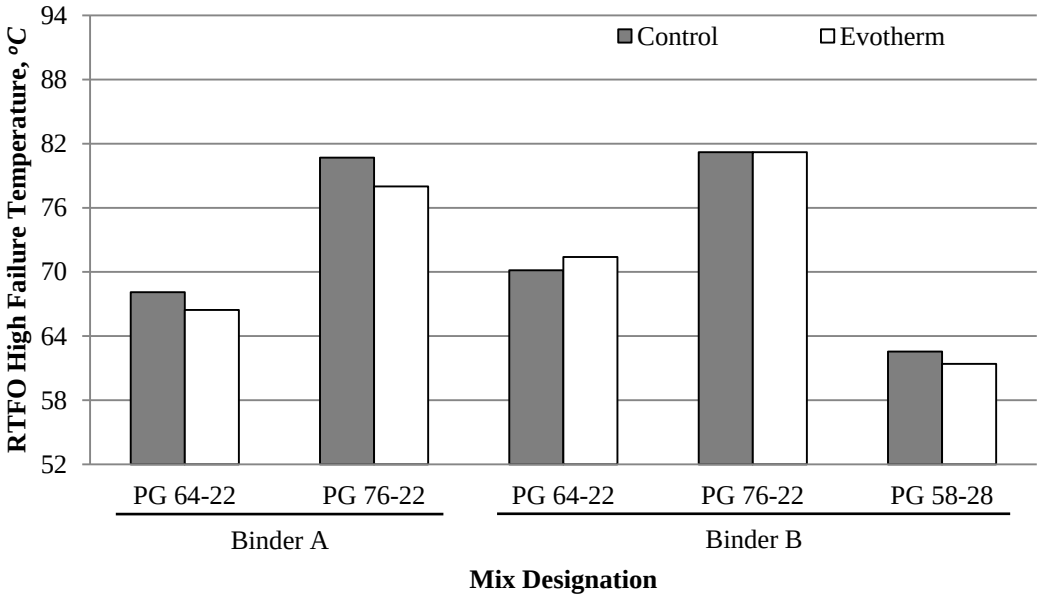
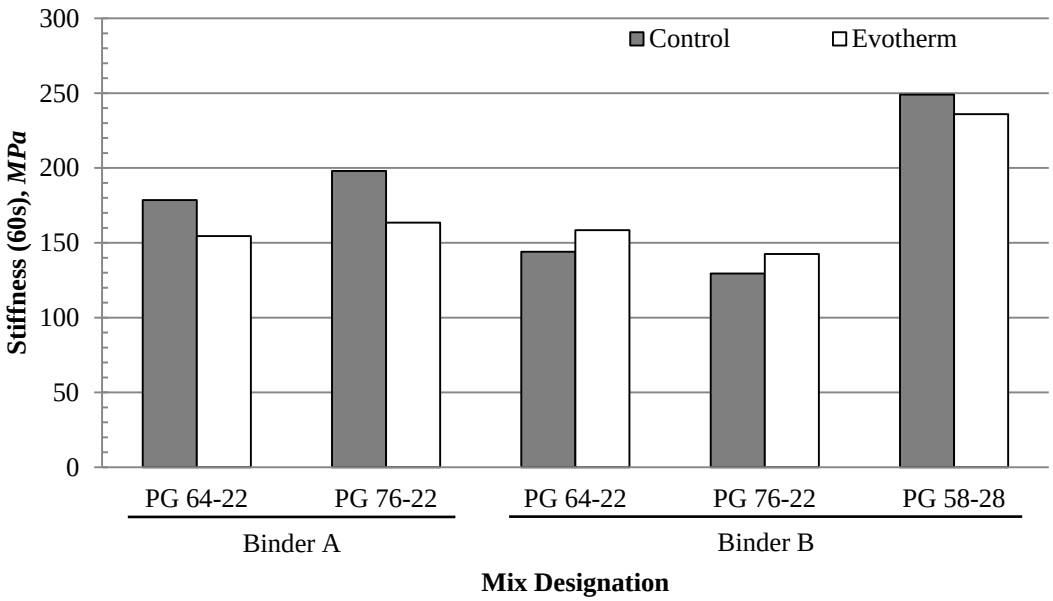


(b)

Figure 5.4. Failure temperature of binders with and without Evotherm™ measured using the dynamic shear rheometer in (a) unaged state and (b) RTFO aged state.



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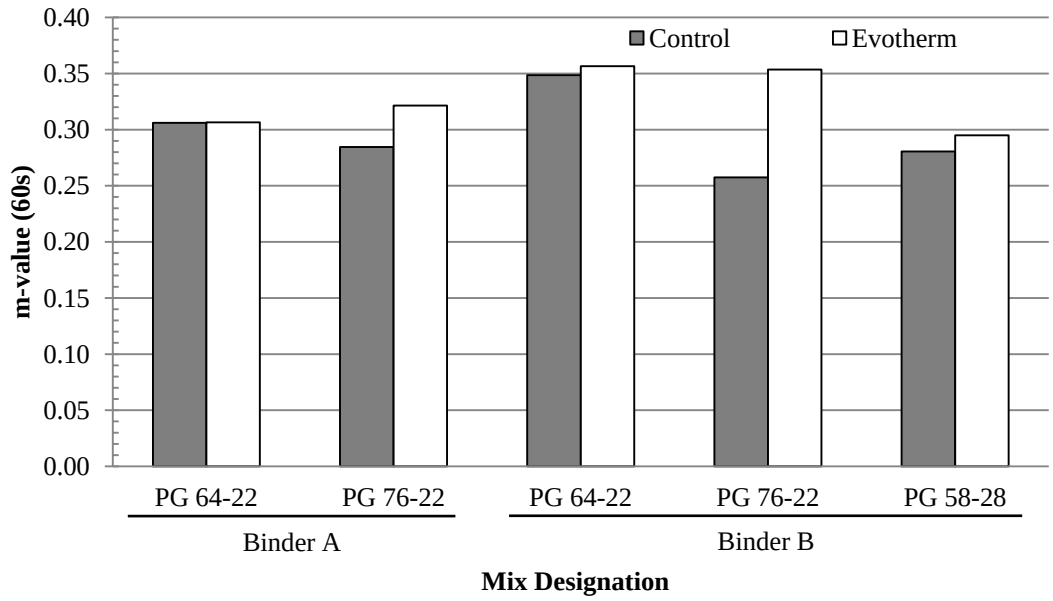


(b)

Figure 5.5. (a) Creep stiffness and (b) m-value results of RTFO/PAV aged binder with and without Evotherm™ measured with the bending beam rheometer at -12°C for PG 64-22 and PG 76-22 binders and -18°C for PG 58-28 binder.

EFFECTS OF WMA ON MIX DESIGN

SCDOT Surface Type B mixes were designed for each aggregate and binder source combination using typical HMA practices as a control as well as Evotherm™ and foaming technologies. The gradation of each mixture is included in Table 5.4. The optimum binder contents (OBC) were determined at an air void content of 4.0%. Table 5.5 summarizes the OBC and volumetric properties (voids in mineral aggregate [VMA] and voids filled with asphalt [VFA]) of each mixture. The results are also graphically presented in Figures 5.6 through 5.8. The SCDOT specifications for this type of mixture state that the VMA must be greater than or equal to 14.5% and the VFA must be between 70 and 80%.

Table 5.4. Gradations used for HMA and WMA Surface Type B mixtures.

	Percent Passing		
Sieve Size	**Aggregate B**	**Aggregate C**	**SCDOT Specifications**
1 inch	100	100	100
¾ inch	99.6	99.7	98 – 100
½ inch	93.7	94.3	90 – 100
⅜ inch	83.7	84.7	72 – 90
No. 4	49.3	50.9	44 – 62
No. 8	39.1	32.7	23 – 43
No. 30	18.3	17.8	10 – 25
No. 100	9.2	8.9	4 – 12
No. 200	5.7	5.6	2 – 8

Table 5.5. Optimum binder content (OBC) and volumetrics of HMA and WMA mixtures.

			OBC, %	**VMA, %**	**VFA, %**
Aggregate B	Binder A PG 64-22	HMA	4.50	15.2	73.3
		Evotherm	4.25	14.2	72.4
		Foaming	4.25	14.2	72.0
	Binder B PG 64-22	HMA	4.75	15.3	74.0
		Evotherm	4.30	14.0	74.0
		Foaming	4.60	14.9	73.6
Aggregate C	Binder A PG 64-22	HMA	5.20	15.5	74.8
		Evotherm	4.90	14.8	75.1
		Foaming	4.75	14.7	72.6
	Binder B PG 64-22	HMA	5.10	15.6	73.5
		Evotherm	4.80	14.7	73.5
		Foaming	4.60	13.8	76.4

Based on the results, it can be seen that the OBCs for all of the WMA designs were less than the HMA for the same set of materials. Coincidentally, the VMA values for each of the WMA mix designs were also lower than the control HMA mixtures. In fact, some of the values were lower than the minimum value of 14.5%. Based on this finding, the VMA could likely be increased by increasing the OBC to that used for the respective HMA control mixture. Alternatively, the aggregate gradation could also be adjusted to bring the VMA above the specified value. Additionally, all of the VFA values were within the specified limits.

For this study, the mixtures were not adjusted so that the properties of mixtures having identical gradations and designed at the same air void content could be evaluated.

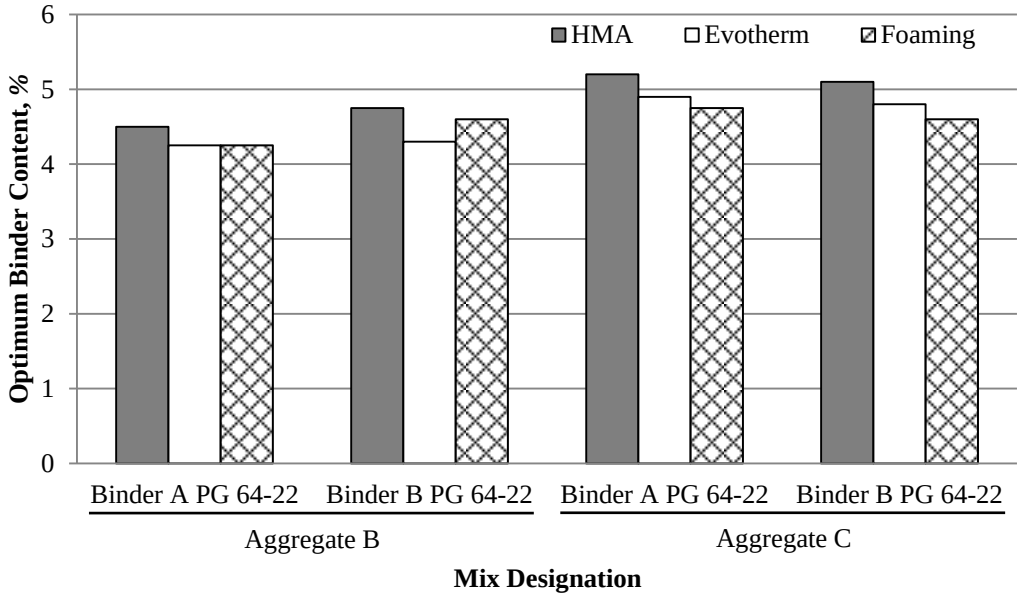


Figure 5.6. Optimum binder contents of mixtures designed as HMA and using Evotherm™ and Foaming WMA technologies.

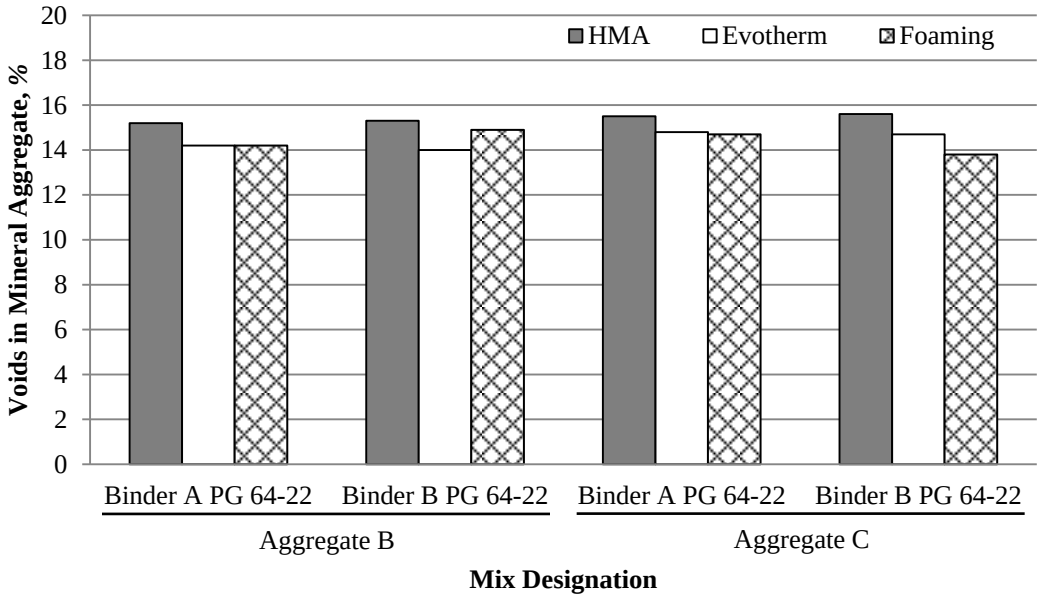


Figure 5.7. Voids in mineral aggregate (VMA) of mixtures at optimum binder content designed as HMA and using Evotherm™ and Foaming WMA technologies.

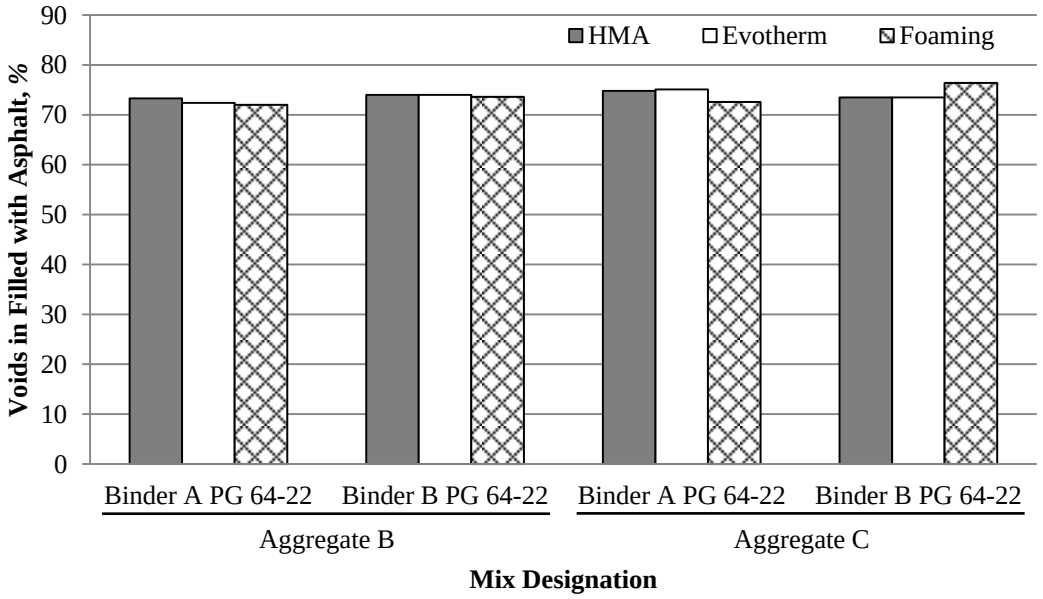


Figure 5.8. Voids in filled with asphalt (VFA) of mixtures at optimum binder content designed as HMA and using Evotherm™ and Foaming WMA technologies.

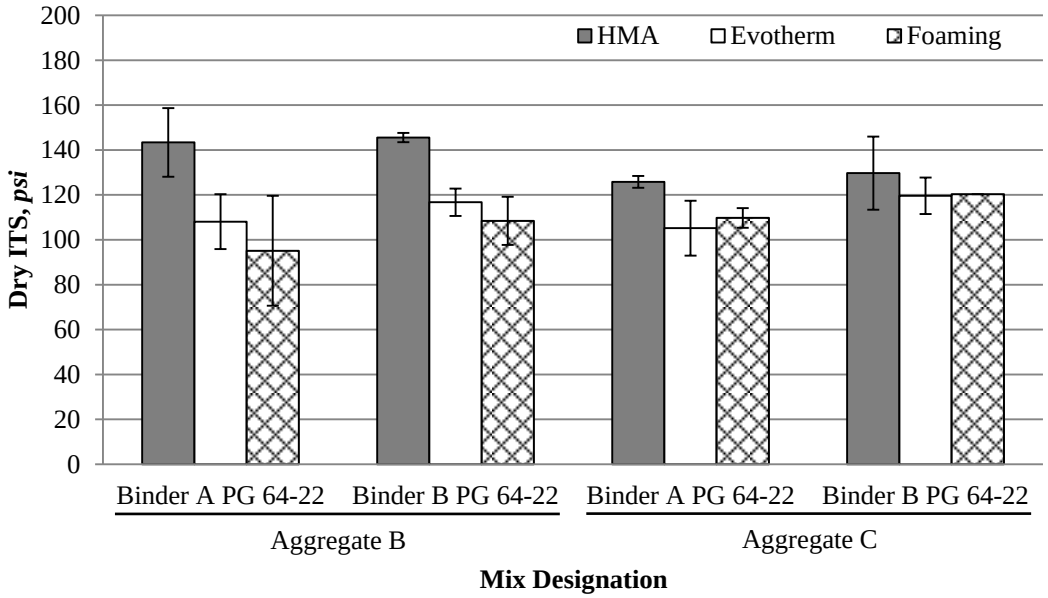
MOISTURE SUSCEPTIBILITY OF WMA MIXTURES

To evaluate the moisture susceptibility of WMA mixtures, the tensile strength ratio (TSR) of each mixture was determined using SC-T-70. Each of the specimens had an air void content of 7 ± 1% and half of the specimens were wet conditioned while the other half were dry conditioned before measuring the indirect tensile strength (ITS). The TSR for each mix design was then calculated by dividing the wet ITS by the dry ITS. The results are summarized in Table 5.6 and Figures 5.9 and 5.10.

Table 5.6. Indirect tensile strength (ITS) and tensile strength ratio (TSR) results of HMA and WMA mixtures.

			Dry ITS, *psi*	**Wet ITS, *psi***	**TSR, *%***
Aggregate B	Binder A PG 64-22	HMA	143	155	108
		Evotherm	108	135	125
		Foaming	95	113	119
	Binder B PG 64-22	HMA	146	158	108
		Evotherm	117	92	79
		Foaming	108	103	95
Aggregate C	Binder A PG 64-22	HMA	126	132	105
		Evotherm	105	149	142
		Foaming	110	120	109
	Binder B PG 64-22	HMA	130	179	138
		Evotherm	120	125	104
		Foaming	120	110	92

The results of the moisture susceptibility testing indicate that the ITS of the WMA mixtures was generally lower than the HMA control mixtures. However, none of the wet strength values fell below the minimum specified value of 65 psi. When considering the TSR of the mixtures, the binder source appeared to have more of an influence as the HMA mixtures made with binder A had higher TSR values than the WMA mixtures. However, with binder B, the WMA mixtures had greater TSR values than the HMA mixtures. Of the twelve mixtures evaluated in this phase of the research, only one mix failed to meet the minimum TSR value of 85%. That mix was the Evotherm™ mix made with aggregate B and binder C, which had a TSR of 79%.



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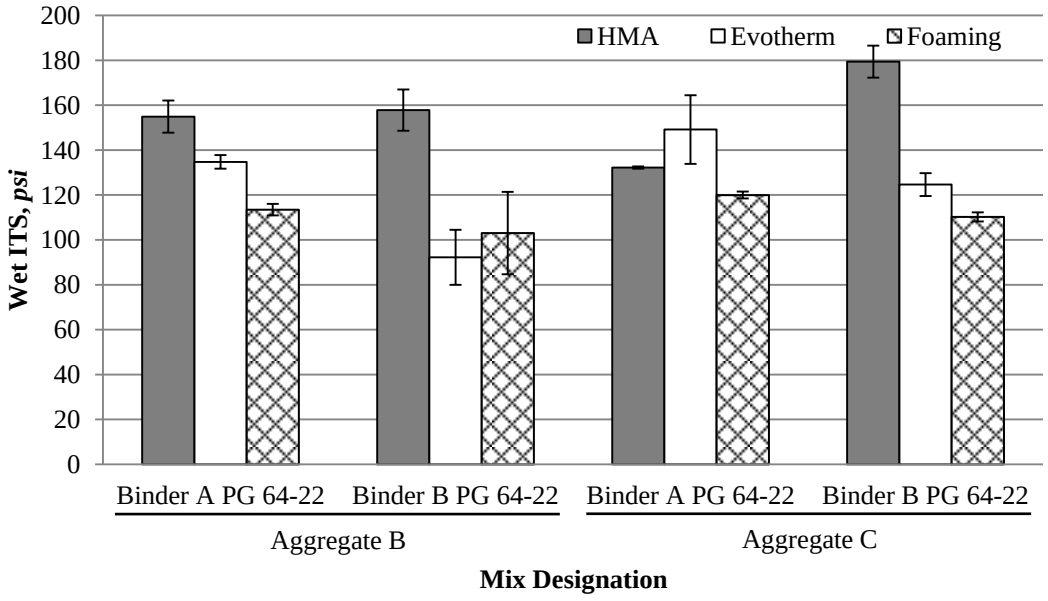

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Figure 5.9. Indirect tensile strength (ITS) results of HMA and WMA mixtures at optimum binder content after (a) dry conditioning and (b) wet conditioning.

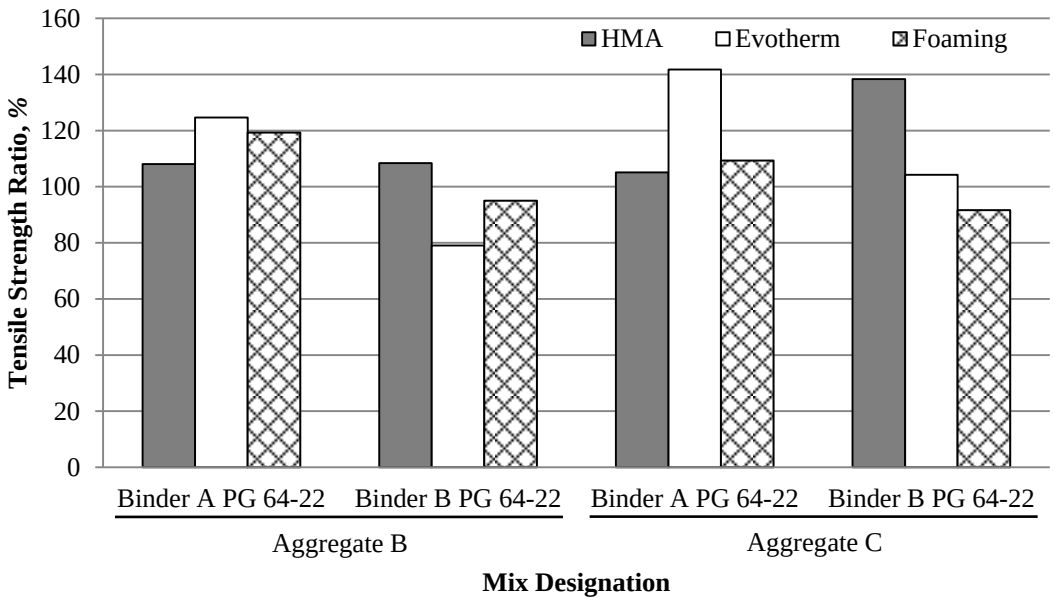


Figure 5.10. Tensile strength ratio (TSR) of HMA and WMA mixtures at optimum binder content.

EFFECTS OF WMA ON COMPACTIBILITY AS MEASURED BY GYRATION NUMBER

When compacting the specimens used for the ITS testing, the number of gyrations of the gyratory compactor were recorded to compare the relative compactibility of the different mixtures. Each of the specimens were prepared at the respective OBC, had identical aggregate gradations, were compacted to a height of 95 mm, and an air void content of 7 ± 1%. To further identify the influence of the WMA technologies on mixture compactibility, the temperature of the mix was also included as a variable as summarized in Figure 5.11.

These results indicate that Evotherm™ had the greatest influence on mixture compactibility as it required significantly fewer gyrations to reach the desired density. The compactibility of the Evotherm™ mixtures was not significantly affected by lowering the compaction temperature to as low as 185°F. The foaming technology reduced the number of gyrations compared to the HMA at a temperature of 275°F, but then the compactability reduced as the compaction temperature decreased. In fact, the foamed mixtures required a significantly higher amount of compactive effort (number of gyrations) than the HMA at a compaction temperature of 185°F.

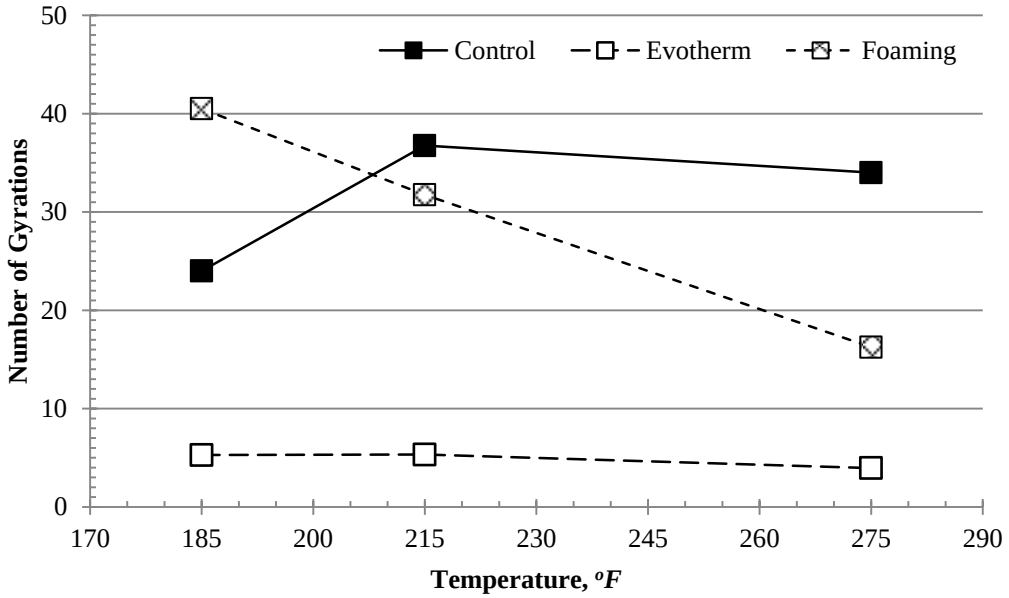


Figure 5.11. Relative compactibility of HMA and WMA mixtures at optimum binder content based on the number of gyrations required to compact the 95mm tall specimens used for ITS testing.

PERFORMANCE CHARACTERISTICS OF WMA MIXTURES

Two performance characteristics of the WMA mixtures were evaluated in the laboratory phase of the research: Rutting susceptibility and resilient modulus. Both of these properties are critical to ensuring long lasting, functional asphalt pavements. The overall results of the performance evaluation are summarized in Table 5.7. Additionally, the rutting and resilient modulus results are graphically summarized in Figures 5.12 and 5.13, respectively.

The results of the rutting resistance indicate that the effect of WMA technology is dependent on the aggregate source. For Aggregate B, there was no consistent trend in the data indicating that the WMA was superior or inferior with respect to rutting resistance compared to the HMA. However, for the mixtures made with Aggregate C, the HMA was significantly more resistant to rutting when compared to the Evotherm™ and foaming WMA technologies. Reasons for this could be due to the reduction in mixture aging as the WMA mixes are conditioned at lower compaction temperatures prior to compaction. It should also be noted that this rutting susceptibility has not been routinely noticed in field projects (Prowell et al 2007; Kristjánsdóttir 2006).

The results of the resilient modulus testing also do not reveal much of an effect of the WMA technologies on the stiffness of the mixtures. While it appears that the foaming process produced mixtures having higher resilient moduli than the HMA or Evotherm™ counterparts for Aggregate B, the variability of the data was great enough that the difference is not statistically significant. The same finding was seen for the Aggregate C mixtures where Evotherm™ appeared to produce stiffer mixtures, but the results are not statistically significant.

Table 5.7. Rutting and resilient modulus results of HMA and WMA mixtures prepared in the laboratory. Rutting was measured at 64°C and resilient modulus was measured at 25°C.

			Rut Depth, *mm*	**Resilient Modulus, *ksi***
Aggregate B	Binder A PG 64-22	HMA	3.5	1491
		Evotherm	2.1	1705
		Foaming	3.5	1936
	Binder B PG 64-22	HMA	2.9	2076
		Evotherm	2.7	1481
		Foaming	2.7	3095
Aggregate C	Binder A PG 64-22	HMA	3.4	1556
		Evotherm	4.9	1859
		Foaming	4.8	1089
	Binder B PG 64-22	HMA	3.1	1511
		Evotherm	4.4	2049
		Foaming	4.2	--

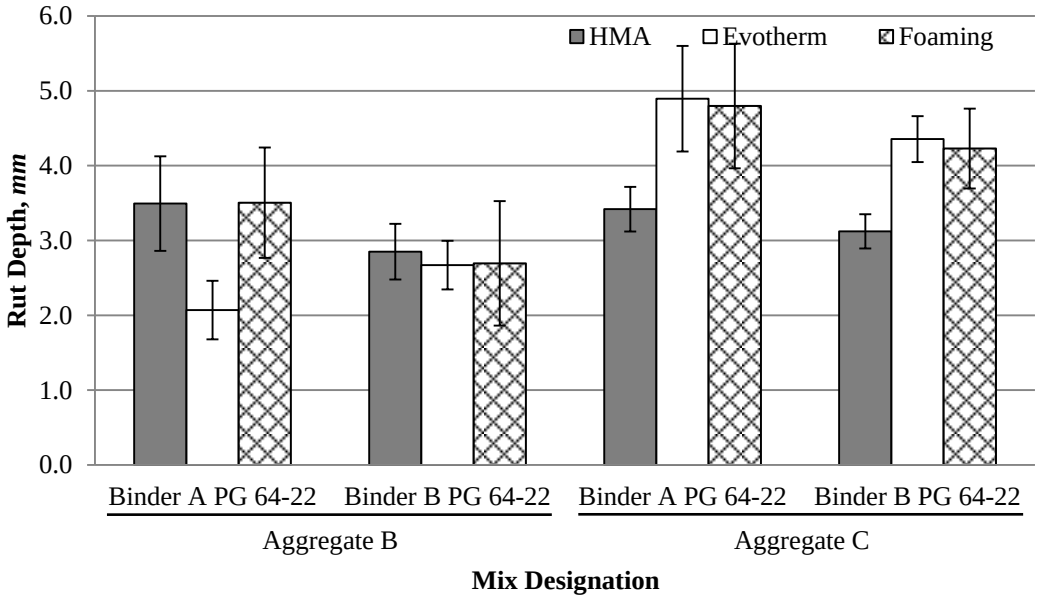


Figure 5.12. Rut depth of HMA and WMA mixtures determined using the APA rutting test at 64°C.

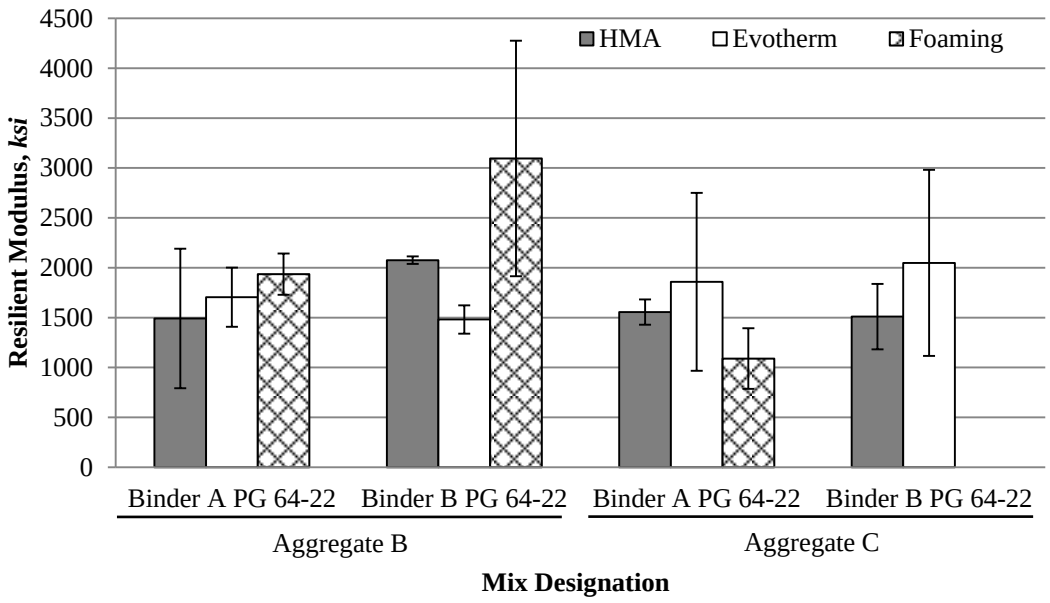


Figure 5.13. Resilient modulus of HMA and WMA mixtures at 25°C.

CHAPTER 6: EFFECTS OF HIGH RAP CONTENTS ON HMA MIXTURES

The primary objective of this phase of the research was to investigate the influence of increased RAP contents (up to 50%) on asphalt mixtures used by SCDOT. To accomplish this objective, an SCDOT Surface Type B mixture was used as the basis of comparison. In addition to a control mixture containing no RAP, mixes made with 20, 30, 40, and 50% RAP by weight of mixture were evaluated. In total, 20 mix designs (five RAP contents, two aggregate sources, and two binder sources) were evaluated in the laboratory portion of this phase and the performance of each was evaluated. The materials and methods used in this portion of the study are summarized in Chapter 4.

PROPERTIES OF RAP MATERIAL

The first step of this phase of the research was to evaluate the properties of the RAP material itself. RAP from two different sources was sampled and used throughout the study. Each RAP source was comprised of a different base aggregate source. RAP B was used in mixtures containing aggregate B although the RAP aggregate was not the same source as aggregate B. RAP C was used in mixtures made with aggregate C and the RAP aggregate was the same source as the virgin aggregate in this case.

To determine the binder content of the RAP materials, the RAP was first separated into two separate size fractions: Finer than the No. 4 sieve (-No. 4) and greater than the No. 4 sieve, but passing the ½ inch sieve (+No. 4). The binder content of each fraction was determined using the ignition oven test (SC-T-75). Following the ignition oven test, the gradation of the remaining aggregate material was determined in accordance with AASHTO T27. The gradation and binder content of each RAP material is summarized in Table 6.1.

In addition to the binder content, the properties of the RAP binder were also determined. After extracting and recovering the binder from each RAP source using SC-T-95. The viscosity and G*/sinδ of the recovered binders were then measured. The upper PG failure temperatures of the RAP binders were determined based on the temperature sweep test using the dynamic shear rheometer. The results are summarized in Table 6.1 and Figures 6.1 and 6.2.

Table 6.1. Properties of RAP materials.

	RAP B		**RAP C**	
	+No. 4	**-No. 4**	**+No. 4**	**-No. 4**
Sieve Size	**% Passing**			
½ inch	100	100	96.3	100
⅜ inch	95.2	100	82.8	99.3
No. 4	57.7	99.8	44.2	90.7
No. 8	42.9	88.7	34.9	74.4
No. 30	28.2	58.8	22.7	45.6
No. 100	12.7	23.8	7.7	14.3
No. 200	6.6	12.3	3.1	7.0
Binder Content, *%*	4.98	7.37	3.94	6.50
Binder Failure Temp, ^oC	102.1		97.6	

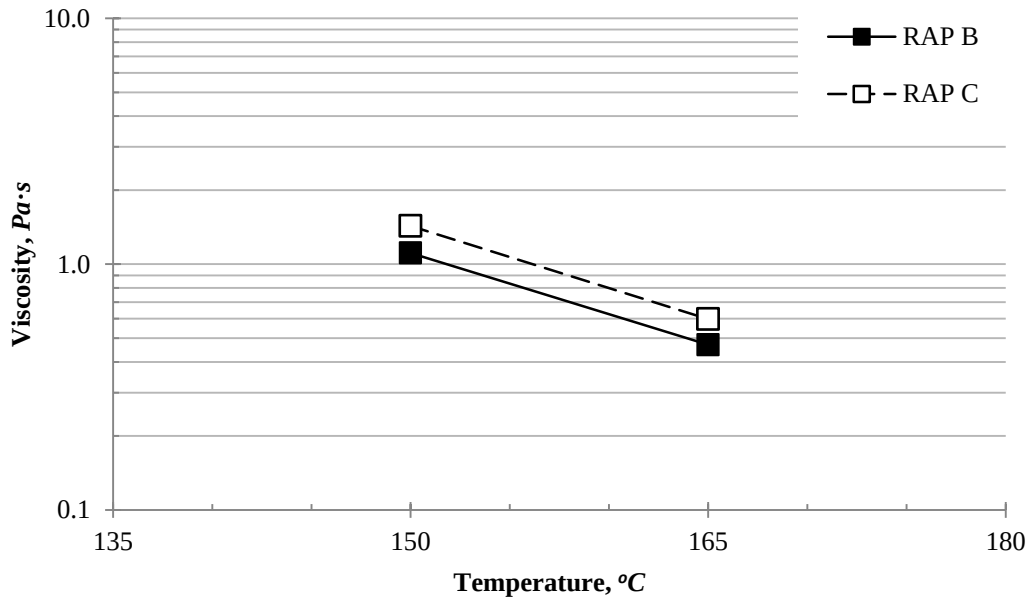


Figure 6.1. Viscosity of extracted binders from RAP sources B and C.

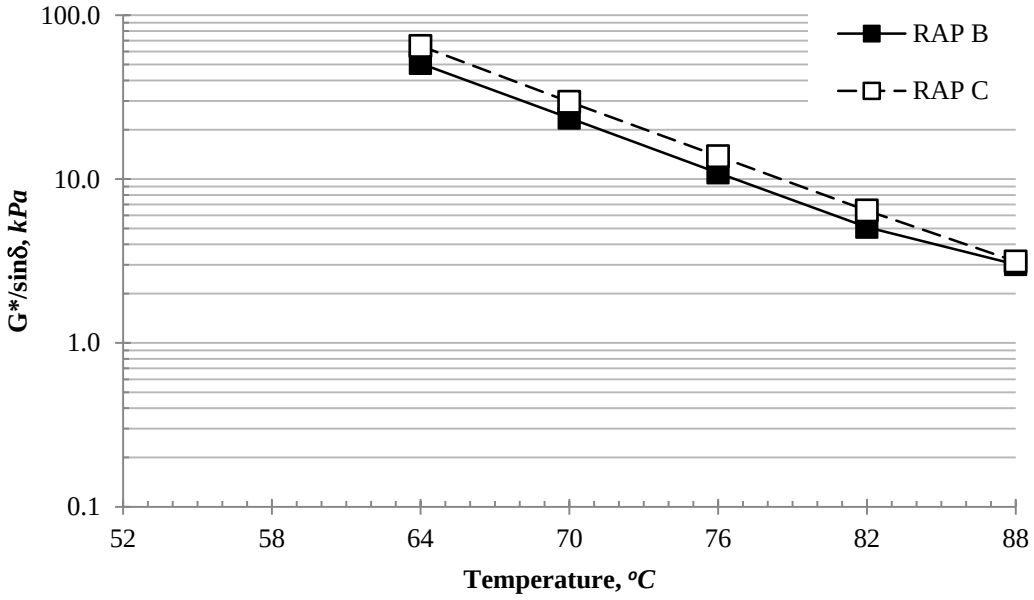


Figure 6.2. Temperature sweep results of extracted binders from RAP sources B and C.

PROPERTIES OF COMPOSITE BINDERS

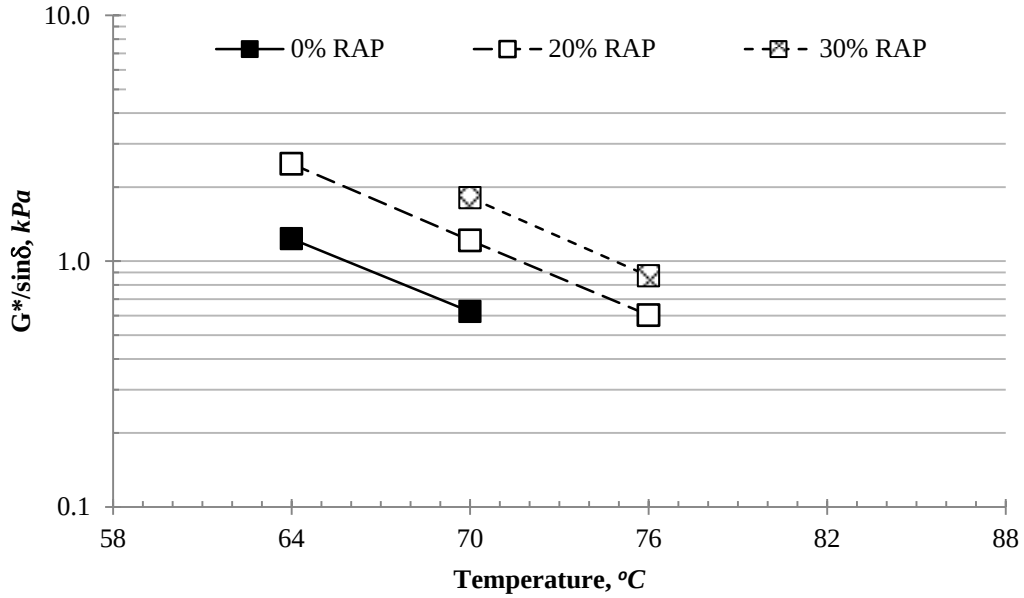
Once the properties of the RAP were determined, the next step was to evaluate the performance of composite binders consisting of virgin and RAP binders. Composite binders were prepared by blending the appropriate amount of recovered RAP binders based on the RAP percentages used in the mix design phase (20, 30, 40, and 50% RAP by weight of mixture). Table 6.2 summarizes the RAP content and the corresponding content of the RAP binder as a percentage of the overall binder content.

Table 6.2. RAP contents and corresponding RAP binder content in the mix.

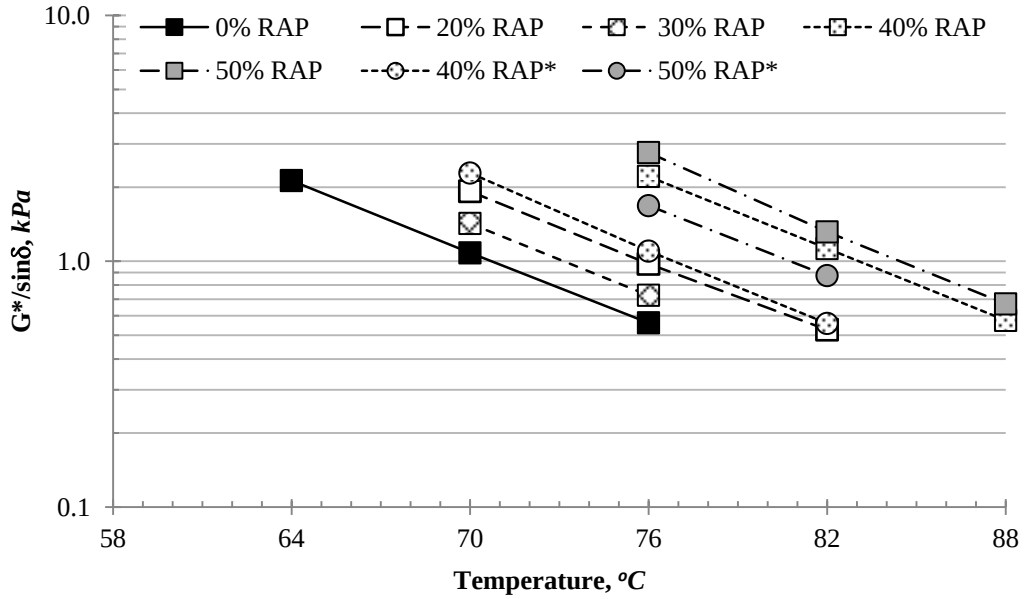
RAP Content, ***% of total mix***	**RAB Binder Content,** ***% of total binder***					
	Aggregate B / RAP B			**Aggregate C / RAP C**		
	Binder A *(PG 64-22)*	**Binder B** *(PG 64-22)*	**Binder B** *(PG 58-28)*	**Binder A** *(PG 64-22)*	**Binder B** *(PG 64-22)*	**Binder B** *(PG 58-28)*
0	0	0	--	0	0	--
20	24.2	24.2	--	21.5	23.6	--
30	36.5	36.5	--	36.5	36.5	--
40	--	46.8	46.8	48.3	48.3	48.3
50	--	52.4	52.4	60.2	60.2	53.5

Figures 6.3 and 6.4 summarize the results of the temperature sweep performed on the composite binders using RAP B and RAP C, respectively, in the original condition while Figures 6.5 and 6.6 present the RTFO aged results. Additionally, the effects of increasing RAP content on the DSR failure temperature are summarized in Table 6.3 and Figures 6.7 and 6.8. Based on the results, it is obvious that increasing the RAP content of the mix has a stiffening effect on the composite binder due to the increased stiffness of the RAP binder. To help reduce this stiffening effect at higher binder contents, a softer binder grade (PG 58-28) was also evaluated for the mixes containing 40 and 50% RAP. The results show that the softer binder helps to reduce the composite binder stiffness by lowering the failure temperature by approximately 5-6^{o}C for the unaged binders and 4-5^{o}C for the RTFO aged binders. It is also noted that even the 20% RAP composite binder exceeded the virgin binder grade of PG 64-22. This is likely due to the high stiffness of the recovered binder.

The stiffness of the composite binders at low temperatures, measured using the bending beam rheometer, indicate that the effects of RAP are dependent on the virgin binder as seen in Figure 6.9. The composite binders made with binder A were not negatively affected by the addition of 20 or 30% RAP. In fact, the stiffness actually decreased with the addition of 20% RAP. For binder B, however, the stiffness did increase with RAP content. When the softer PG 58-28 binder was used, the stiffness decreased approximately 25% for RAP B and 42% for RAP C. As seen in Table 6.1, RAP B was stiffer than RAP C, which explains this difference.

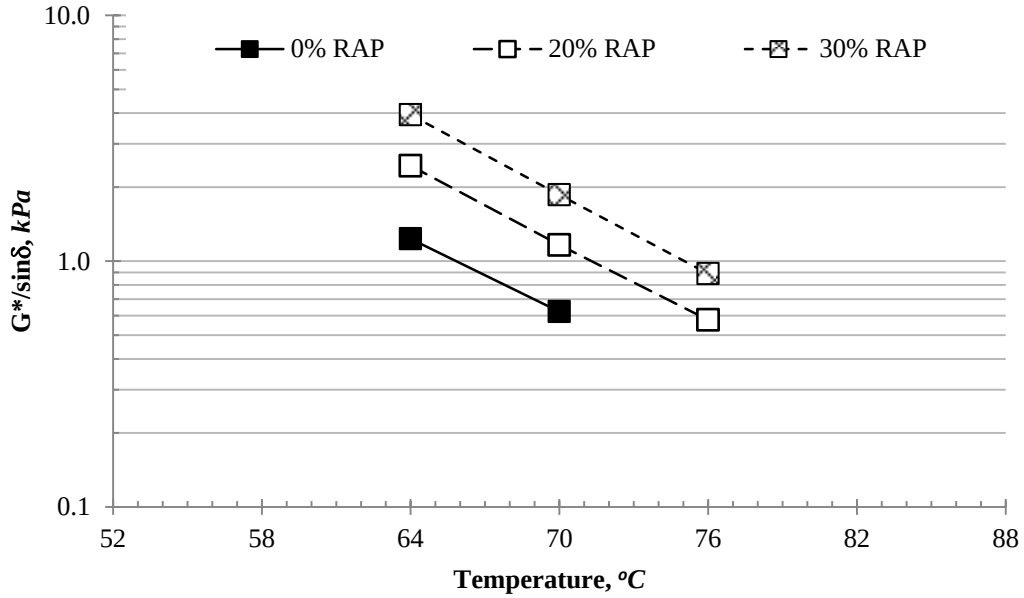


(a)



(b)

*Figure 6.3. Temperature sweep results of unaged composite binders made with extracted binder from RAP source B and virgin binders from (a) source A and (b) source B. * indicates that PG 58-28 binder was used instead of PG 64-22.*



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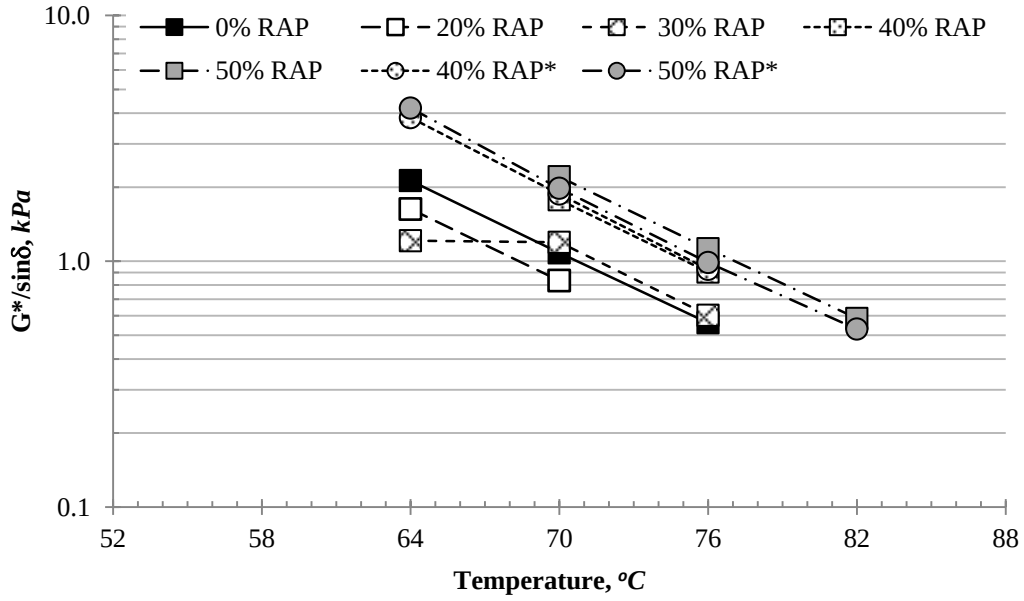
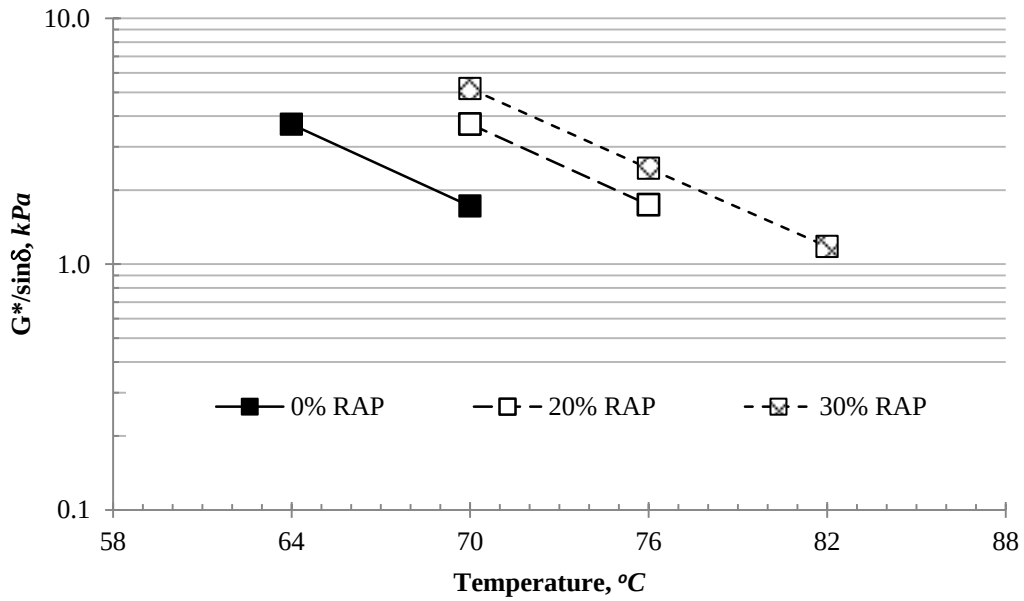


(b)

*Figure 6.4. Temperature sweep results of unaged composite binders made with extracted binder from RAP source C and virgin binders from (a) source A and (b) source B. * indicates that PG 58-28 binder was used instead of PG 64-22.*



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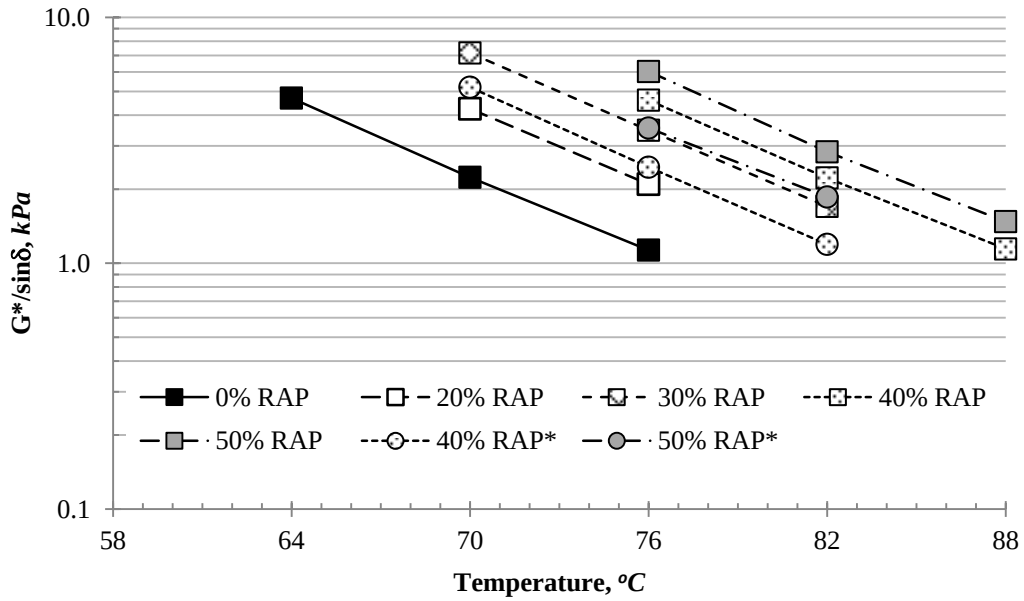
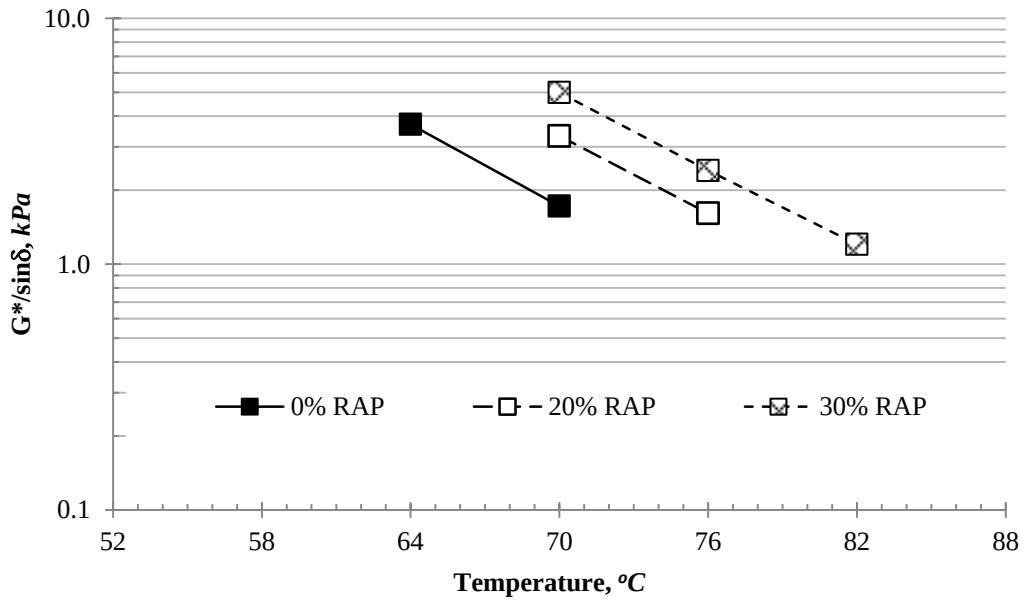
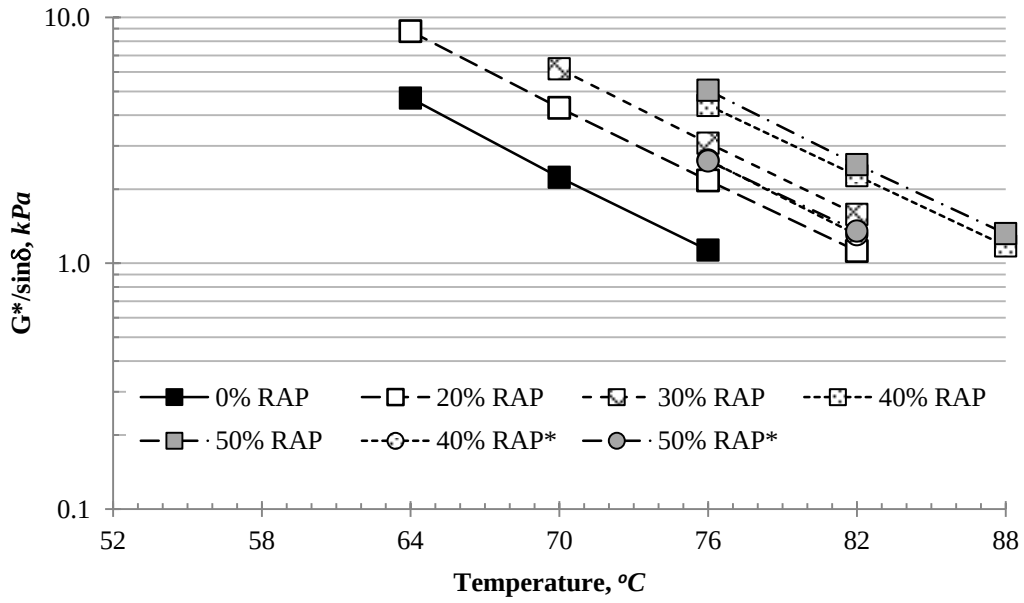


(b)

*Figure 6.5. Temperature sweep results of RTFO aged composite binders made with extracted binder from RAP source B and virgin binders from (a) source A and (b) source B. * indicates that PG 58-28 binder was used instead of PG 64-22.*



(a)

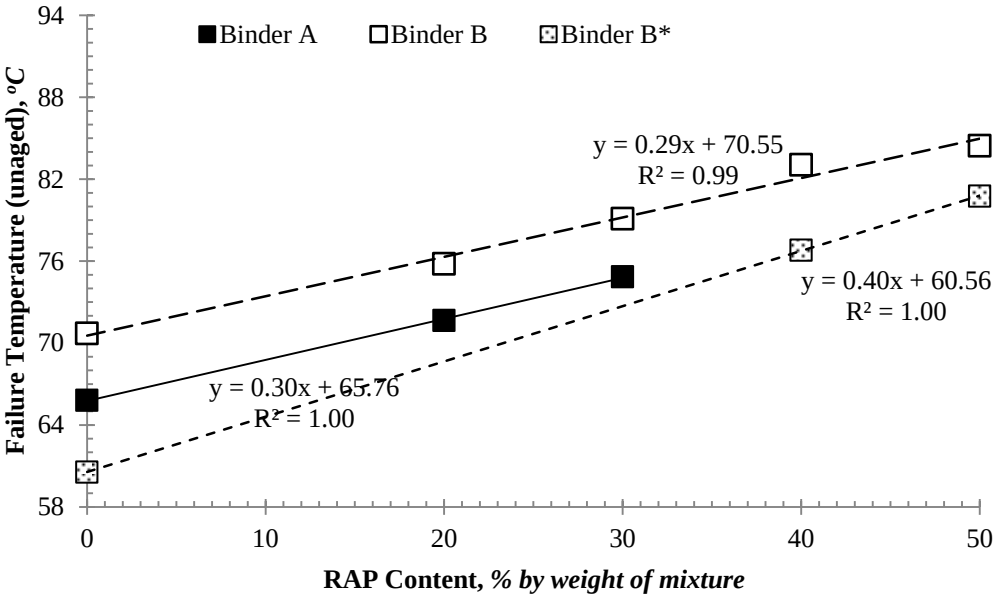


(b)

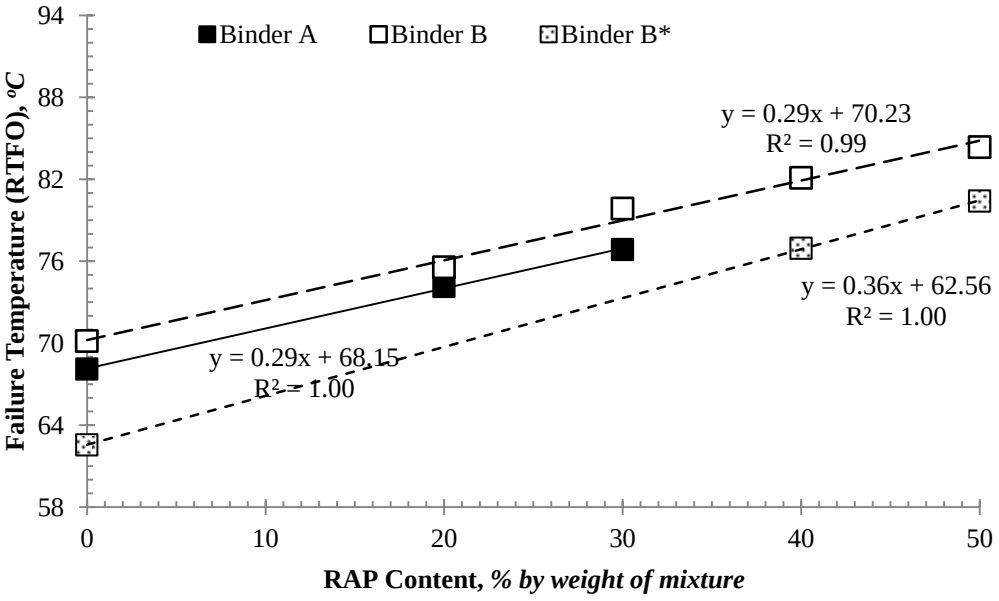
*Figure 6.6. Temperature sweep results of RTFO aged composite binders made with extracted binder from RAP source C and virgin binders from (a) source A and (b) source B. * indicates that PG 58-28 binder was used instead of PG 64-22.*

Table 6.3. Failure temperature of unaged and RTFO aged composite HMA binders.

		% RAP	Unaged Failure Temp., ^oC	RTFO Failure Temp., ^oC
RAP B	Binder A PG 64-22	0%	65.8	68.1
		20%	71.7	74.2
		30%	74.9	76.9
	Binder B PG 58-28	40%	76.8	77.0
		50%	80.8	80.4
	Binder B PG 64-22	0%	70.7	70.2
		20%	75.8	75.6
		30%	79.1	79.9
		40%	83.1	82.1
		50%	84.5	84.4
RAP C	Binder A PG 64-22	0%	65.8	68.1
		20%	71.3	73.4
		30%	75.1	76.8
	Binder B PG 58-28	40%	75.3	77.6
		50%	75.9	77.6
	Binder B PG 64-22	0%	70.7	70.2
		20%	74.4	75.9
		30%	77.6	79.0
		40%	81.1	82.3
		50%	83.1	83.3

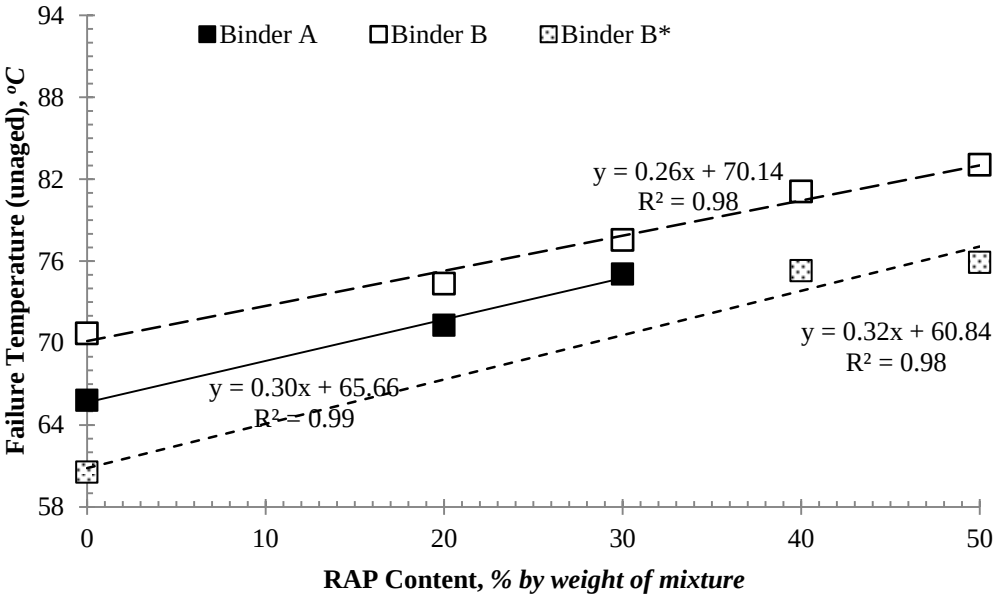


(a)

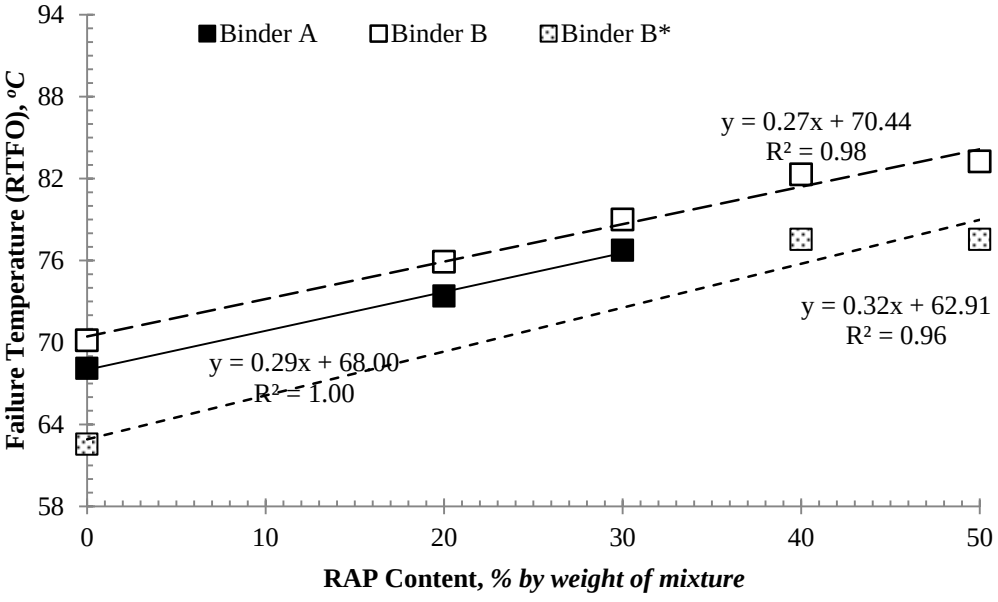


(b)

*Figure 6.7. Effect of RAP content on composite binder failure temperature measured using the dynamic shear rheometer for the (a) unaged and (b) RTFO aged binders made with RAP from source B. * indicates that PG 58-28 binder was used instead of PG 64-22.*

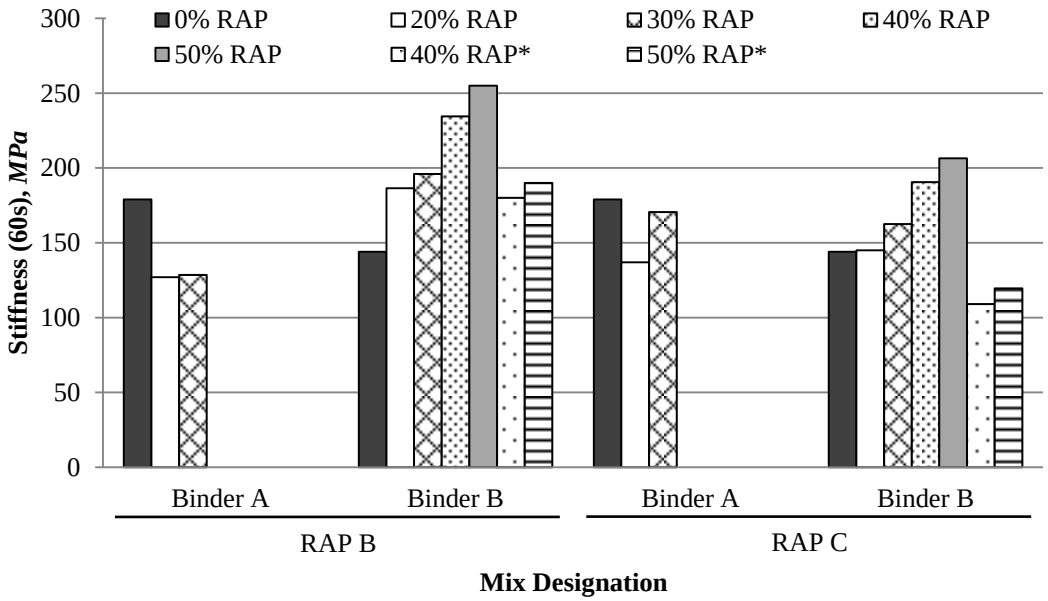


(a)



(b)

*Figure 6.8. Effect of RAP content on composite binder failure temperature measured using the dynamic shear rheometer for the (a) unaged and (b) RTFO aged binders made with RAP from source C. * indicates that PG 58-28 binder was used instead of PG 64-22.*



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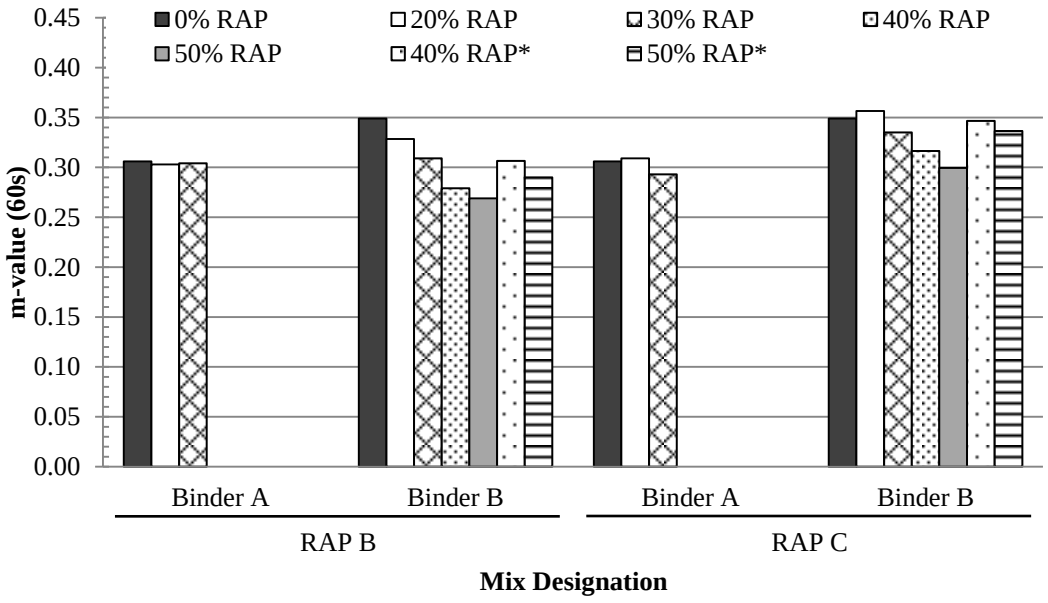


(b)

*Figure 6.9. Effect of RAP content on low temperature properties of composite binders using the bending beam rheometer at -12^{o}C to measure the (a) stiffness and (b) m-value of PAV aged binders. * indicates that PG 58-28 binder was used instead of PG 64-22.*

EFFECTS OF RAP CONTENT ON MIX DESIGN

Twenty Surface Type B mix designs were conducted to determine the optimum binder content (OBC) for each aggregate and binder combination with RAP contents varying from 0 to 50% by weight of the mixture. The OBC was originally intended to be determined as the binder content at which the mixture had 4.0% air voids. However, it was decided that the binder content of a given mixture should not be less than 4.5% based on the SCDOT mixture requirements outlined in SC-M-402 (SCDOT 2011). In the cases where an air void content of 4.0% yielded a binder content lower than 4.5%, 4.5% was selected as the OBC and the volumetric properties were determined at that binder content. The gradation of each mix is included in Tables 6.4 and 6.5, while the OBC and volumetric properties (air voids, VMA, and VFA) for the RAP mixtures are summarized in Table 6.6 and Figures 6.10 through 6.12.

Table 6.4. Gradations of Surface Type B HMA mixes made with aggregate B containing RAP.

Sieve Size	**Percent Passing**					
	0% RAP	**20% RAP**	**30% RAP**	**40% RAP**	**50% RAP**	**SCDOT Specification**
1 inch	100	100	100	100	100	100
¾ inch	99.6	97.6	97.6	97.6	97.6	98 – 100
½ inch	93.7	94.2	94.2	94.3	94.3	90 – 100
⅜ inch	83.7	81.9	81.7	83.1	82.6	72 – 90
No. 4	49.3	52.3	50.2	53.5	48.4	44 – 62
No. 8	39.1	38.6	36.4	39.7	34.8	23 – 43
No. 30	18.3	18.7	19.3	22.0	21.8	10 – 25
No. 100	9.2	8.6	8.4	9.4	9.7	4 – 12
No. 200	5.7	5.1	4.9	5.3	5.5	2 – 8
% RAP	-No. 4	9	14	18	16	
Added	+No. 4	11	16	22	34	

Table 6.5. Gradations of Surface Type B HMA mixes made with aggregate C containing RAP.

Sieve Size	Percent Passing					
	0% RAP	20% RAP	30% RAP	40% RAP	50% RAP	SCDOT Specification
1 inch	100	100	100	100	100	100
¾ inch	99.7	99.4	99.4	99.4	99.5	98 – 100
½ inch	94.3	94.7	94.5	94.4	94.6	90 – 100
⅜ inch	84.7	87.4	86.9	86.5	86.6	72 – 90
No. 4	50.9	58.2	57.5	57.7	58.1	44 – 62
No. 8	32.7	35.2	35.9	37.7	39.5	23 – 43
No. 30	17.8	18.8	19.9	21.5	23.2	10 – 25
No. 100	8.9	6.4	6.8	7.3	7.9	4 – 12
No. 200	5.6	3.0	3.3	3.5	3.9	2 – 8
% RAP Added	-No. 4	9	14	18	22	
	+No. 4	11	16	22	28	

Table 6.6. Optimum binder content (OBC) and volumetrics of HMA mixtures containing RAP.

		% RAP	OBC, %	AV, %	VMA, %	VFA, %	D/B
Aggregate B	Binder A PG 64-22	0%	4.50	4.0	15.2	73.3	0.78
		20%	4.50	3.5	14.1	76.2	0.88
		30%	4.50	3.6	14.4	73.4	1.08
	Binder B PG 58-28	40%	4.70	4.0	15.0	74.0	1.12
		50%	4.90	4.0	15.5	75.5	1.12
	Binder B PG 64-22	0%	4.25	4.0	15.3	74.0	0.83
		20%	4.60	4.0	14.8	77.5	1.10
		30%	4.50	3.5	14.0	75.8	1.08
		40%	4.70	4.0	15.1	74.8	1.11
		50%	4.90	4.0	15.6	76.1	1.12
Aggregate C	Binder A PG 64-22	0%	4.90	4.0	15.5	74.8	0.92
		20%	4.50	3.4	13.4	75.5	0.66
		30%	4.50	3.8	13.9	73.0	0.72
	Binder B PG 58-28	40%	4.50	4.0	14.4	72.0	0.79
		50%	4.50	3.5	13.8	75.0	0.86
	Binder B PG 64-22	0%	4.50	4.0	15.6	73.5	0.90
		20%	4.60	4.0	13.8	74.0	0.65
		30%	4.50	3.9	14.2	71.0	0.72
		40%	4.50	4.0	14.4	70.1	0.79
		50%	4.50	4.0	13.8	73.5	0.86

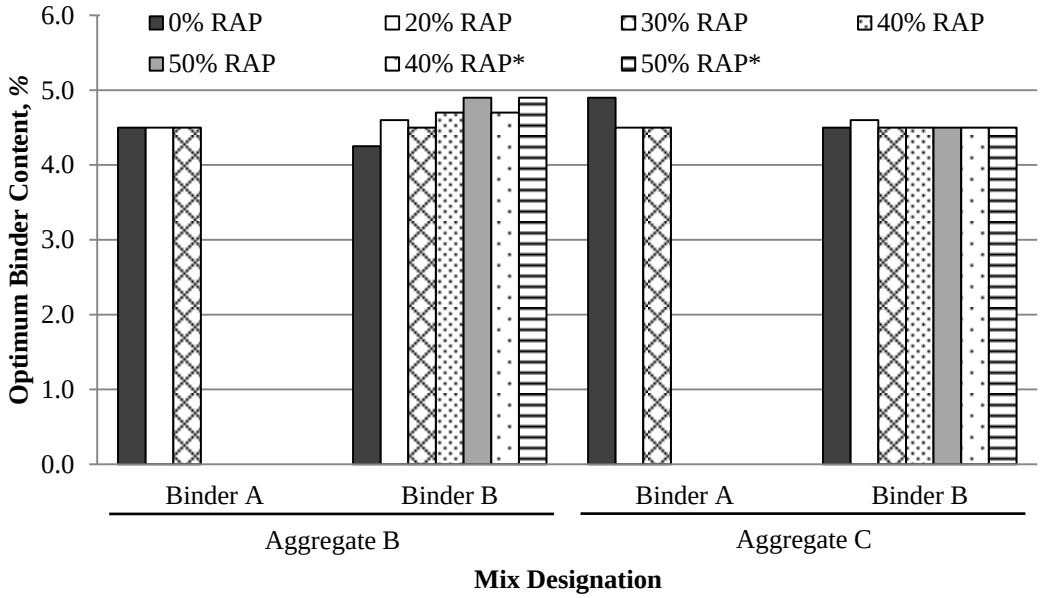


*Figure 6.10. Optimum binder contents of HMA mixtures containing RAP. * indicates that PG 58-28 binder was used instead of PG 64-22.*

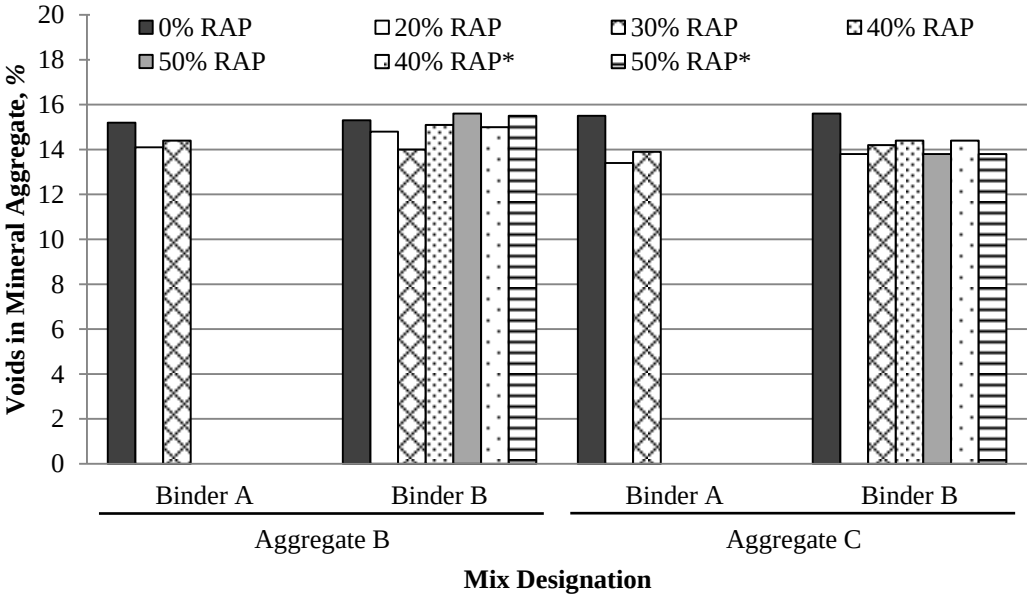


*Figure 6.11. Voids in mineral aggregate (VMA) of HMA mixtures containing RAP at optimum binder content. * indicates that PG 58-28 binder was used instead of PG 64-22.*

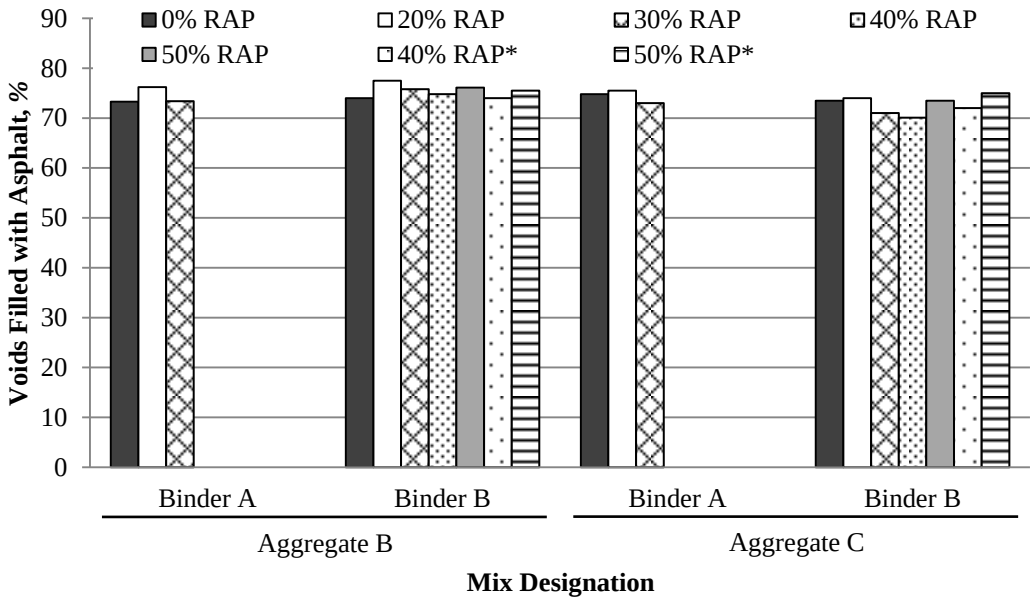


*Figure 6.12. Voids filled with asphalt (VFA) of HMA mixtures containing RAP at optimum binder content. * indicates that PG 58-28 binder was used instead of PG 64-22.*

From the results, it can be seen that the VMA values for some of the mixtures were less than the minimum value of 14.5% required by SCDOT specifications. The low VMA values are likely due to the increased amount of fines included in the RAP. As the objective of the study was to investigate the effects of increased RAP contents on the properties of asphalt mixtures, the research team opted to maintain a consistent gradation instead of introducing another variable into the experimental design.

The results indicate that the effect of RAP content on the mix design properties are aggregate, binder, and/or RAP source dependent. For aggregates B and C with binder A, the incorporation of 20 and 30% RAP generally lowered the overall OBC of the mixture, but the minimum binder content of 4.5% was maintained. As a result, the VMA also fell below the minimum specified value of 14.5%. This could also be due to fines present in the RAP material, even though this was considered in the gradation design. For aggregate B with binder B, the increase in RAP content, generally increased the OBC of the mixture. This was more noticeable at the higher RAP contents and can be attributed to the higher quantity of stiffer RAP binder in the mixture. When PG 58-28 was used as the virgin binder in place of the PG 64-22, the OBC of the mixtures did not change as seen for the 40 and 50% RAP mixtures. However, the addition of RAP did not appear to have any effect on the binder content or volumetric properties for the mixtures made with aggregate C and binder B. This is likely due to the differences in the properties of the recovered binders from RAP B and RAP C.

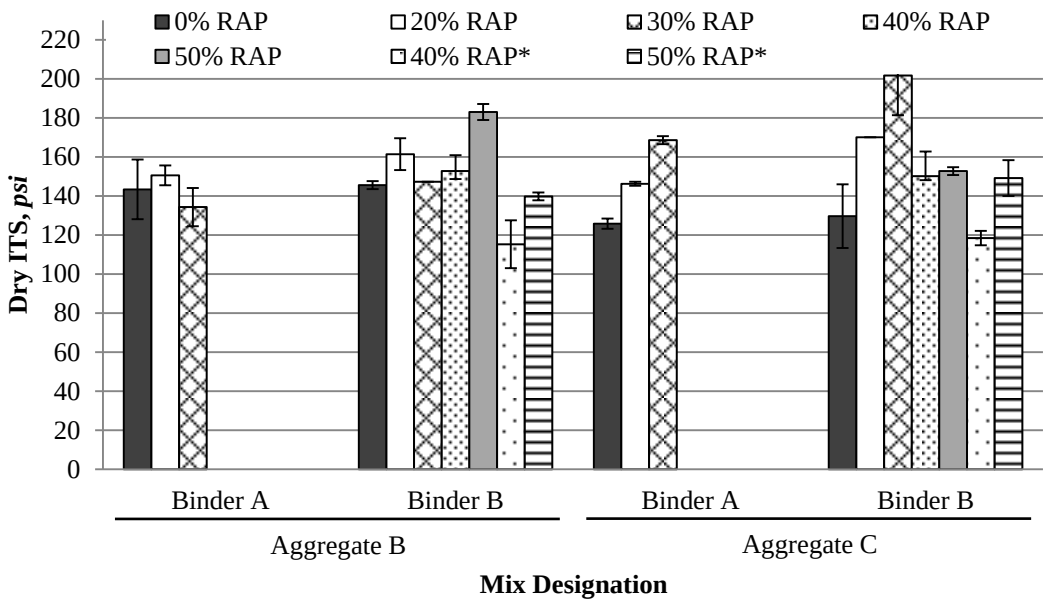
MOISTURE SUSCEPTIBILITY OF MIXTURES CONTAINING RAP

To evaluate the moisture susceptibility of HMA mixtures containing RAP, the tensile strength ratio (TSR) of each mixture was determined using SC-T-70. Each of the specimens had an air void content of 7 ± 1% and half of the specimens were wet conditioned while the other half were dry conditioned before measuring the indirect tensile strength (ITS) of each specimen. The TSR of each mix design was then calculated by dividing the wet ITS by the dry ITS. The results are summarized in Table 6.7 and Figures 6.13 and 6.14.

The results of the moisture susceptibility testing indicate that there was no clear trend relating the increase in RAP content with the ITS (dry or wet). All of the dry and wet ITS values exceeded 100 psi. The use of PG 58-28 binder in place of PG 64-22 binder for the 40 and 50% mixtures made with binder B generally resulted in a reduction in the ITS. This should not be viewed as a detrimental effect because while the use of the softer binder is expected reduce the overall strength, the difference could potentially be made up for with fatigue resistance. With regard to TSR, all of the mixtures exceeded the minimum value of 85% and none of the mixtures showed visible signs of stripping. It should be noted that the mixtures made with 0% RAP generally had higher TSR values than the RAP mixtures. All of the mixtures evaluated were also made with 1% hydrated lime by weight of aggregate.

Table 6.7. Indirect tensile strength (ITS) and tensile strength ratio (TSR) results of HMA mixtures containing RAP.

		% RAP	Dry ITS, *psi*	Wet ITS, *psi*	TSR, *%*
Aggregate B	Binder A PG 64-22	0%	143	155	108
		20%	151	140	93
		30%	134	143	106
	Binder B PG 58-28	40%	115	108	94
		50%	140	147	105
	Binder B PG 64-22	0%	146	158	108
		20%	161	143	88
		30%	147	141	95
		40%	153	148	97
		50%	183	184	101
Aggregate C	Binder A PG 64-22	0%	126	132	105
		20%	146	145	99
		30%	169	154	91
	Binder B PG 58-28	40%	118	106	90
		50%	149	147	99
	Binder B PG 64-22	0%	130	179	138
		20%	170	148	87
		30%	202	205	101
		40%	150	148	98
		50%	153	185	121



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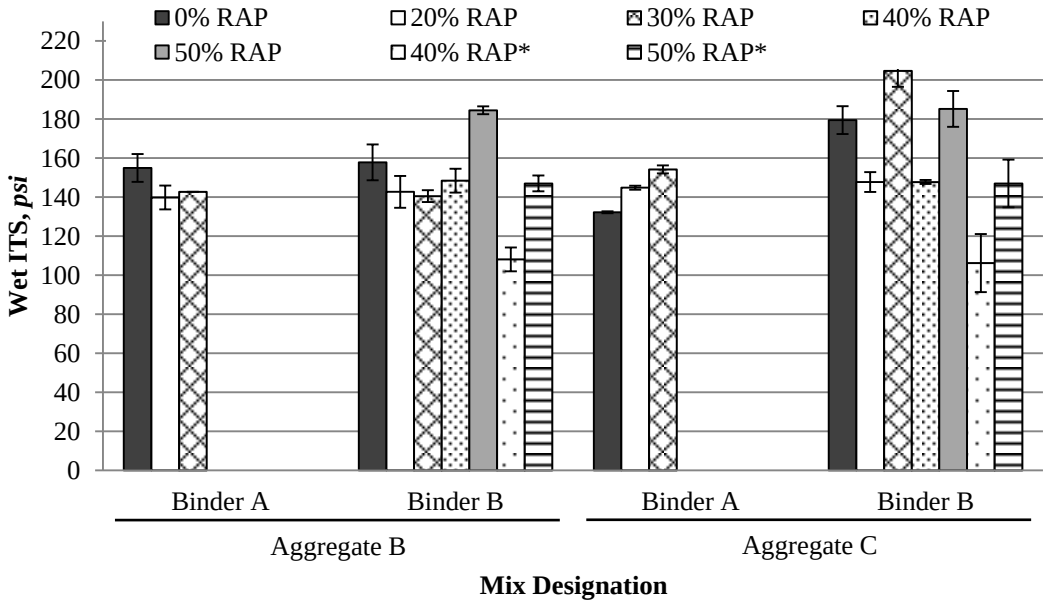


(b)

*Figure 6.13. Indirect tensile strength (ITS) results of HMA mixtures containing RAP after (a) dry conditioning and (b) wet conditioning. * indicates that PG 58-28 binder was used instead of PG 64-22.*

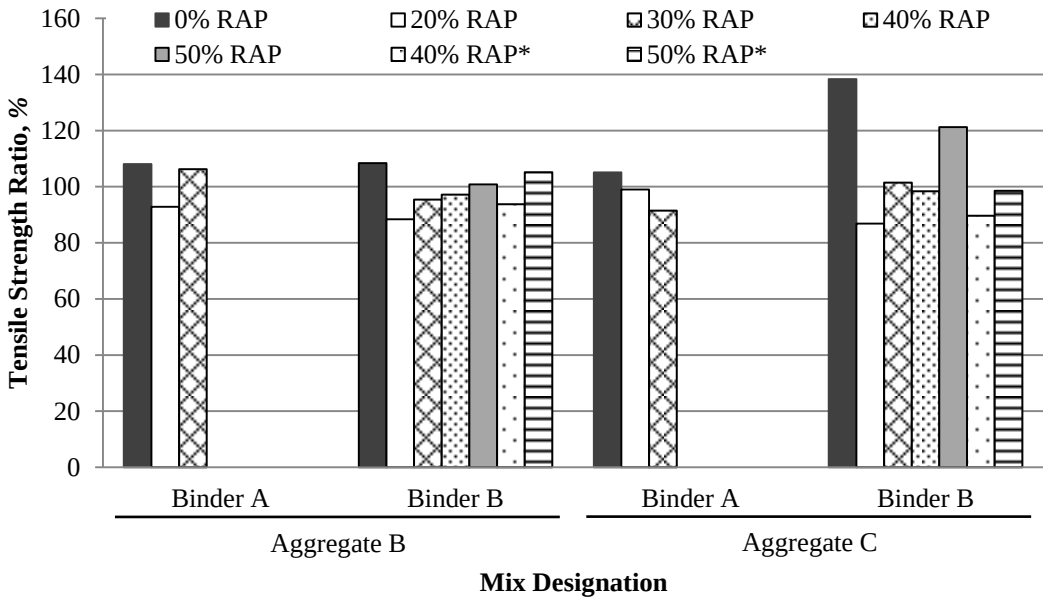


*Figure 6.14. Tensile strength ratio (TSR) of HMA mixtures containing RAP. * indicates that PG 58-28 binder was used instead of PG 64-22. * indicates that PG 58-28 binder was used instead of PG 64-22.*

PERFORMANCE CHARACTERISTICS OF MIXTURES CONTAINING RAP

Two performance characteristics of the RAP mixtures were evaluated in the laboratory phase of the research: Rutting susceptibility and resilient modulus. Both of these properties are critical to ensuring long lasting, functional asphalt pavements. The overall results of the performance evaluation are summarized in Table 6.8. Additionally, the rutting and resilient modulus results are graphically summarized in Figures 6.15 and 6.16, respectively.

The results of the rutting resistance in Figure 6.15 indicate that the addition of RAP to the HMA mixtures significantly increased the rutting resistance of the mixtures, which is to be expected due to the increased stiffness of the RAP binder being added to the mix. It can also be noticed that a higher RAP content does not necessarily mean that the rutting resistance will necessarily be significantly increased. For instance, the mixture containing 50% RAP for the aggregate C / binder B mix had a higher rut depth than the 20, 30, or 40% RAP mixes for the same materials. Additionally, the substitution of PG 58-28 binder for the PG 64-22 binder for the 40 and 50% RAP mixes resulted in a higher rut depth compared to the PG 64-22 mixes made with 40 and 50% RAP. This was also expected due to the effect of the softer virgin binder.

Table 6.8. Rutting and resilient modulus results of HMA mixtures containing RAP. Rutting was measured at 64°C and resilient modulus was measured at 25°C.

		% RAP	Rut Depth, *mm*	Resilient Modulus, *ksi*
Aggregate B	Binder A PG 64-22	0%	3.5	1491
		20%	1.3	2274
		30%	1.6	2520
	Binder B PG 58-28	40%	2.0	1607
		50%	1.6	2612
	Binder B PG 64-22	0%	2.9	2076
		20%	1.2	2189
		30%	1.3	2465
		40%	1.0	2614
		50%	0.9	3163
Aggregate C	Binder A PG 64-22	0%	3.4	1556
		20%	2.2	1917
		30%	1.6	2137
	Binder B PG 58-28	40%	2.2	1656
		50%	2.1	1407
	Binder B PG 64-22	0%	3.1	1511
		20%	2.1	1214
		30%	1.7	1614
		40%	1.6	2457
		50%	2.5	2184

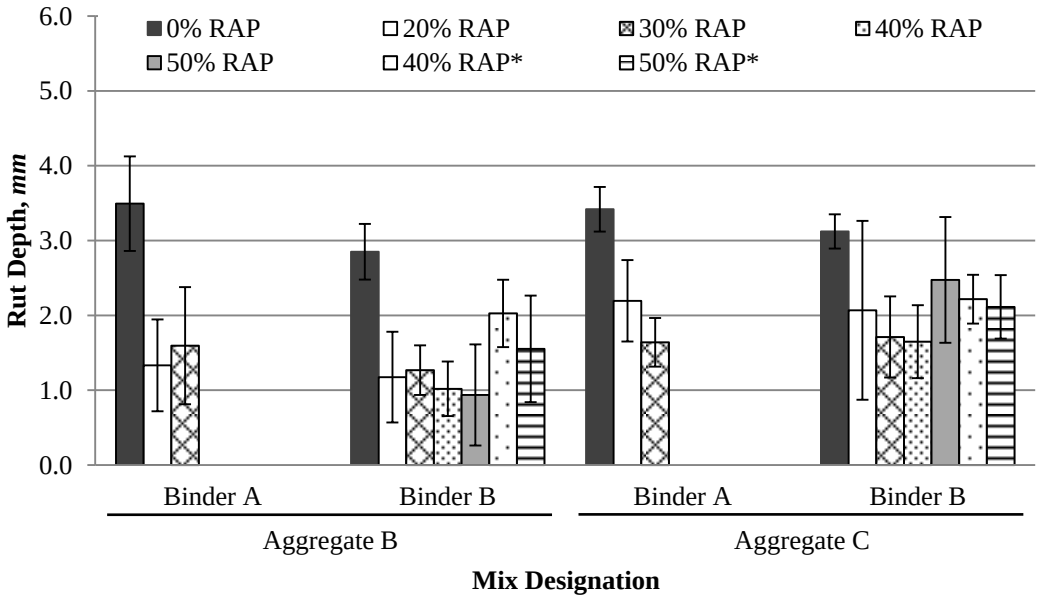


*Figure 6.15. Rut depth of HMA mixtures containing RAP measured using the APA rutting test at 64°C. * indicates that PG 58-28 binder was used instead of PG 64-22.*

The results of the resilient modulus testing illustrated in Figure 6.16 show that the addition of RAP generally increases the resilient modulus of the HMA mixes. Additionally, the resilient modulus generally increases as the RAP content increases. This trend is expected because the addition of greater amounts of stiffer RAP binder should increase the stiffness of the mixture as quantified by the resilient modulus. As with the rutting results, the substitution of PG 58-28 virgin binder reduced the stiffness of the mixtures compared to the mixes made with PG 64-22 virgin binder.

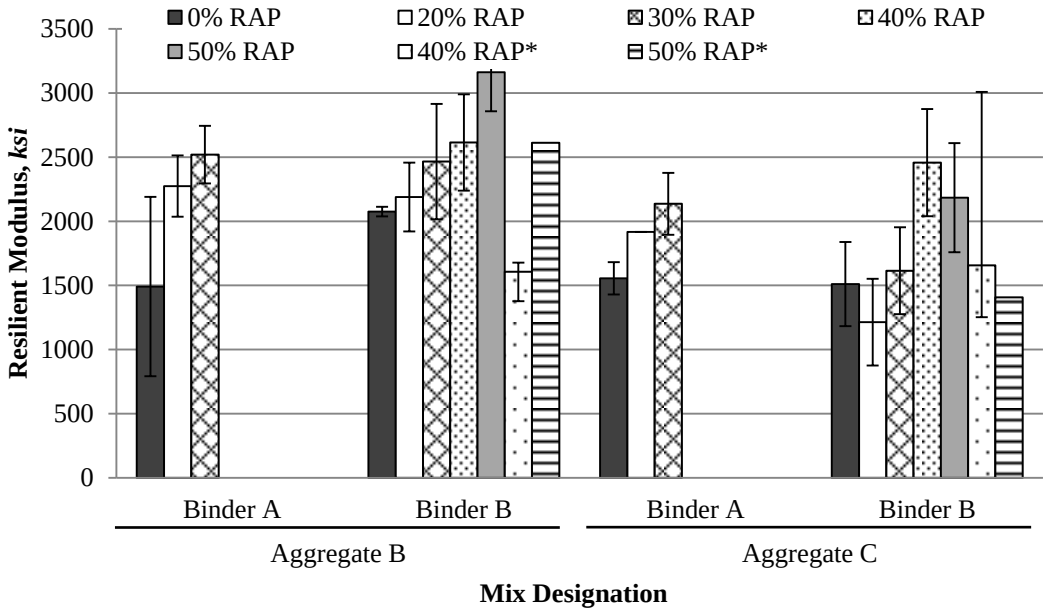


*Figure 6.16. Resilient modulus of HMA mixtures containing RAP tested at 25°C. * indicates that PG 58-28 binder was used instead of PG 64-22.*

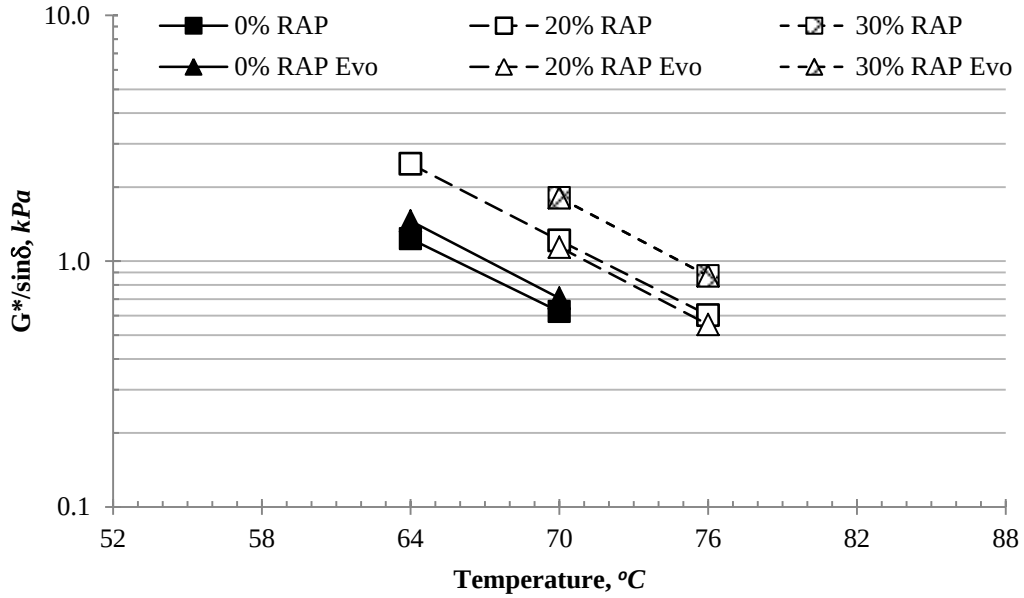
CHAPTER 7: EFFECTS OF WARM MIX ASPHALT TECHNOLOGIES ON HIGH RAP CONTENT MIXTURES

The primary objective of this phase of the research was to investigate the influence of WMA technologies (Evotherm™ and foaming) on mixtures containing RAP (up to 50%) in asphalt mixtures used by SCDOT. To accomplish this objective, an SCDOT Surface Type B mixture was used as the basis of comparison. In addition to a control mixture containing no RAP, mixes made with 20, 30, 40, and 50% RAP by weight of mixture were evaluated as HMA mixtures and also using Evotherm™ and foaming WMA technologies. In total, 60 mix designs (five RAP contents, two aggregate sources, two binder sources, and HMA plus two WMA technologies) were evaluated in the laboratory portion of this phase and the performance of each was evaluated. The materials and procedures used to complete this portion of the study are detailed in Chapter 4 and the properties of the RAP materials are provided in Chapter 6.

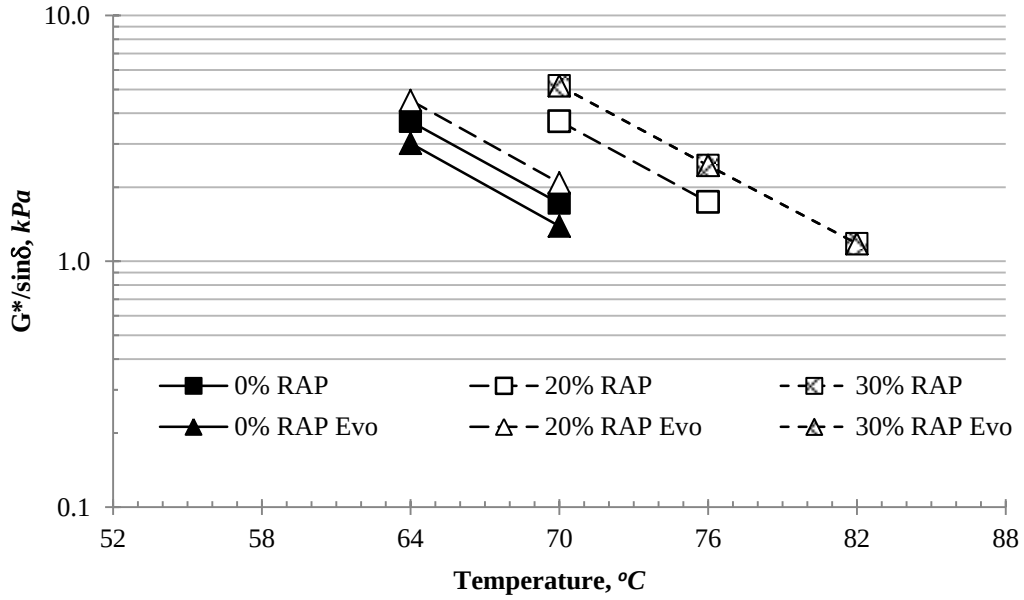
PROPERTIES OF COMPOSITE WMA BINDERS CONTAINING RAP

The performance of composite binders made with Evotherm™ as the WMA technology were evaluated to investigate any effects that the additive may have on composite RAP binders. The results of the virgin binder evaluation presented in Chapter 5 indicated that Evotherm™ had no significant effect on the binder performance. In this phase, the same composite binders that were evaluated in Chapter 6 were evaluated with Evotherm™. Composite binders were prepared by blending the appropriate amount of recovered RAP binders based on the RAP percentages used in the mix design phase (20, 30, 40, and 50% RAP by weight of mixture). Table 6.2 summarized the RAP content and the corresponding content of the RAP binder as a percentage of the overall binder content. Evotherm™ was added to the binders as recommended by the manufacturer and the binder testing was completed. Only Evotherm™ binders were evaluated in this study as foaming does not really modify the binder and the effects of the foaming action cannot be accurately captured by conventional binder testing at this time.

Figures 7.1, 7.2, and 7.3 summarize the results of the temperature sweep performed on the control and Evotherm™ composite binders using RAP B in the original and RTFO aged condition for binder A (PG 64-22), binder B (PG 64-22), and binder B (PG 58-28), respectively. The temperature sweep results for the RAP C composite binders are summarized in Figures 7.4-7.6. Additionally, the effects of Evotherm™ and increasing RAP content on the DSR failure temperatures are summarized in Tables 7.1 and 7.2 and Figures 7.7 through 7.11. Based on the results, it is apparent that the addition of Evotherm™ to the composite binders generally lessened the stiffening effect of increasing RAP contents. This trend was more pronounced as the RAP content increased. The difference was more pronounced after RTFO aging of the binders, which could be a result of the fact that the Evotherm™ binders were RTFO aged at 275^{o}F (135^{o}C) instead of 325^{o}F (163^{o}C) as used for HMA binders. The reduction in RTFO temperature was selected to be more representative of actual WMA production temperatures.

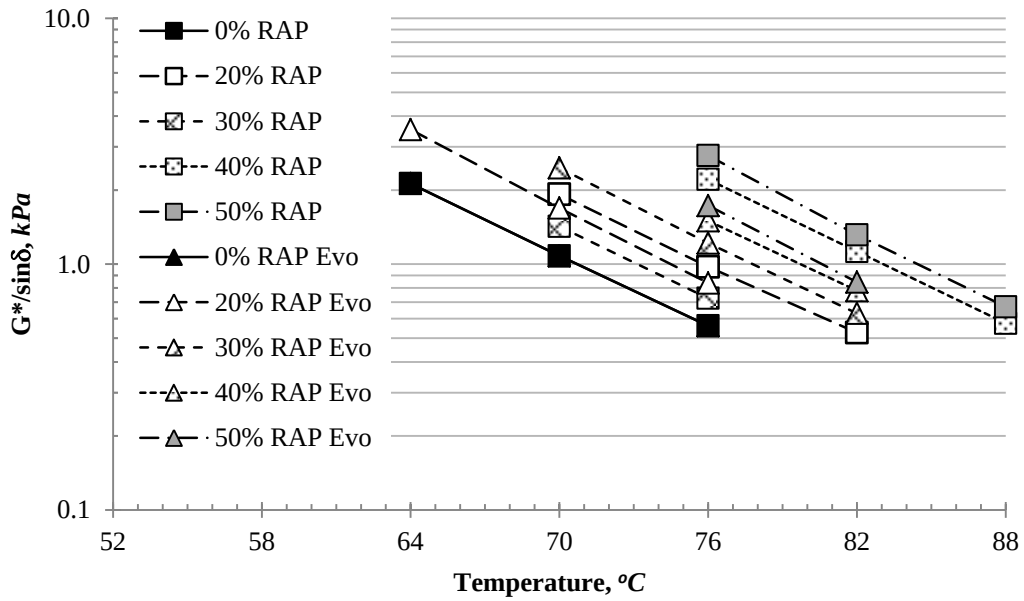


(a)

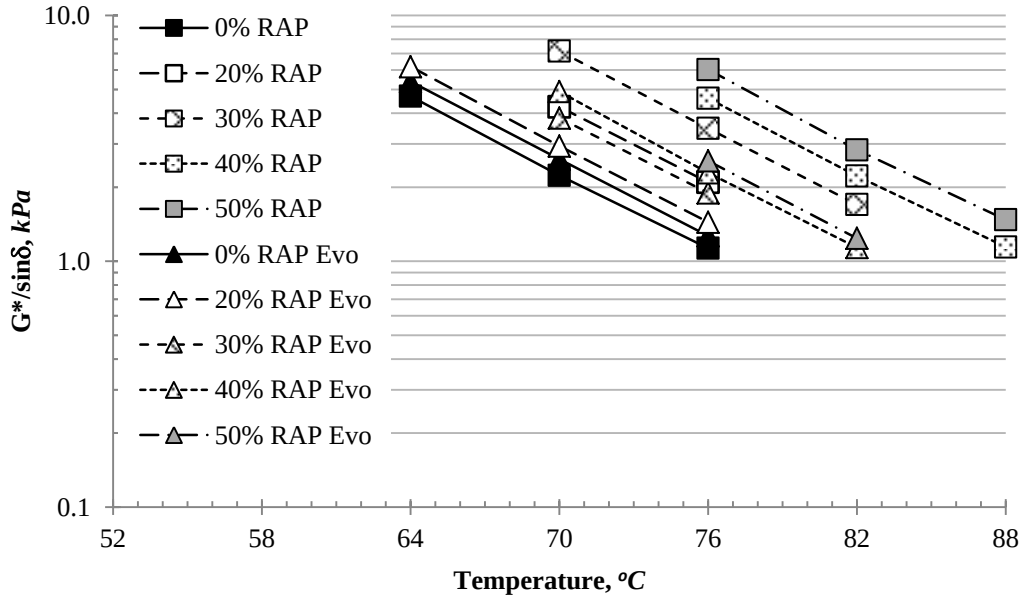


(b)

Figure 7.1. Temperature sweep results of composite binders made with extracted binder from RAP source B and virgin binder from source A (PG 64-22) in (a) unaged condition and (b) RTFO aged condition. Binders were either control or modified with Evotherm™ (denoted as "Evo").

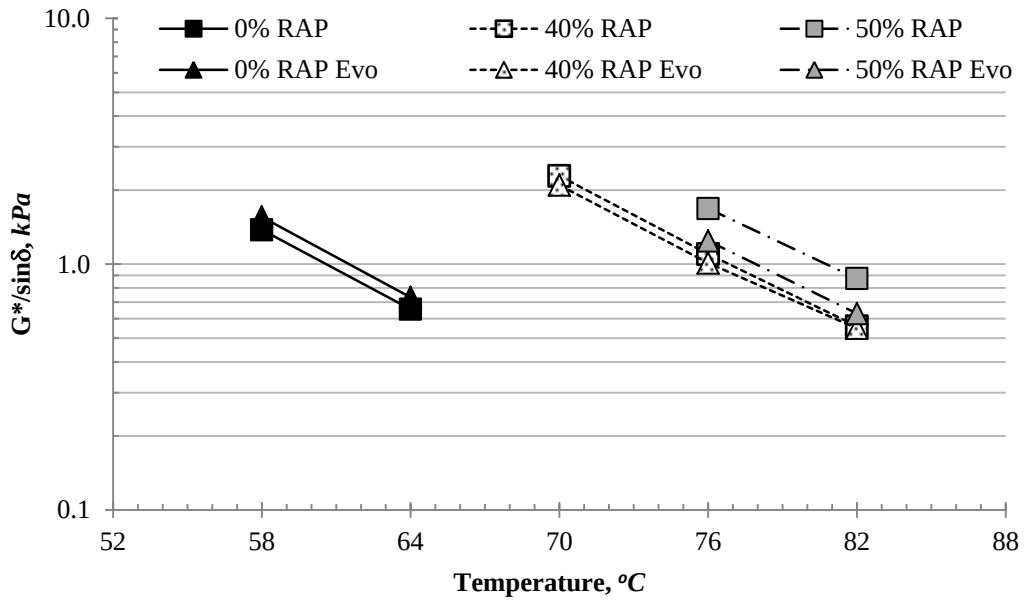


(a)

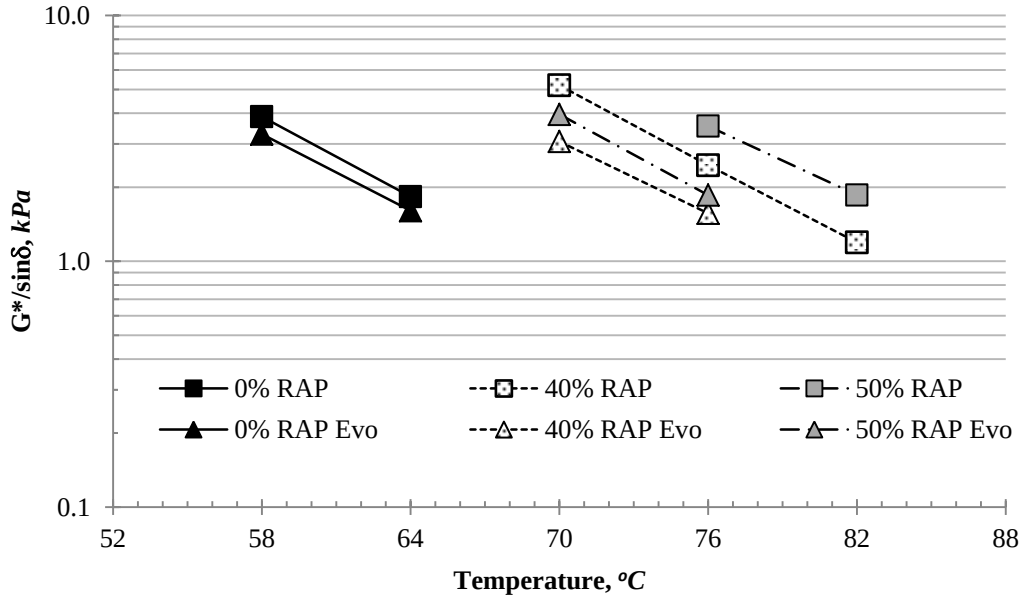


(b)

Figure 7.2. Temperature sweep results of composite binders made with extracted binder from RAP source B and virgin binder from source B (PG 64-22) in (a) unaged condition and (b) RTFO aged condition. Binders were either control or modified with Evotherm™ (denoted as "Evo").

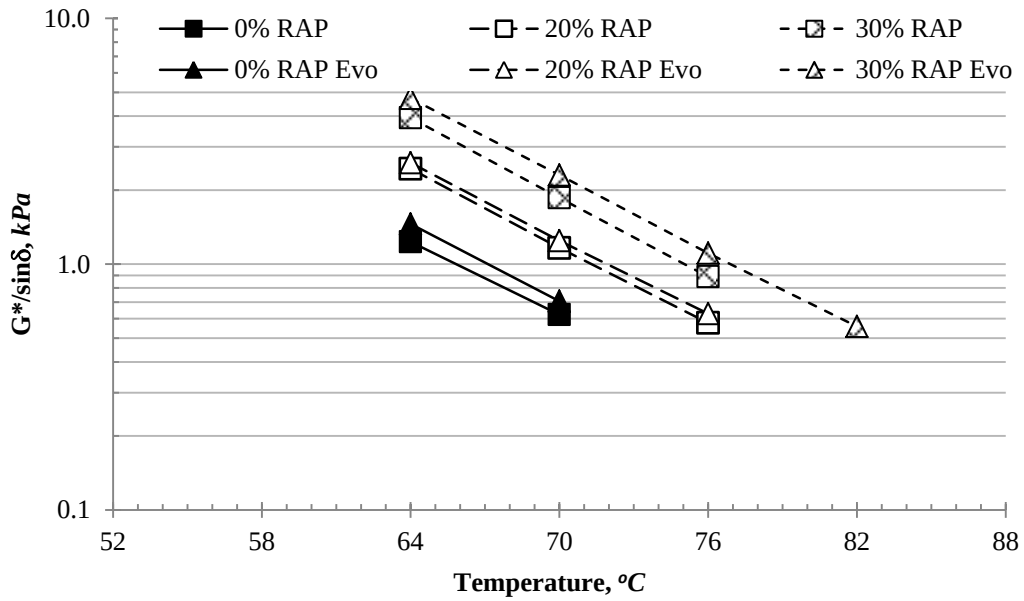


(a)

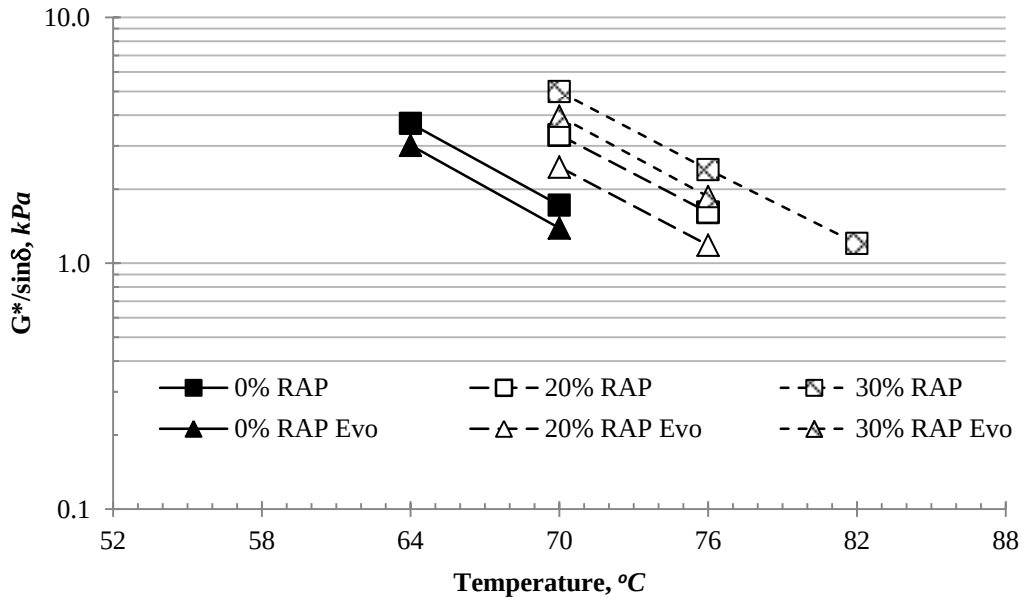


(b)

Figure 7.3. Temperature sweep results of composite binders made with extracted binder from RAP source B and virgin binder from source B (PG 58-28) in (a) unaged condition and (b) RTFO aged condition. Binders were either control or modified with Evotherm (denoted as "Evo").

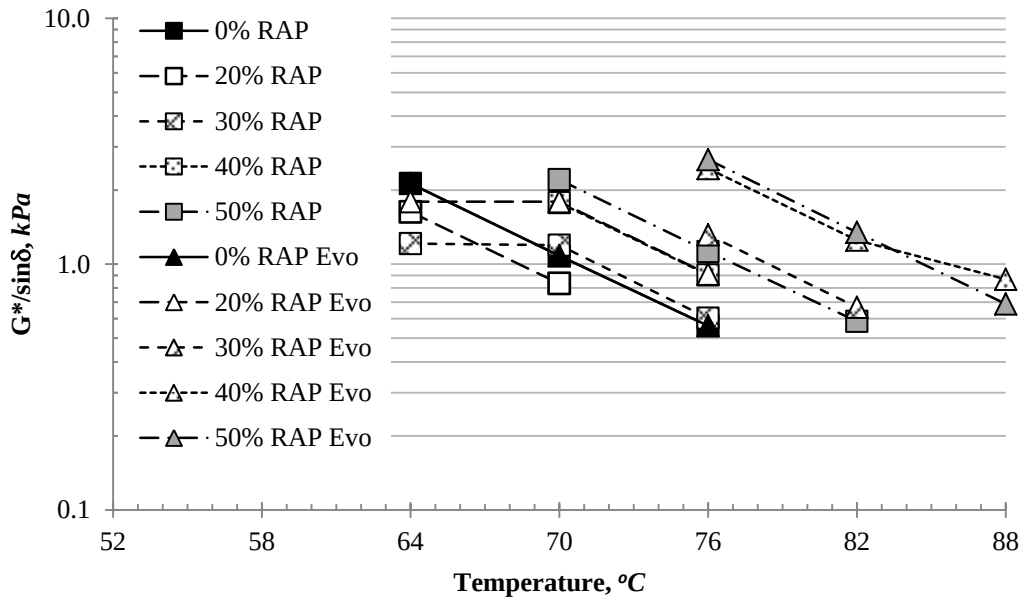


(a)

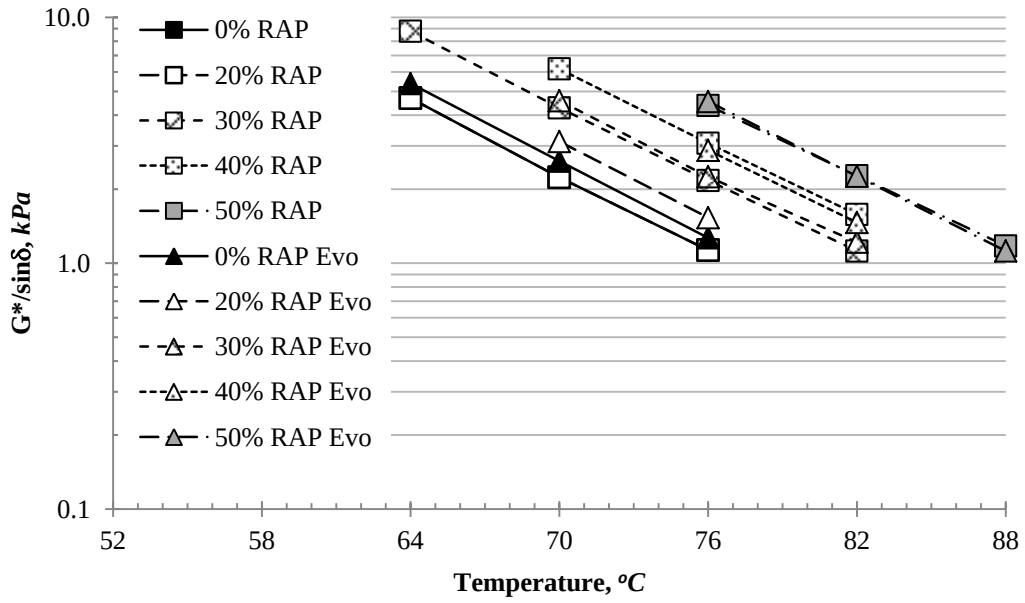


(b)

Figure 7.4. Temperature sweep results of composite binders made with extracted binder from RAP source C and virgin binder from source A (PG 64-22) in (a) unaged condition and (b) RTFO aged condition. Binders were either control or modified with Evotherm (denoted as "Evo").

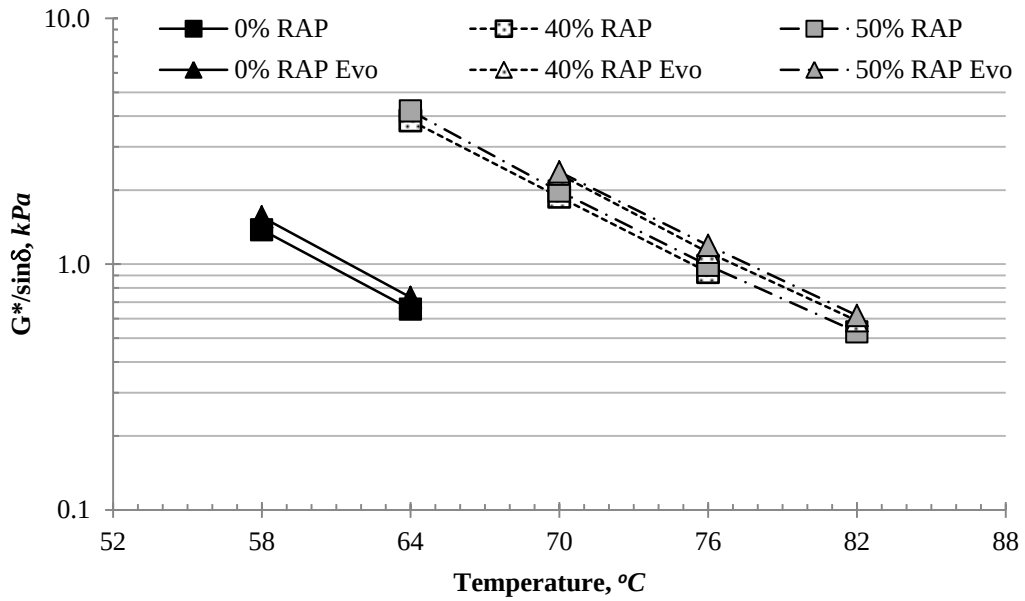


(a)

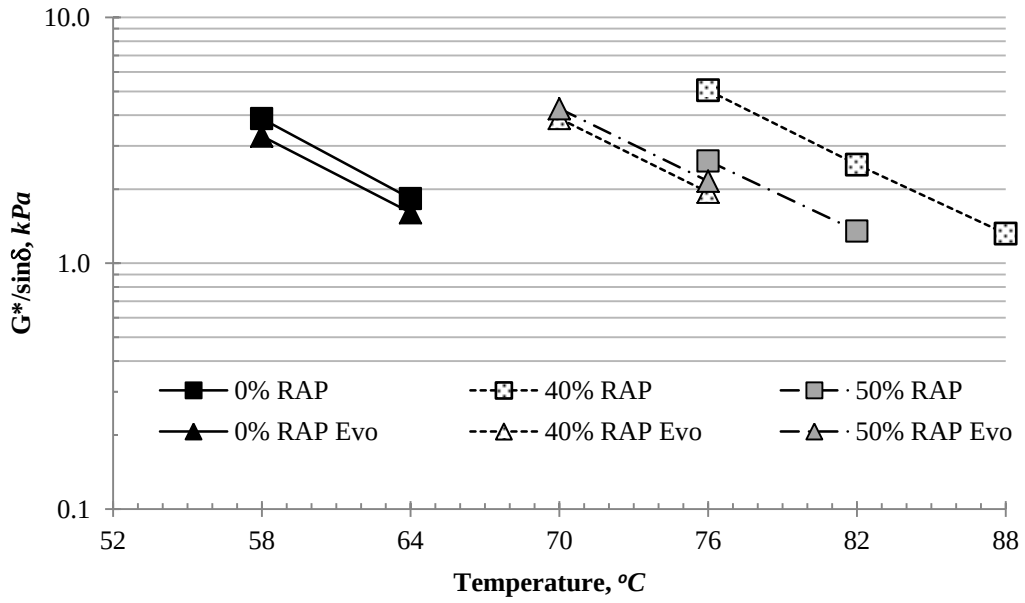


(b)

Figure 7.5. Temperature sweep results of composite binders made with extracted binder from RAP source C and virgin binder from source B (PG 64-22) in (a) unaged condition and (b) RTFO aged condition. Binders were either control or modified with Evotherm™ (denoted as "Evo").



(a)



(b)

Figure 7.6. Temperature sweep results of composite binders made with extracted binder from RAP source C and virgin binder from source B (PG 58-28) in (a) unaged condition and (b) RTFO aged condition. Binders were either control or modified with Evotherm™ (denoted as "Evo").

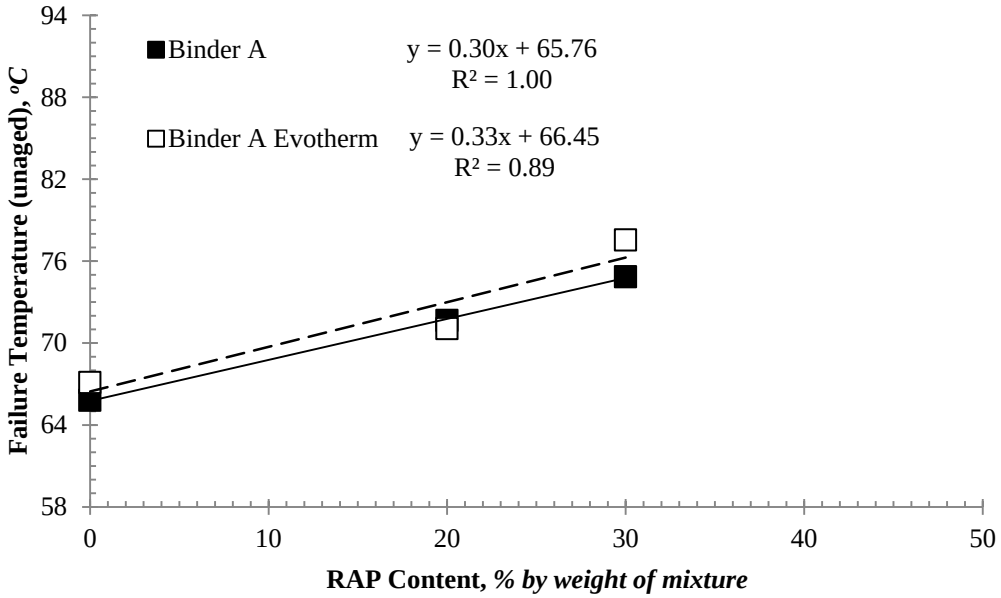
Table 7.1. Failure temperature of unaged and RTFO aged composite HMA and WMA binders made from RAP source B.

		% RAP	Unaged Failure Temp., ^oC	RTFO Failure Temp., ^oC
Binder A PG 64-22	Control	0%	65.8	68.1
		20%	71.7	74.2
		30%	74.9	76.9
	Evotherm	0%	67.1	66.5
		20%	71.1	69.6
		30%	77.6	75.5
Binder B PG 64-22	Control	0%	70.7	70.2
		20%	75.8	75.6
		30%	79.1	79.9
		40%	83.1	82.1
		50%	84.5	84.4
	Evotherm	0%	70.7	71.4
		20%	74.5	72.5
		30%	77.8	74.8
		40%	79.8	76.4
		50%	80.6	77.3
Binder B PG 58-28	Control	0%	60.6	62.6
		40%	76.8	77.0
		50%	80.8	80.4
	Evotherm	0%	61.5	61.4
		40%	76.1	73.0
		50%	78.0	74.7

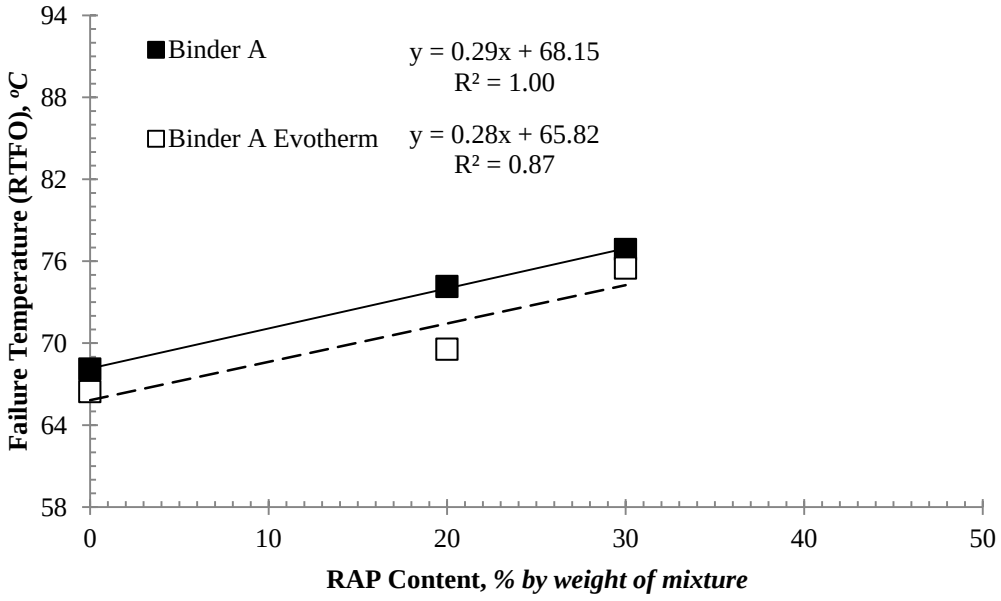
Table 7.2. Failure temperature of unaged and RTFO aged composite HMA and WMA binders made from RAP source C.

		% RAP	Unaged Failure Temp., ^oC	RTFO Failure Temp., ^oC
Binder A PG 64-22	Control	0%	65.8	68.1
		20%	71.3	73.4
		30%	75.1	76.8
	Evotherm	0%	67.1	66.5
		20%	72.0	70.9
		30%	76.9	74.7
Binder B PG 64-22	Control	0%	70.7	70.2
		20%	74.4	70.2
		30%	77.6	75.9
		40%	81.1	79.0
		50%	83.1	82.3
	Evotherm	0%	70.7	71.4
		20%	75.2	73.0
		30%	78.4	76.2
		40%	83.7	78.4
		50%	85.2	77.6
Binder B PG 58-28	Control	0%	60.6	62.6
		40%	75.3	77.6
		50%	75.9	77.6
	Evotherm	0%	61.5	61.4
		40%	77.1	75.0
		50%	77.6	75.8

The effects of RAP and Evotherm™ on the creep stiffness properties of the composite binders at low temperature as measured with the BBR are summarized in Figures 7.12 through 7.17. The results indicate that the Evotherm™ generally reduced the stiffness of the binders especially when RAP binder was included. Additionally, the impact of RAP content on the stiffness properties of the binder was dependent on the binder source as the PG 64-22 from binder source B was more impacted by the addition of RAP from both sources, compared to the PG 64-22 binder from source A. The stiffness values of binder B increased with RAP content, while binder A exhibited decreased, or similar stiffness values with RAP compared to the control. Finally, the PG 58-28 binder from source B had reduced stiffness values when 40 and 50% RAP was added.

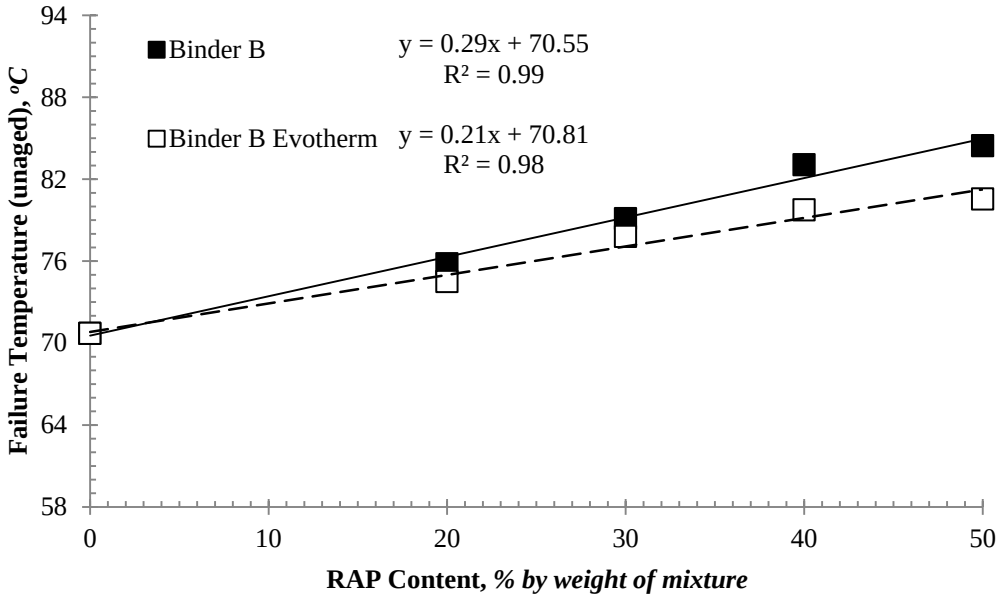


(a)

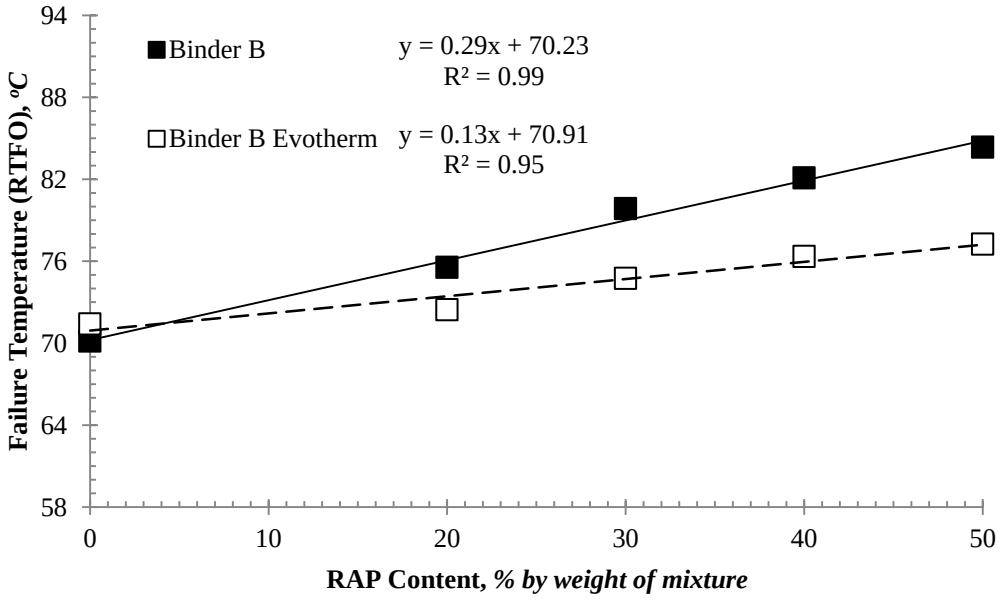


(b)

Figure 7.7. Effect of RAP content (RAP B) and WMA technology (Evotherm™) on composite binder (source A PG 64-22) failure temperature measured using the dynamic shear rheometer in an (a) unaged state and (b) RTFO aged state.

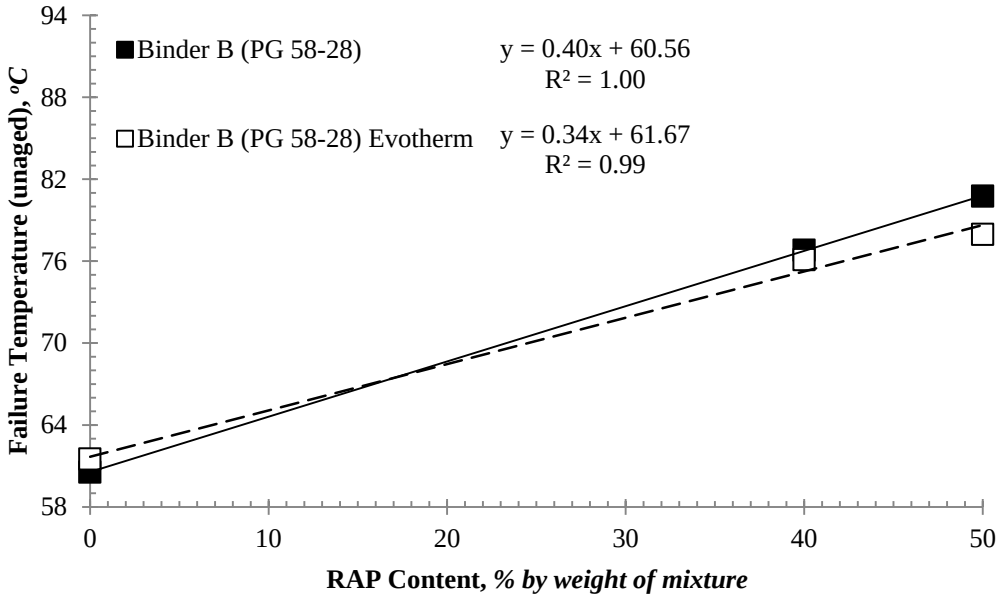


(a)

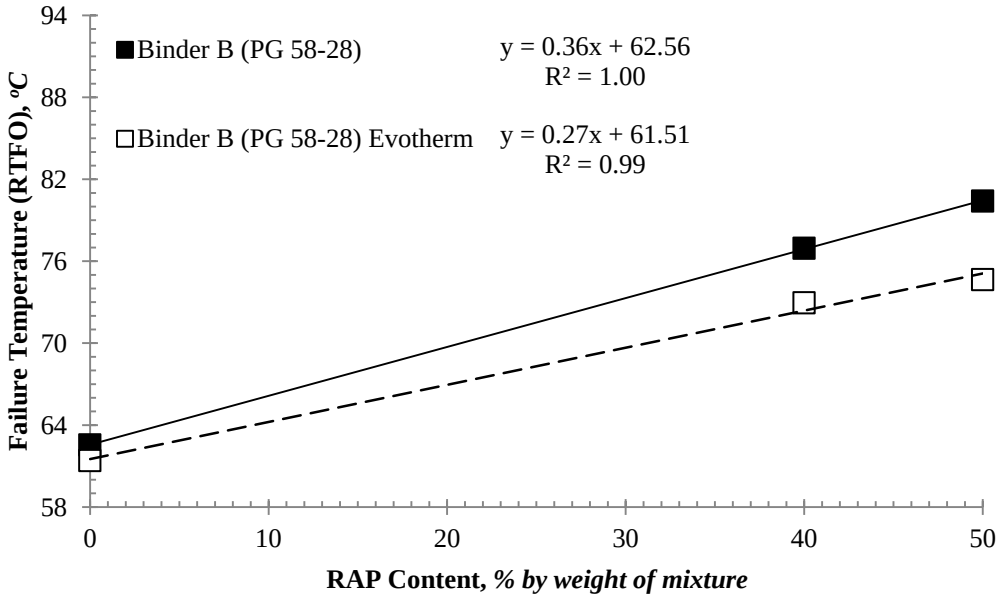


(b)

Figure 7.8. Effect of RAP content (RAP B) and WMA technology (Evotherm™) on composite binder (source B PG 64-22) failure temperature measured using the dynamic shear rheometer in an (a) unaged state and (b) RTFO aged state.

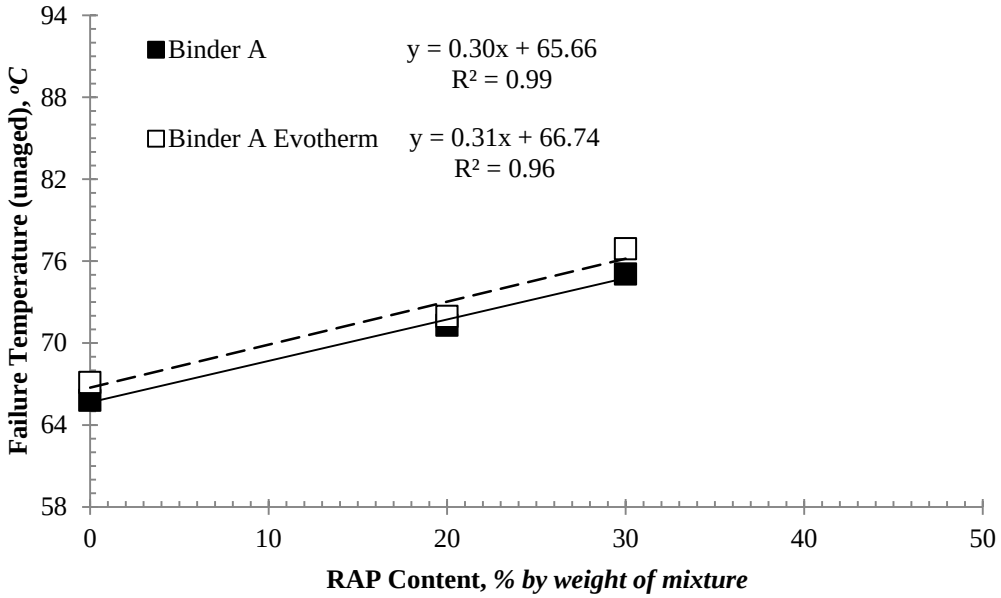


(a)

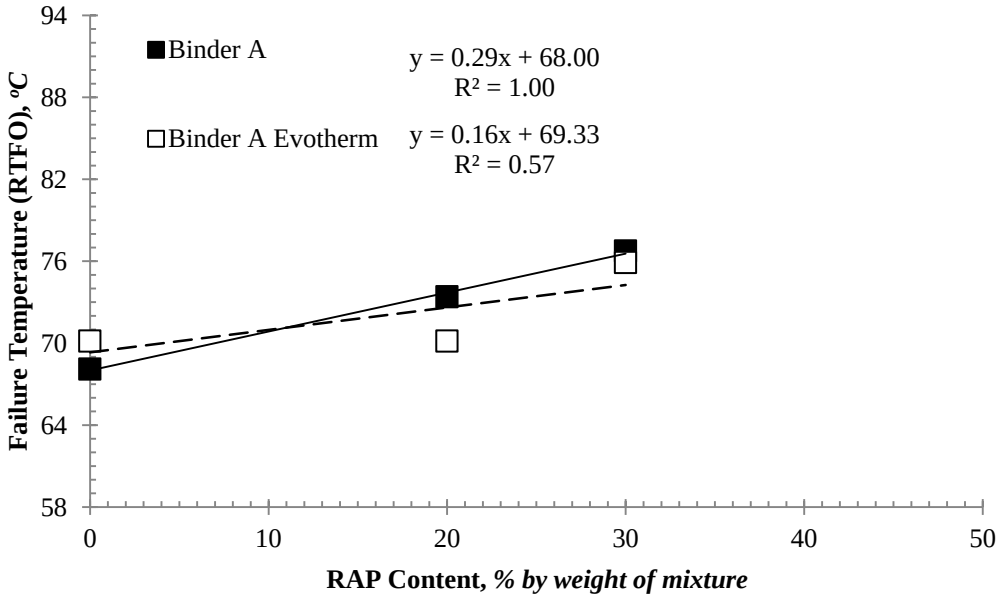


(b)

Figure 7.6. Effect of RAP content (RAP B) and WMA technology (Evotherm™) on composite binder (source B PG 58-28) failure temperature measured using the dynamic shear rheometer in an (a) unaged state and (b) RTFO aged state.

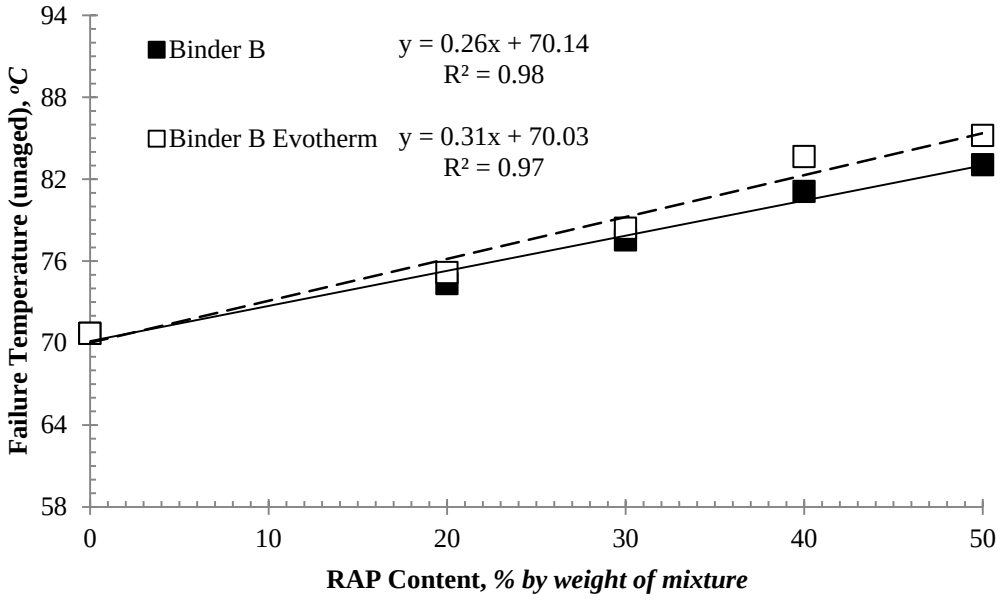


(a)

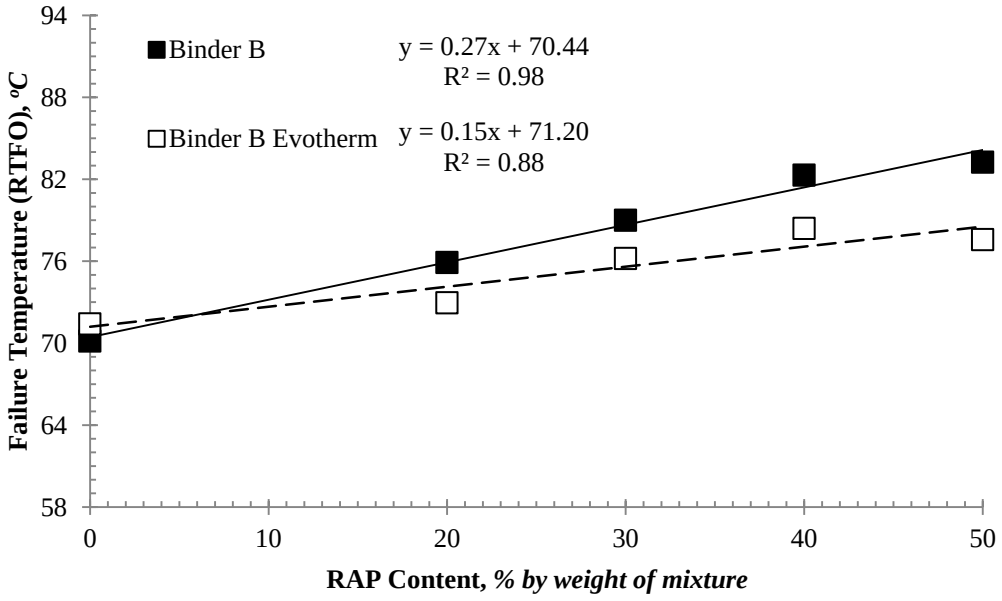


(b)

Figure 7.9. Effect of RAP content (RAP C) and WMA technology (Evotherm™) on composite binder (source A PG 64-22) failure temperature measured using the dynamic shear rheometer in an (a) unaged state and (b) RTFO aged state.

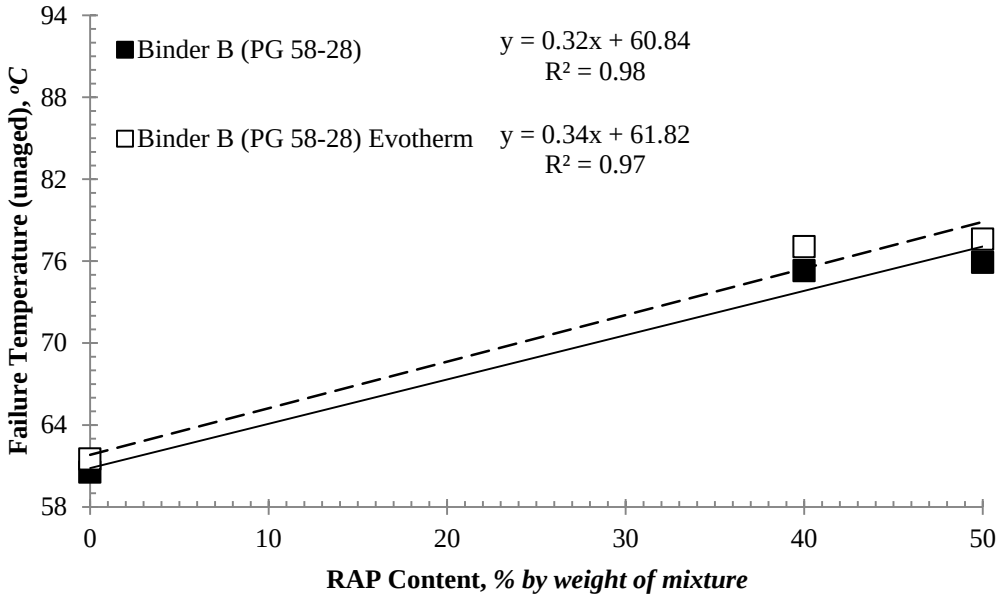


(a)

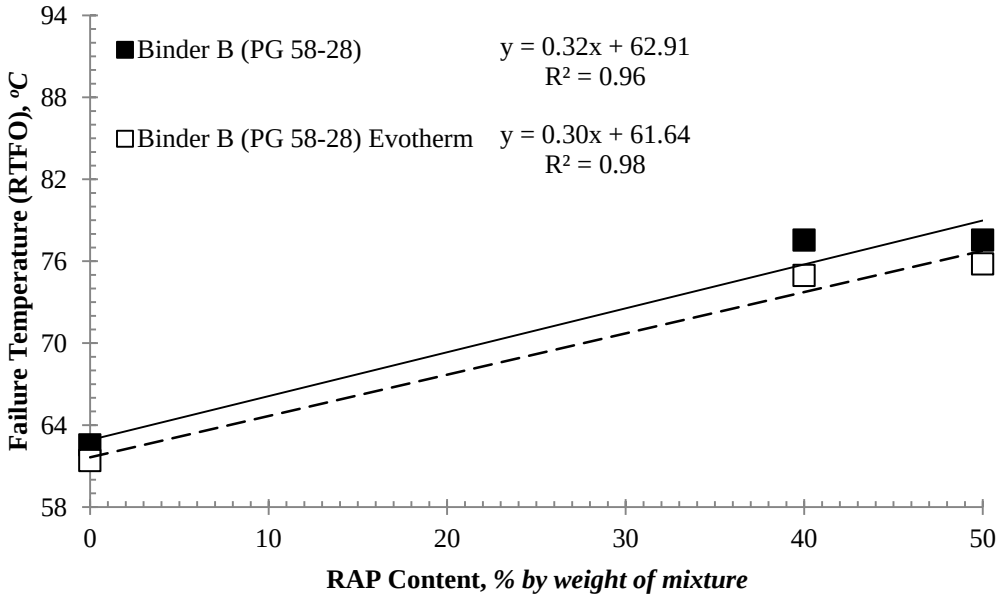


(b)

Figure 7.10. Effect of RAP content (RAP C) and WMA technology (Evotherm™) on composite binder (source B PG 64-22) failure temperature measured using the dynamic shear rheometer in an (a) unaged state and (b) RTFO aged state.

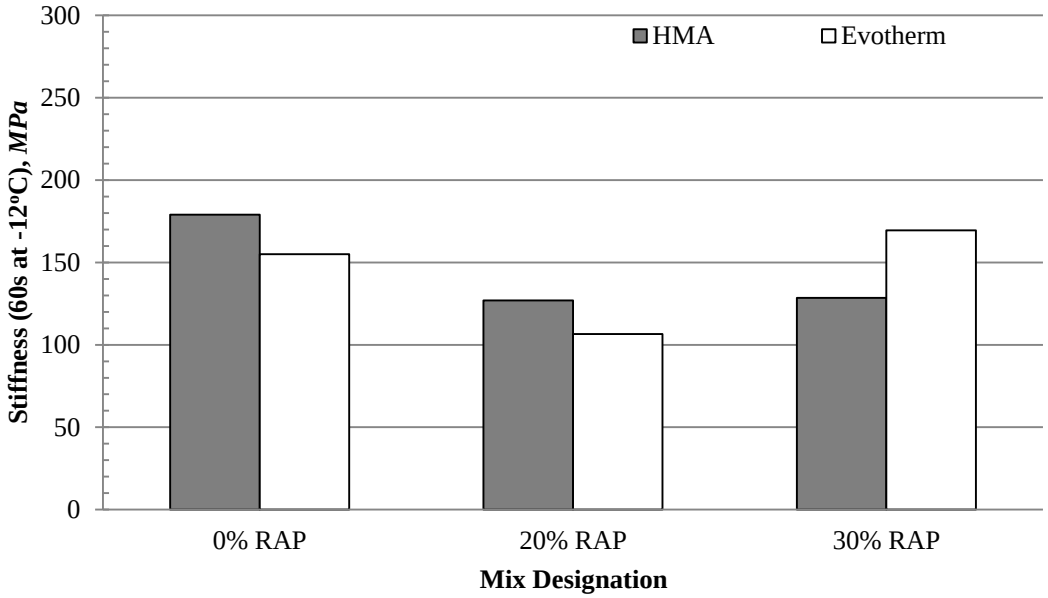


(a)

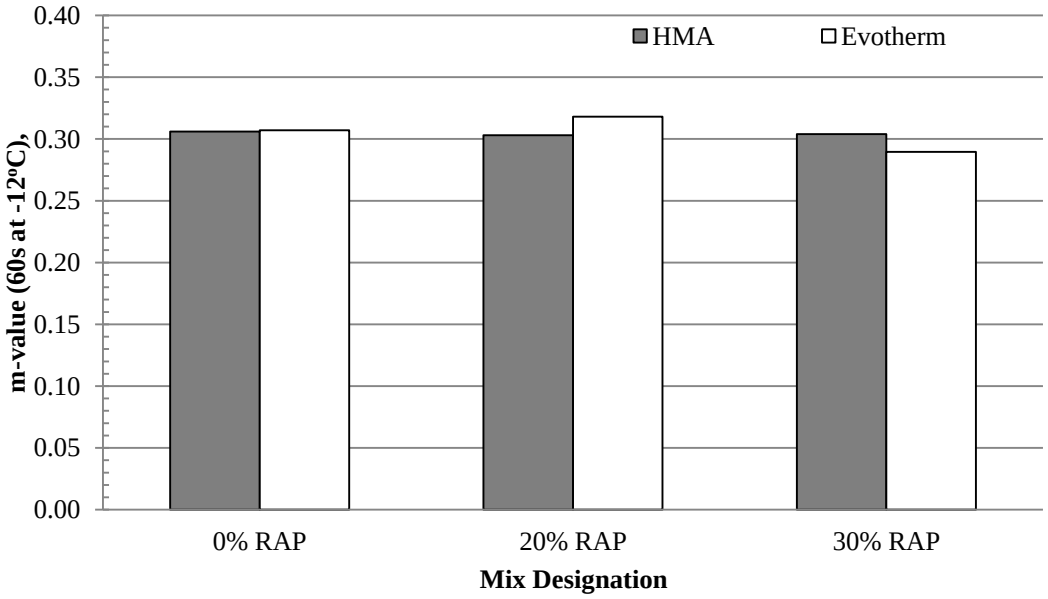


(b)

Figure 7.11. Effect of RAP content (RAP C) and WMA technology (Evotherm™) on composite binder (source B PG 58-28) failure temperature measured using the dynamic shear rheometer in an (a) unaged state and (b) RTFO aged state.

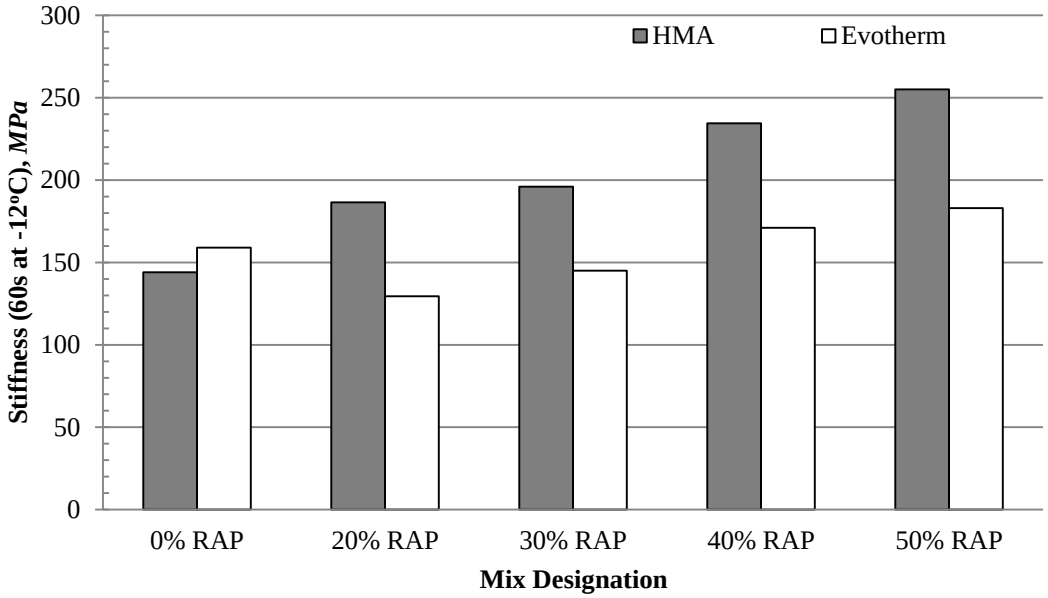


(a)

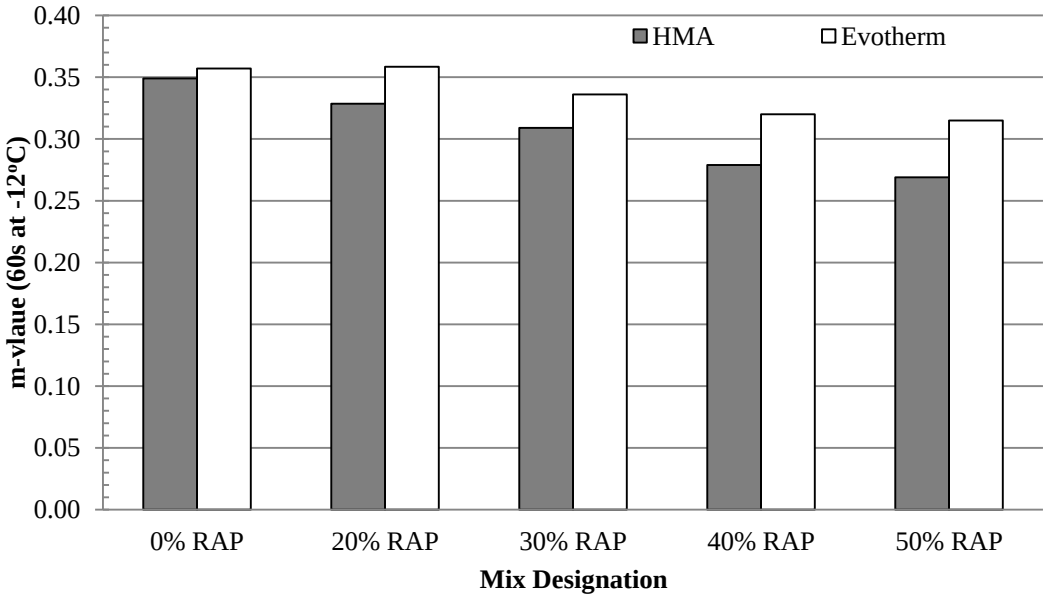


(b)

Figure 7.12. Effect of WMA technology (Evotherm™) and RAP content (RAP B) on low temperature properties of composite binders made with binder source A tested using the bending beam rheometer at -12°C to measure the (a) stiffness and (b) m-value of PAV aged binders.

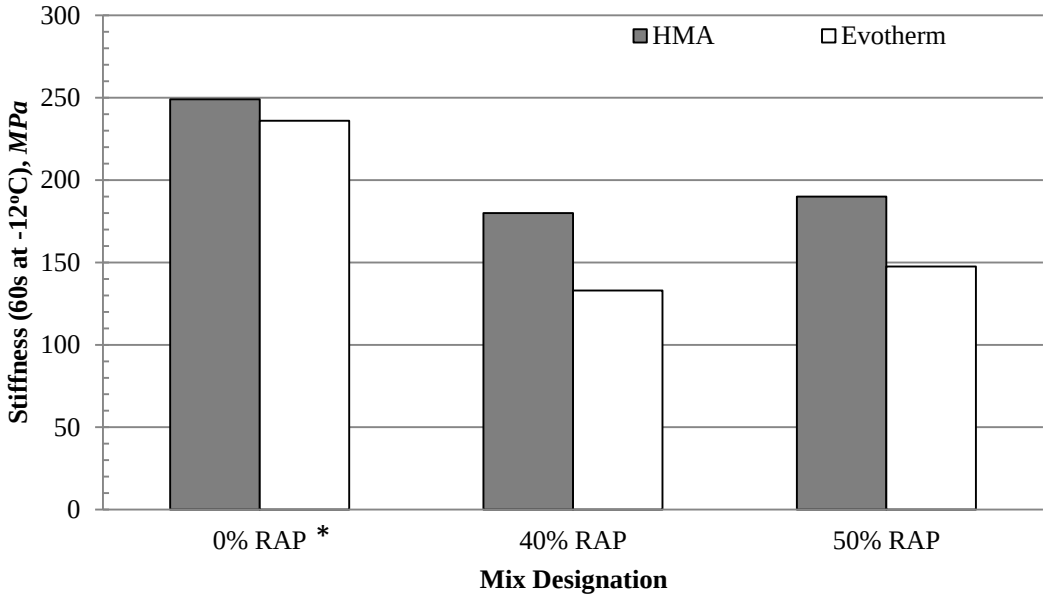


(a)

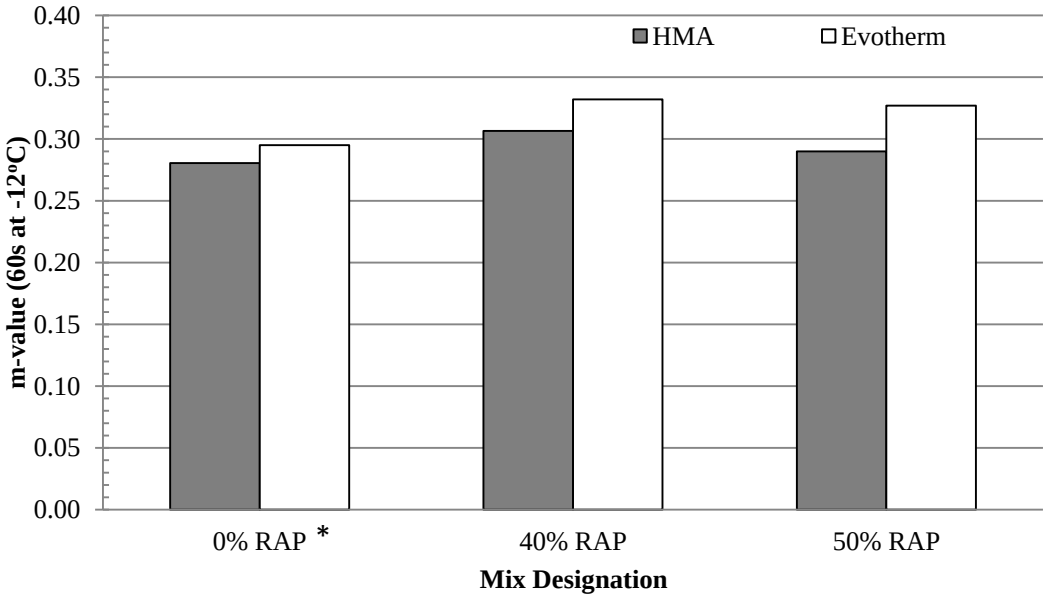


(b)

Figure 7.13. Effect of WMA technology (Evotherm™) and RAP content (RAP B) on low temperature properties of composite binders made with binder source B (PG 64-22) tested using the bending beam rheometer at -12°C to measure the (a) stiffness and (b) m-value of PAV aged binders.

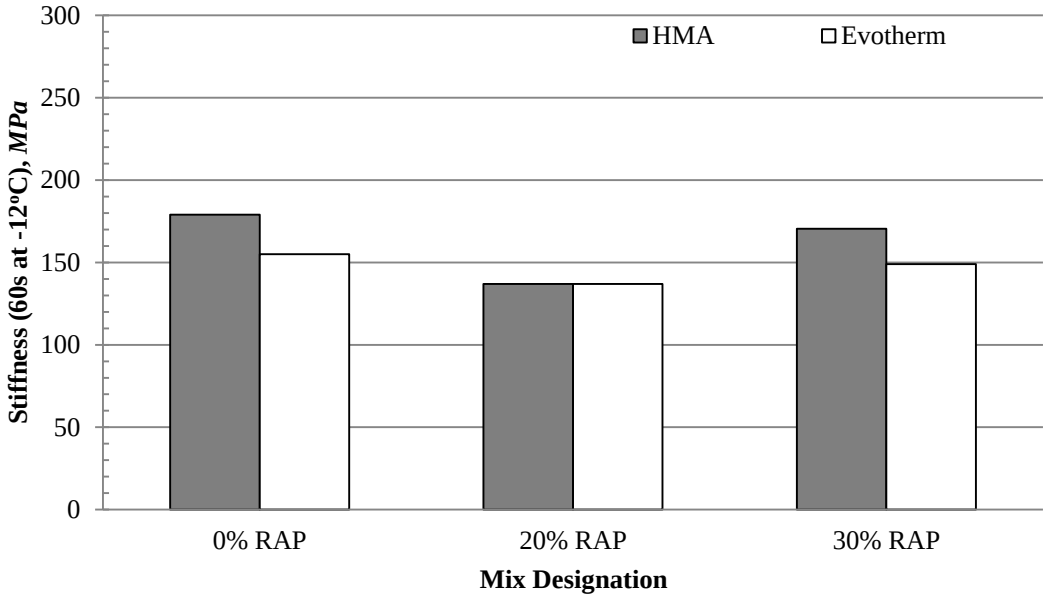


(a)

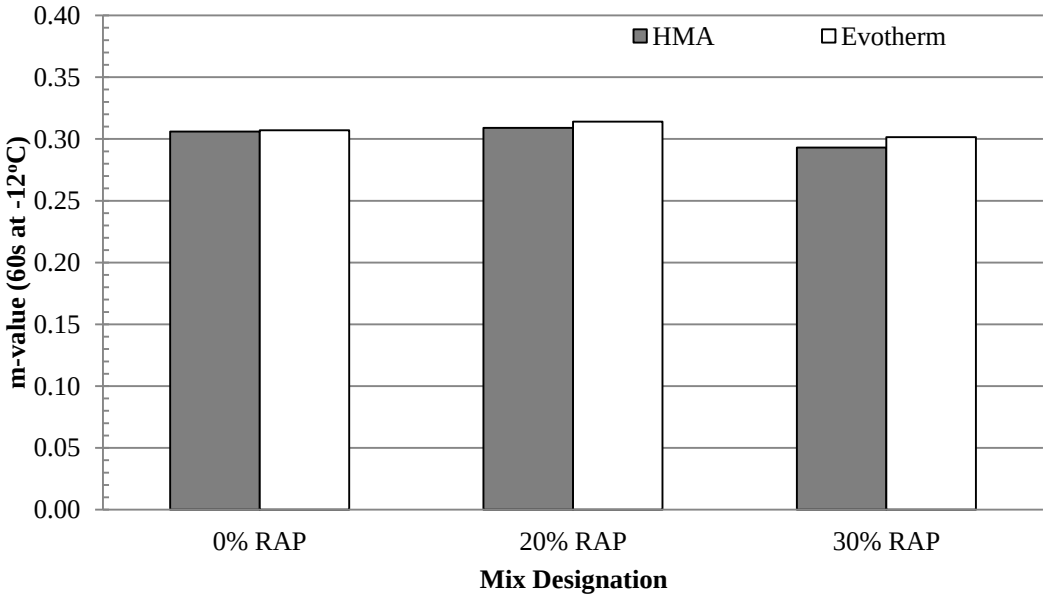


(b)

*Figure 7.14. Effect of WMA technology (Evotherm™) and RAP content (RAP B) on low temperature properties of composite binders made with binder source B (PG 58-28) tested using the bending beam rheometer at -12°C to measure the (a) stiffness and (b) m-value of PAV aged binders. * indicates that PG 58-28 binder was tested at -18°C.*

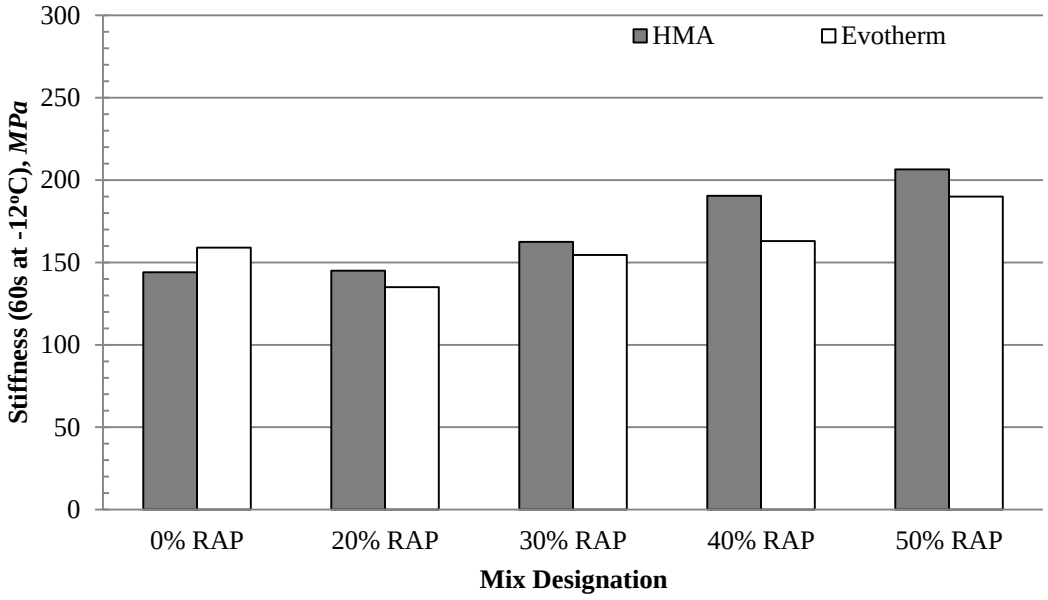


(a)

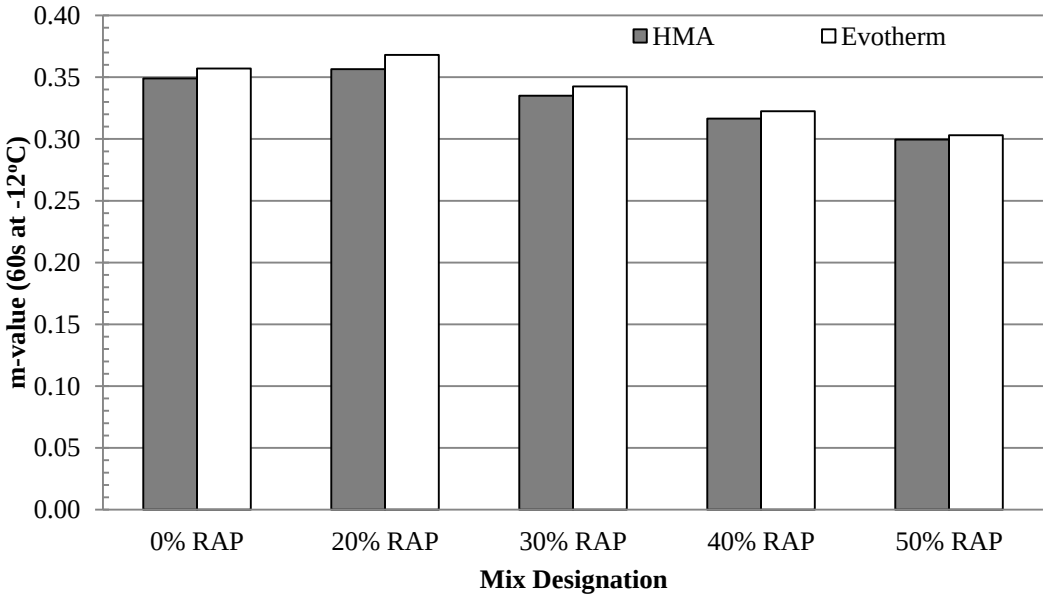


(b)

Figure 7.15. Effect of WMA technology (Evotherm™) and RAP content (RAP C) on low temperature properties of composite binders made with binder source A tested using the bending beam rheometer at -12°C to measure the (a) stiffness and (b) m-value of PAV aged binders.

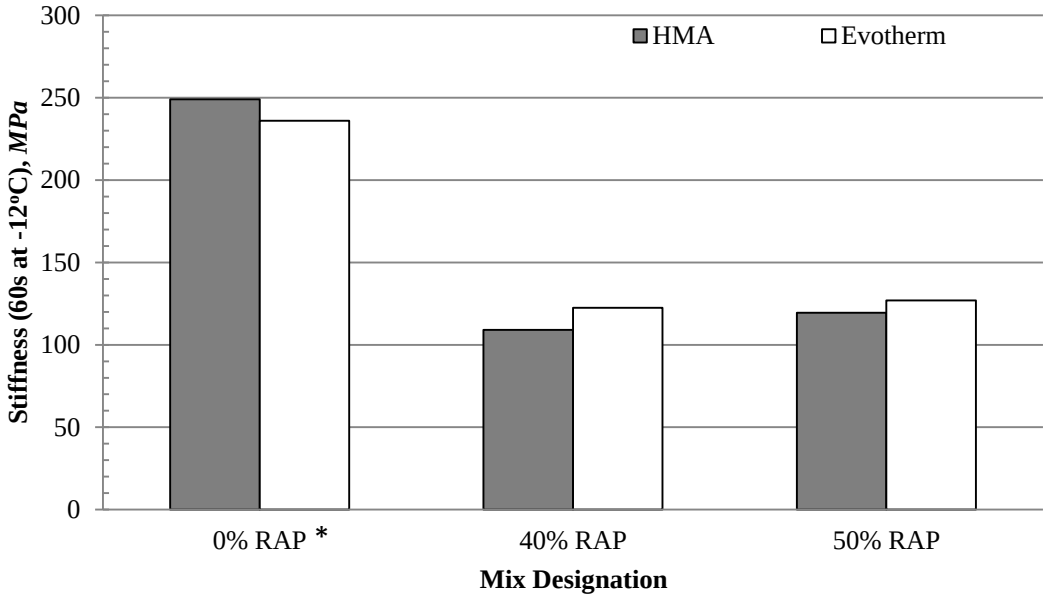


(a)

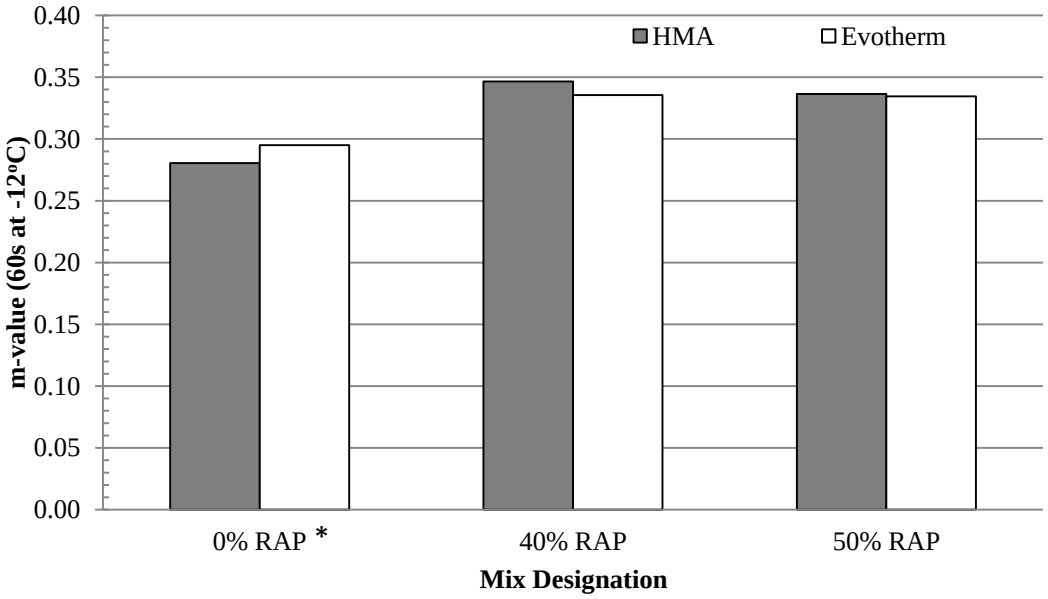


(b)

Figure 7.16. Effect of WMA technology (Evotherm™) and RAP content (RAP C) on low temperature properties of composite binders made with binder source B (PG 64-22) tested using the bending beam rheometer at -12°C to measure the (a) stiffness and (b) m-value of PAV aged binders.



(a)



(b)

*Figure 7.17. Effect of WMA technology (Evotherm™) and RAP content (RAP C) on low temperature properties of composite binders made with binder source B (PG 58-28) tested using the bending beam rheometer at -12°C to measure the (a) stiffness and (b) m-value of PAV aged binders. * indicates that PG 58-28 binder was tested at -18°C.*

EFFECTS OF WMA TECHNOLOGY ON MIX DESIGNS CONTAINING RAP

Surface Type B mix designs were conducted to determine the optimum binder content (OBC) for each aggregate and binder combination with RAP contents varying from 0 to 50% by weight of the mixture and use of Evotherm™ and foaming WMA technologies. The OBC was originally to be determined as the binder content at which the mixture had 4.0% air voids. However, it was decided that the binder content of a given mixture should not be less than 4.5% based on the SCDOT mixture requirements outlined in SC-M-402 (SCDOT 2011). Additionally, a minimum of 4.5% binder content ensured that the dust-to-binder ratio would remain within the specified range of 0.6 to 1.2. The dust-to-binder ratio was of more concern for the mixtures containing RAP as the RAP sources had relatively high amounts of material passing the No. 200 sieve (Table 6.1). In the cases where an air void content of 4.0% yielded a binder content lower than 4.5% or the dust-to-binder ratio was an issue, 4.5% was selected as the OBC and the volumetrics were determined at that binder content. The gradation of each mix is included in Tables 6.4 and 6.5 and the OBC and volumetric properties (air voids, VMA, and VFA) for the mixtures are summarized in Tables 7.3 and 7.4. Graphical representation of the mix design results for the mixes made with aggregate C are presented in Figures 7.18 through 7.21. Figures are not included for aggregate B because the binder content selected for the WMA mixes were the same as the OBC determined for the corresponding HMA mixture.

The selection of the mixing and compaction temperatures (T_{mix} and T_{comp}) were determined based on the viscosity of the composite binders for the HMA mixtures. Additionally, engineering judgment was used in some cases as proper coating or compaction could not be achieved for some mixtures having higher RAP contents. In such cases, the compaction temperature was increased to the reported value. The mixing and compaction temperatures for the WMA mixtures were based on the manufacturer's recommendation for Evotherm™. The same temperatures used for the Evotherm™ were also used for the foaming technology to maintain consistency.

From the results, it can be seen that the VMA values for some of the mixtures were less than the minimum value of 14.5% required by SCDOT specifications. The low VMA values are likely due to the increased amount of fines included in the RAP. As the objective of the study was to investigate the effects of WMA technologies and RAP on the properties of asphalt mixtures, the research team opted to maintain a consistent gradation instead of introducing another variable into the already large experimental design.

As noted in Table 7.3, the OBC determined for the HMA mixtures containing RAP were also used for the WMA mixtures containing RAP. This only applies to the mixtures made with aggregate B and was based on the findings from the aggregate C mixtures, which indicated that the mixture properties and OBC for the WMA mixtures were similar to the HMA mixtures. These findings agree with the findings reported in NCHRP Report 691 (Bonaquist 2011). Mix designs for all aggregate C mixtures were conducted and the respective OBC was used for the performance testing.

Table 7.3. Optimum binder content (OBC) and volumetrics of HMA and WMA mixtures made with aggregate B and RAP B.

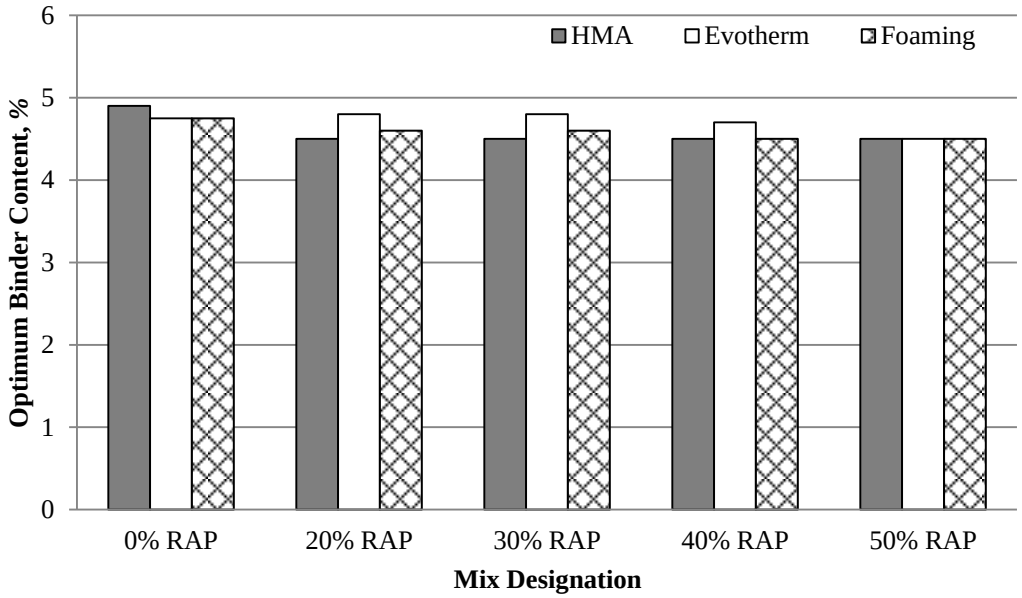
		% RAP	T_{comp}, ^oF	OBC, %	AV, %	VMA, %	VFA, %	D/B Ratio
Binder A PG 64-22	Control	0%	295	4.50	4.0	15.2	73.3	0.78
		20%	300	4.50	3.5	14.1	76.2	0.88
		30%	300	4.50	3.6	14.4	73.4	1.08
	Evotherm	0%	250	4.45	4.0	14.2	72.4	0.75
		20%	275	The OBC determined for the HMA was used for the WMA				
		30%	285					
	Foaming	0%	250	4.25	4.0	14.2	72.0	0.75
		20%	275	The OBC determined for the HMA was used for the WMA				
		30%	285					
Binder B PG 64-22	Control	0%	295	4.25	4.0	15.3	74.0	0.83
		20%	300	4.60	4.0	14.8	77.5	1.10
		30%	300	4.50	3.5	14.0	75.8	1.08
		40%	310	4.70	4.0	15.1	74.8	1.11
		50%	310	4.90	4.0	15.6	76.1	1.12
	Evotherm	0%	250	5.20	4.0	14.0	74.0	0.75
		20%	275	The OBC determined for the HMA was used for the WMA				
		30%	285					
		40%	295					
		50%	300					
	Foaming	0%	250	5.00	4.0	14.9	73.6	0.81
		20%	275	The OBC determined for the HMA was used for the WMA				
		30%	285					
		40%	295					
		50%	300					
Binder B PG 58-28	Control	40%	270	4.70	4.0	15.0	74.0	1.12
		50%	275	4.90	4.0	15.5	75.5	1.12
	Evotherm	40%	250	The OBC determined for the HMA was used for the WMA				
		50%	250					
	Foaming	40%	250	The OBC determined for the HMA was used for the WMA				
		50%	250					

The mixing temperature (T_{mix}) was 10-15^oF higher than the compaction temperature (T_{comp}).

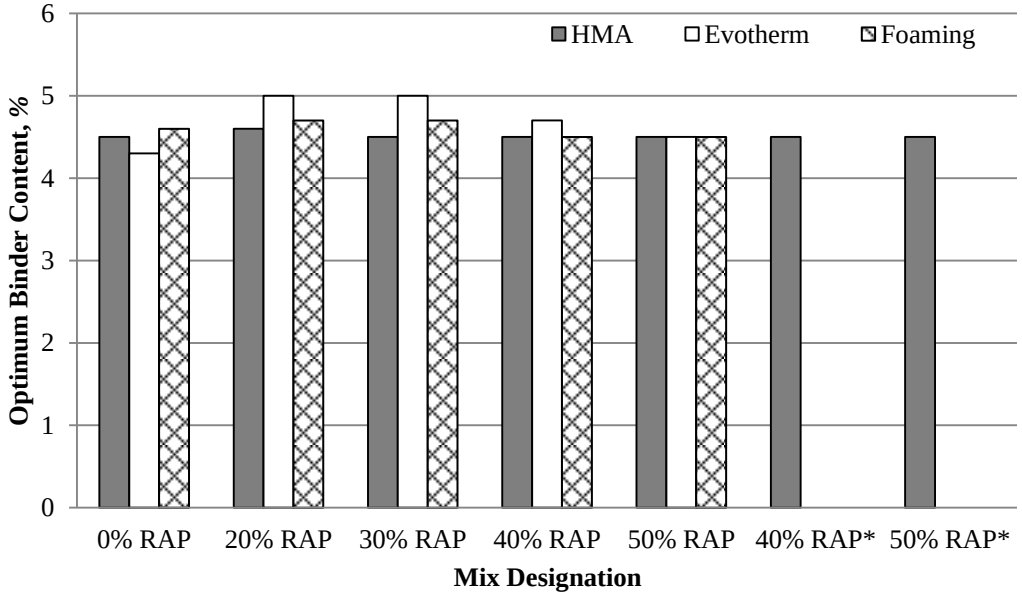
Table 7.4. Optimum binder content (OBC) and volumetrics of HMA and WMA mixtures made with aggregate C and RAP C.

		% RAP	T_{comp}, ^oF	OBC, %	AV, %	VMA, %	VFA, %	D/B Ratio
Binder A PG 64-22	Control	0%	295	4.90	4.0	15.5	74.8	0.92
		20%	300	4.50	3.4	13.4	75.5	0.66
		30%	300	4.50	3.8	13.9	73.0	0.72
		40%	310	4.50	3.6	13.8	73.9	0.79
		50%	310	4.50	3.9	14.0	72.8	0.86
	Evotherm	0%	250	4.75	4.0	14.8	75.1	0.87
		20%	275	4.80	4.0	14.9	72.5	0.62
		30%	285	4.80	4.0	14.7	74.0	0.68
		40%	295	4.70	3.9	14.6	72.0	0.76
		50%	300	4.50	3.9	14.0	72.2	0.86
	Foaming	0%	250	4.75	4.0	14.7	72.6	0.84
		20%	275	4.60	3.9	14.4	72.5	0.66
		30%	285	4.60	4.0	14.2	72.5	0.71
		40%	295	4.50	3.8	14.1	72.5	0.79
		50%	300	4.50	3.8	14.0	72.5	0.86
Binder B PG 64-22	Control	0%	300	4.50	4.0	15.6	73.5	0.90
		20%	300	4.60	4.0	13.8	74.0	0.65
		30%	300	4.50	3.9	14.2	71.0	0.72
		40%	310	4.50	4.0	14.4	70.1	0.79
		50%	310	4.50	4.0	13.8	73.5	0.86
	Evotherm	0%	250	4.30	4.0	14.7	73.5	0.85
		20%	275	5.00	4.2	15.6	74.0	0.59
		30%	285	5.00	4.0	15.1	71.0	0.65
		40%	295	4.70	3.9	14.6	70.1	0.76
		50%	300	4.50	4.0	14.5	73.5	0.86
	Foaming	0%	250	4.60	4.0	13.8	76.4	0.82
		20%	275	4.70	4.0	14.3	72.0	0.63
		30%	285	4.70	3.9	14.5	73.0	0.69
		40%	295	4.50	3.6	13.9	73.5	0.79
		50%	300	4.50	3.9	14.3	72.0	0.86
Binder B PG 58-28	Control	40%	275	4.50	4.0	14.4	72.0	0.79
		50%	285	4.50	3.5	13.8	75.0	0.86
	Evotherm	40%	250	The OBC determined for the HMA was used for the WMA				
		50%	250					
	Foaming	40%	250	The OBC determined for the HMA was used for the WMA				
		50%	250					

The mixing temperature (T_{mix}) was 10-15^oF higher than the compaction temperature (T_{comp}).

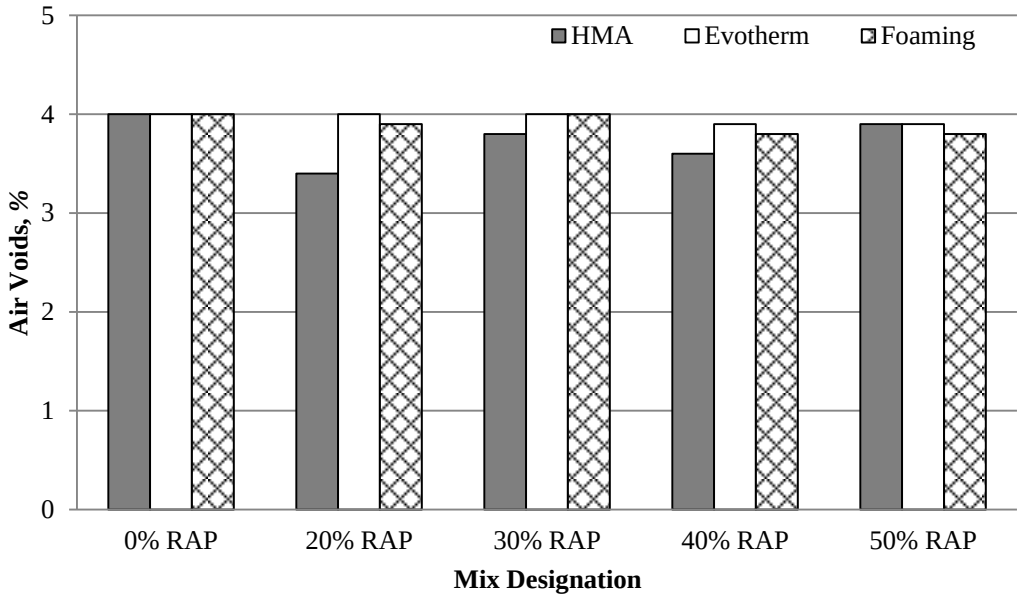


(a)

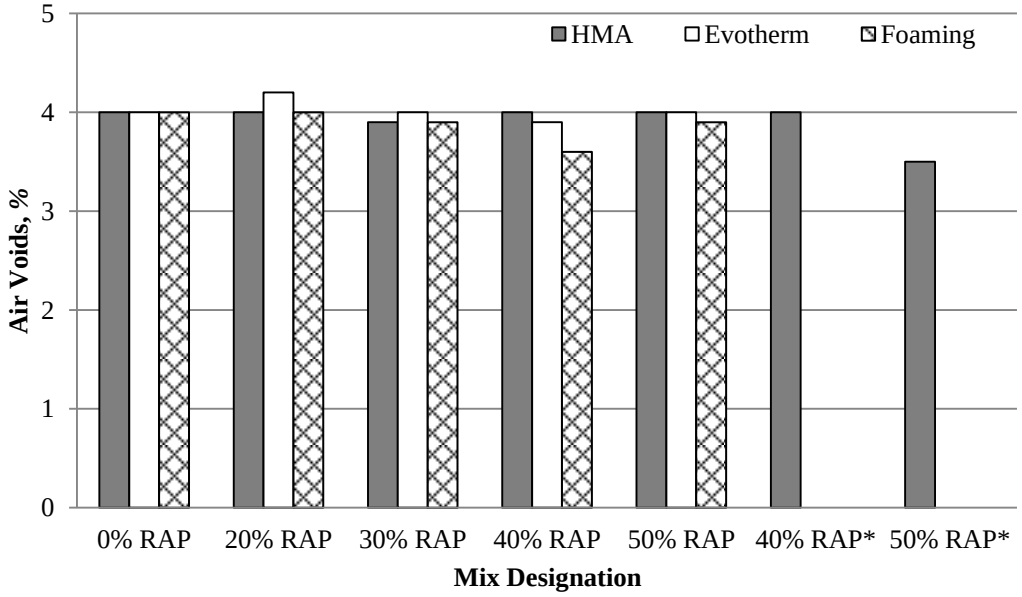


(b)

*Figure 7.18. Optimum binder contents of HMA and WMA mixtures made with Aggregate C and RAP C using binder from (a) source A and (b) source B. * indicates that PG 58-28 binder was used instead of PG 64-22.*

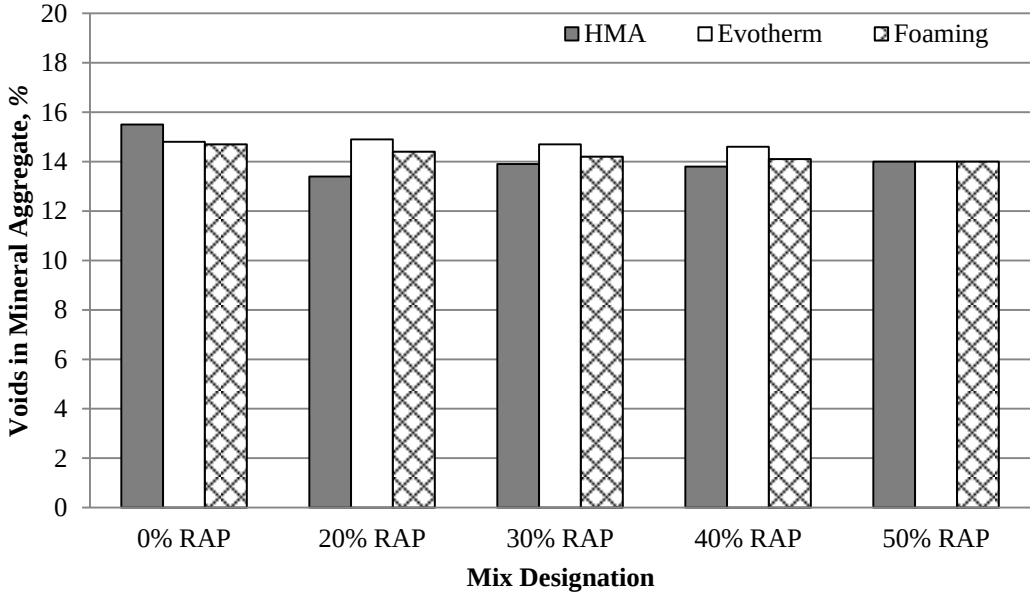


(a)

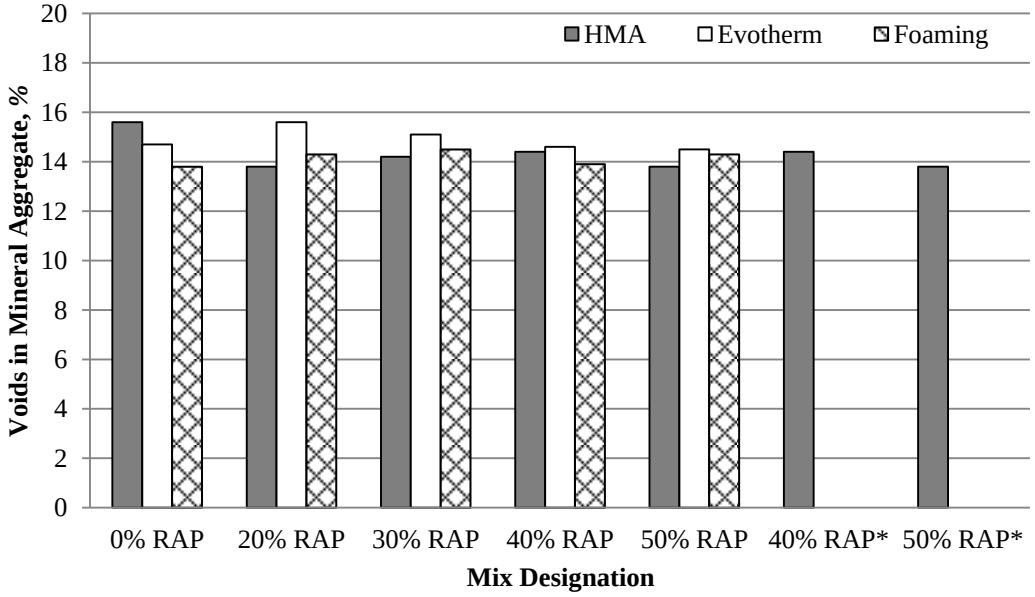


(b)

*Figure 7.19. Air void content of HMA and WMA mixtures at optimum binder content made with Aggregate C and RAP C using binder from (a) source A and (b) source B. * indicates that PG 58-28 binder was used instead of PG 64-22.*

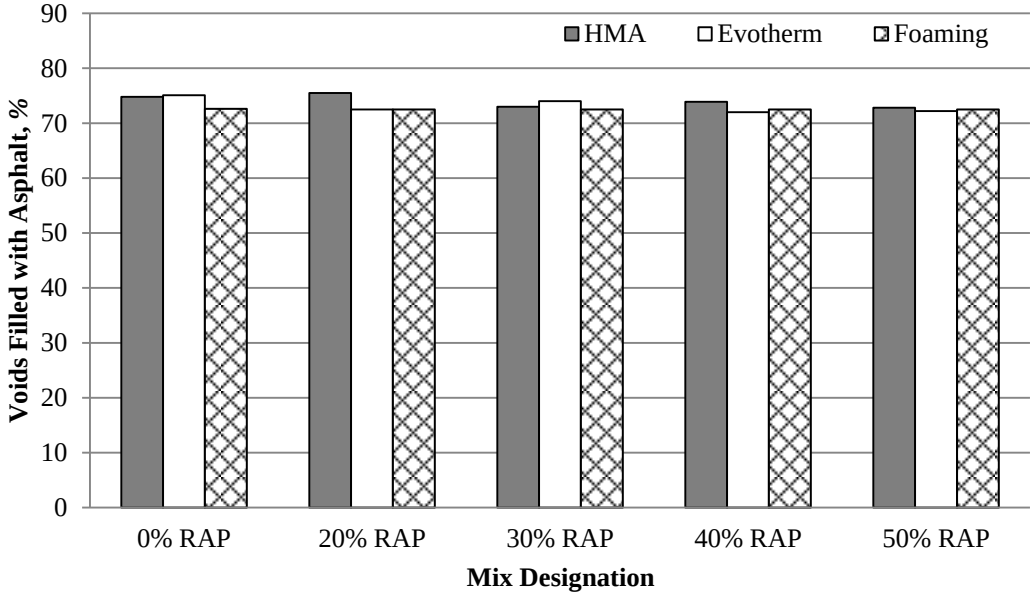


(a)

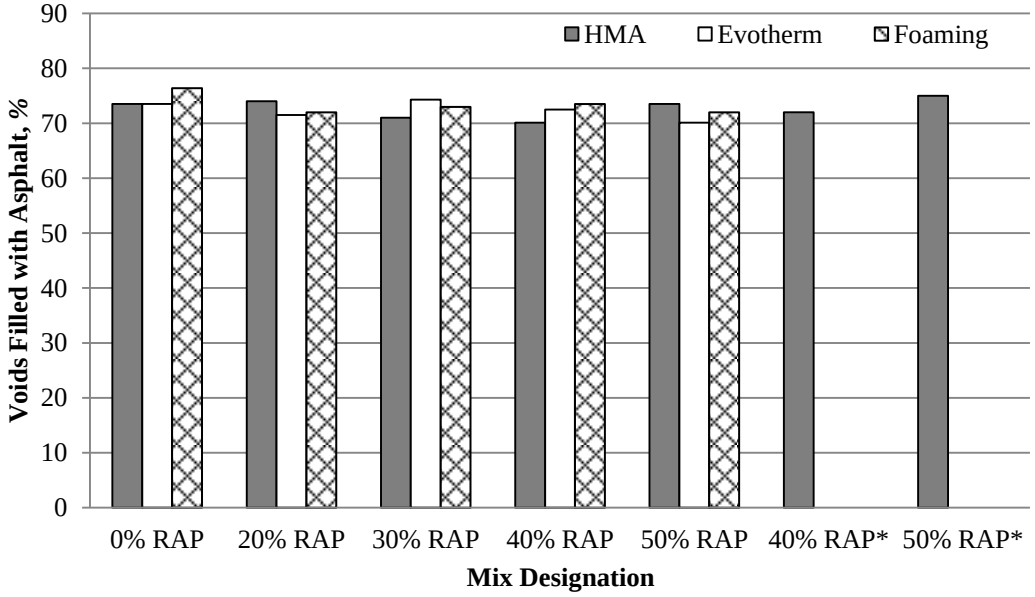


(b)

*Figure 7.20. Voids in mineral aggregate (VMA) of HMA and WMA mixtures at optimum binder content made with Aggregate C and RAP C using binder from (a) source A and (b) source B. * indicates that PG 58-28 binder was used instead of PG 64-22.*



(a)



(b)

*Figure 7.21. Voids filled with asphalt (VFA) of HMA and WMA mixtures at optimum binder content made with Aggregate C and RAP C using binder from (a) source A and (b) source B. * indicates that PG 58-28 binder was used instead of PG 64-22.*

MOISTURE SUSCEPTIBILITY OF WMA MIXTURES CONTAINING RAP

To evaluate the moisture susceptibility of HMA and WMA mixtures containing RAP, the tensile strength ratio (TSR) of each mixture was determined using SC-T-70. Each of the specimens had an air void content of 7 ± 1% and half of the specimens were wet conditioned while the other half were dry conditioned before measuring the indirect tensile strength (ITS) of each specimen. The TSR was then calculated for each mix design.

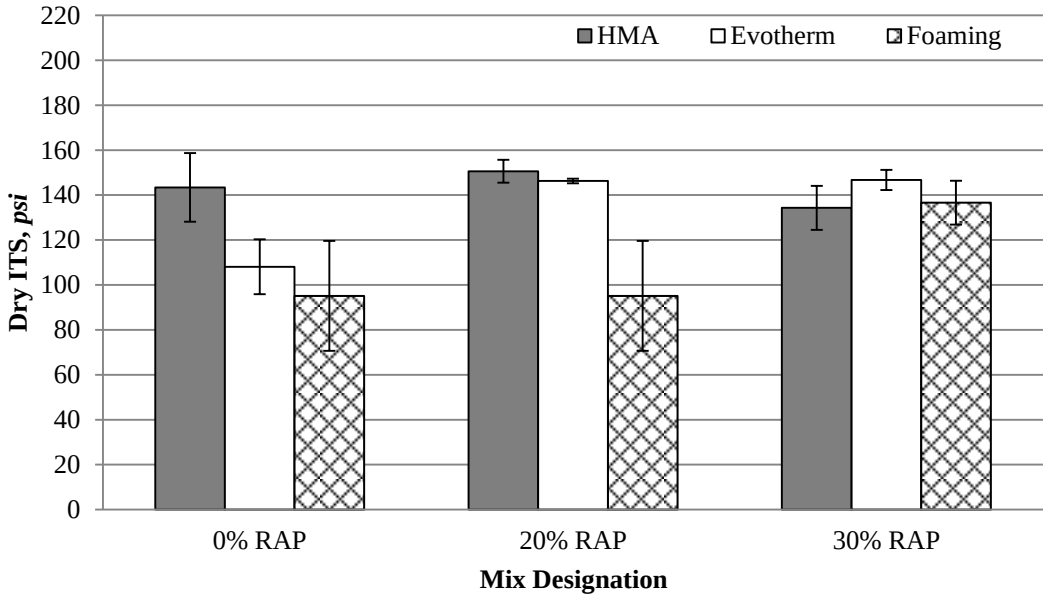
The results for the aggregate B mixtures are summarized in Table 7.5 and Figures 7.22 through 7.25. The results of the moisture susceptibility testing indicate that there was no clear trend to describe effects of WMA technologies on the ITS of the mixtures containing RAP. At 0 and 20% RAP, the foamed WMA mixtures had lower ITS values than the HMA with both binder sources. For the mixtures made with 30, 40, and 50% RAP, the ITS values for the foamed WMA increased to the same level as the HMA or even higher in some cases. The mixtures made with Evotherm™ exhibited similar ITS values (dry and wet) as the HMA mixtures regardless of the RAP content. Finally, only three of the 30 mixtures failed to meet the minimum TSR value of 85%. These three mixtures all contained Evotherm™ and had TSR values of 82%, 83%, and 79%. It should be noted that there was no visible signs of stripping in any of the specimens and the wet ITS values were greater than the minimum value of 65 psi.

The results for the aggregate C mixtures are summarized in Table 7.6 and Figures 7.26 through 7.29. As with the results from the aggregate B mixtures, the foamed WMA mixtures generally had lower ITS (dry and wet) values than the HMA at lower RAP contents for binder A (0 – 20% RAP) and binder B (0 – 30% RAP). Additionally, ITS values of the foamed 50% RAP mixtures were substantially lower than the HMA for the binder B mixes. The mixtures made with Evotherm™, however, generally had similar or higher ITS values when compared to the HMA mixes. As with the aggregate B mixes, all of the wet ITS values were above the minimum value of 65 psi. When considering the TSR values, only two mixtures failed to meet the minimum value of 85% (84% and 78%) and both of these mixtures utilized the foaming WMA technology.

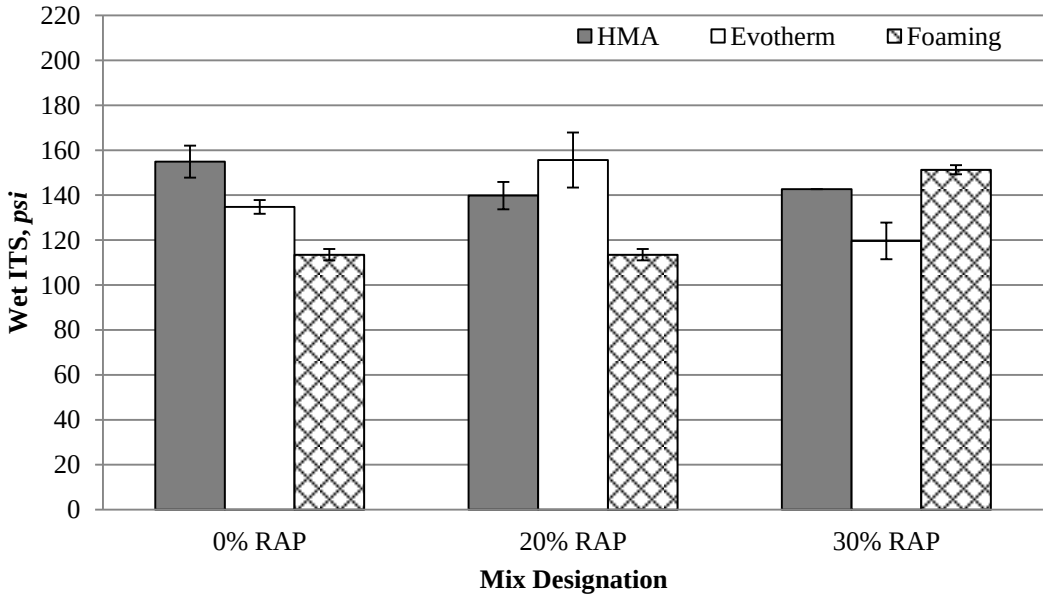
It should also be noted that all of the mixtures contained 1% hydrated lime by weight of aggregate.

Table 7.5. Indirect tensile strength (ITS) and tensile strength ratio (TSR) results of HMA and WMA mixtures made with aggregate B and RAP B.

		% RAP	**Dry ITS, *psi***	**Wet ITS, *psi***	**TSR, *%***
Binder A PG 64-22	Control	0%	143	155	108
		20%	151	140	93
		30%	134	143	106
	Evotherm	0%	108	135	125
		20%	146	156	106
		30%	147	120	82
	Foaming	0%	95	113	119
		20%	95	113	119
		30%	137	151	111
Binder B PG 64-22	Control	0%	146	158	108
		20%	161	143	88
		30%	147	141	95
		40%	153	148	97
		50%	183	184	101
	Evotherm	0%	117	92	79
		20%	170	141	83
		30%	145	141	97
		40%	148	139	94
		50%	183	181	99
	Foaming	0%	108	103	95
		20%	110	143	130
		30%	159	143	90
		40%	173	179	103
		50%	190	184	97
Binder B PG 58-28	Control	40%	115	108	94
		50%	140	147	105
	Evotherm	40%	139	147	106
		50%	157	138	88
	Foaming	40%	129	138	107
		50%	145	170	117



(a)



(b)

Figure 7.22. Indirect tensile strength (ITS) of HMA and WMA mixtures made with Aggregate B and RAP B using binder from source A tested at (a) dry conditioning and (b) wet conditioning.

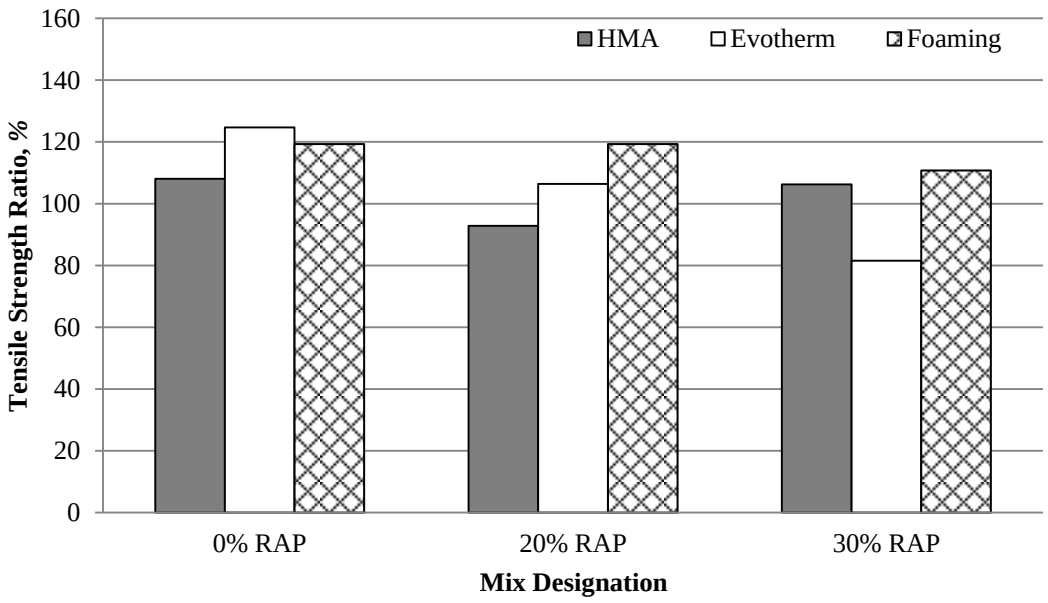
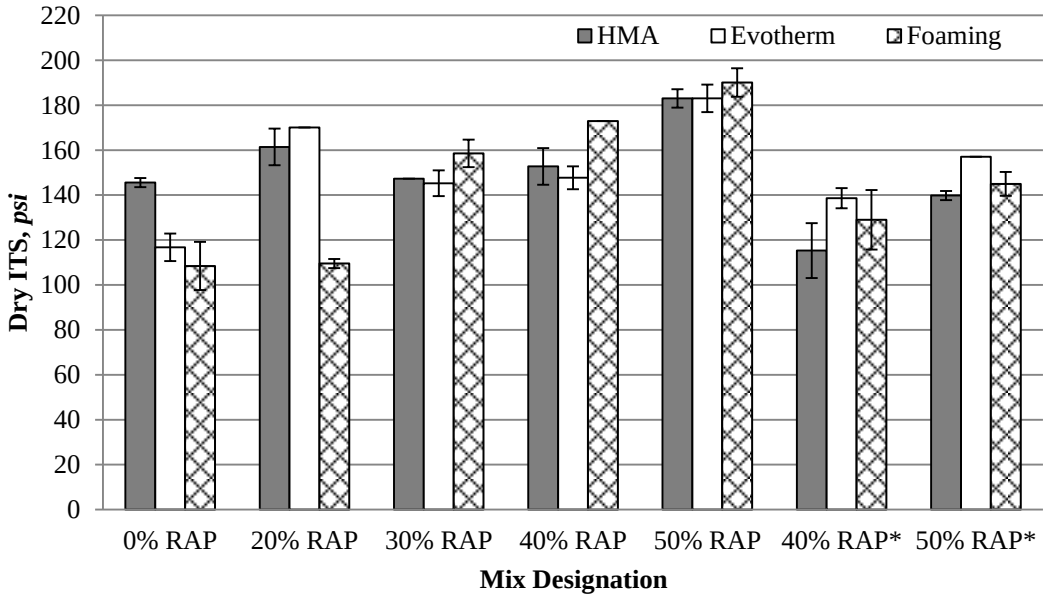
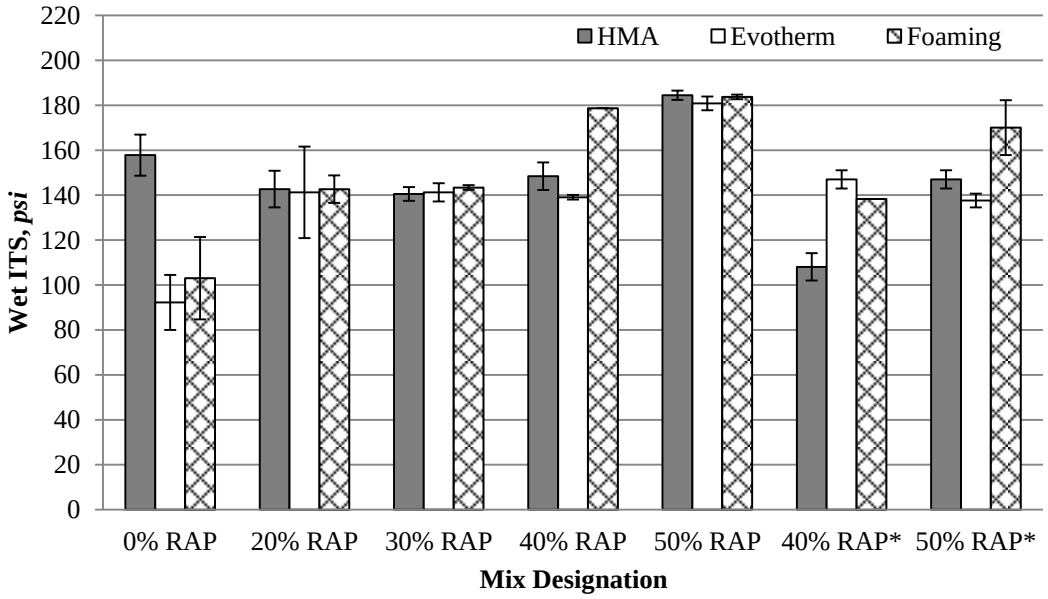


Figure 7.23. Tensile strength ratio (TSR) of HMA and WMA mixtures made with Aggregate B and RAP B using binder from source A.



(a)



(b)

*Figure 7.24. Indirect tensile strength (ITS) of HMA and WMA mixtures made with Aggregate B and RAP B using binder from source B tested at (a) dry conditioning and (b) wet conditioning. * indicates that PG 58-28 binder was used instead of PG 64-22.*

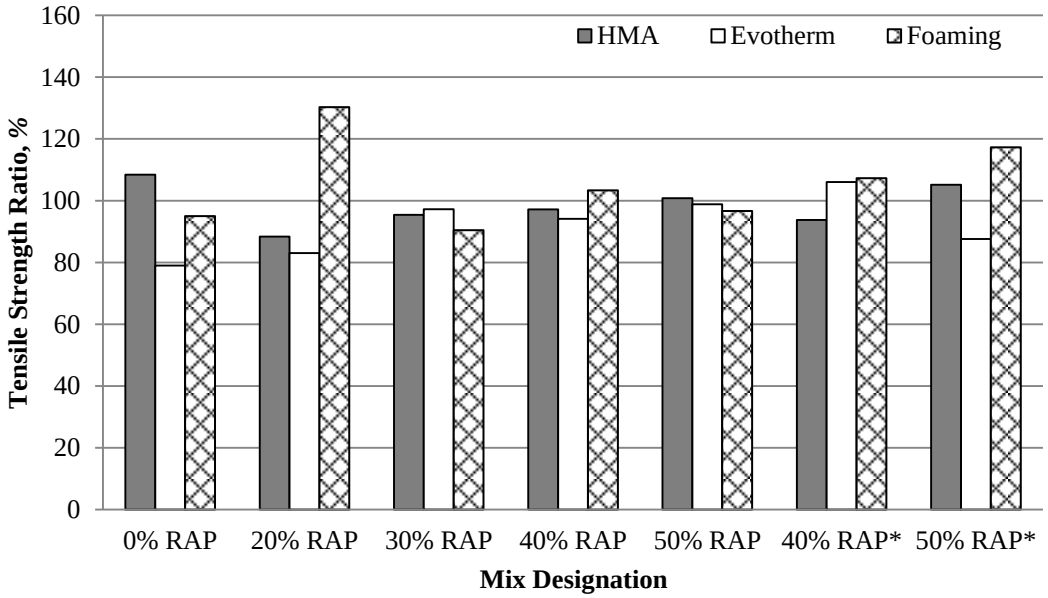
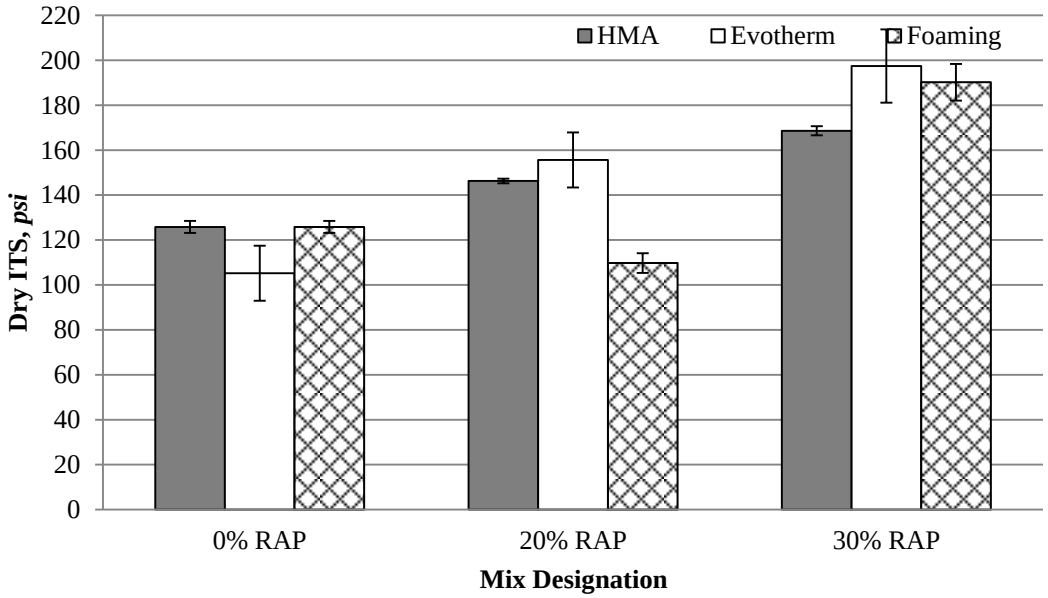


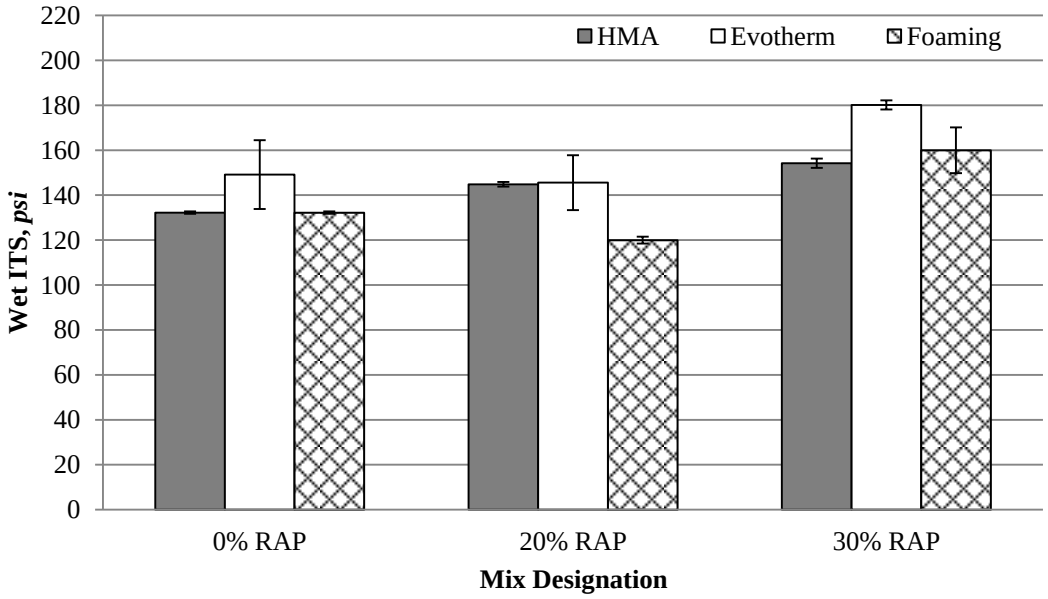
*Figure 7.25. Tensile strength ratio (TSR) of HMA and WMA mixtures made with Aggregate B and RAP B using binder from source B. * indicates that PG 58-28 binder was used instead of PG 64-22.*

Table 7.6. Indirect tensile strength (ITS) and tensile strength ratio (TSR) results of HMA and WMA mixtures made with aggregate C and RAP C.

		% RAP	**Dry ITS, *psi***	**Wet ITS, *psi***	**TSR, *%***
Binder A PG 64-22	Control	0%	126	132	105
		20%	146	145	99
		30%	169	154	91
	Evotherm	0%	105	149	142
		20%	156	146	94
		30%	197	180	91
	Foaming	0%	126	132	105
		20%	110	120	109
		30%	190	160	84
Binder B PG 64-22	Control	0%	130	179	138
		20%	170	148	87
		30%	202	205	101
		40%	150	148	98
		50%	153	185	121
	Evotherm	0%	120	125	104
		20%	141	156	111
		30%	204	180	88
		40%	171	185	108
		50%	164	170	104
	Foaming	0%	120	110	92
		20%	120	110	92
		30%	108	103	95
		40%	174	181	104
		50%	108	103	95
Binder B PG 58-28	Control	40%	118	106	90
		50%	149	147	99
	Evotherm	40%	142	141	99
		50%	163	152	93
	Foaming	40%	136	140	103
		50%	151	118	78



(a)



(b)

Figure 7.26. Indirect tensile strength (ITS) of HMA and WMA mixtures made with Aggregate C and RAP C using binder from source A tested at (a) dry conditioning and (b) wet conditioning.

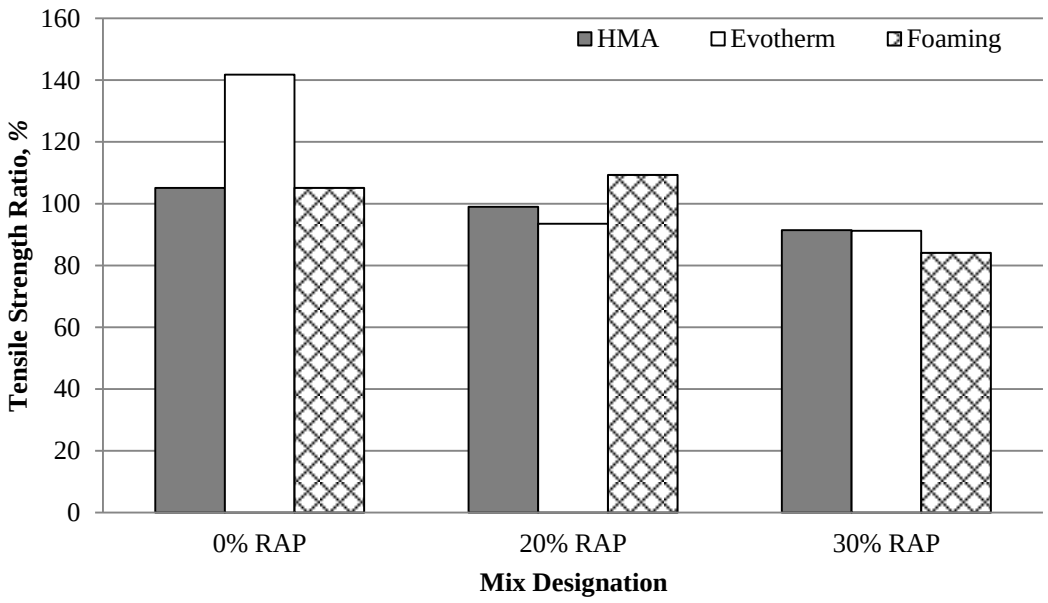
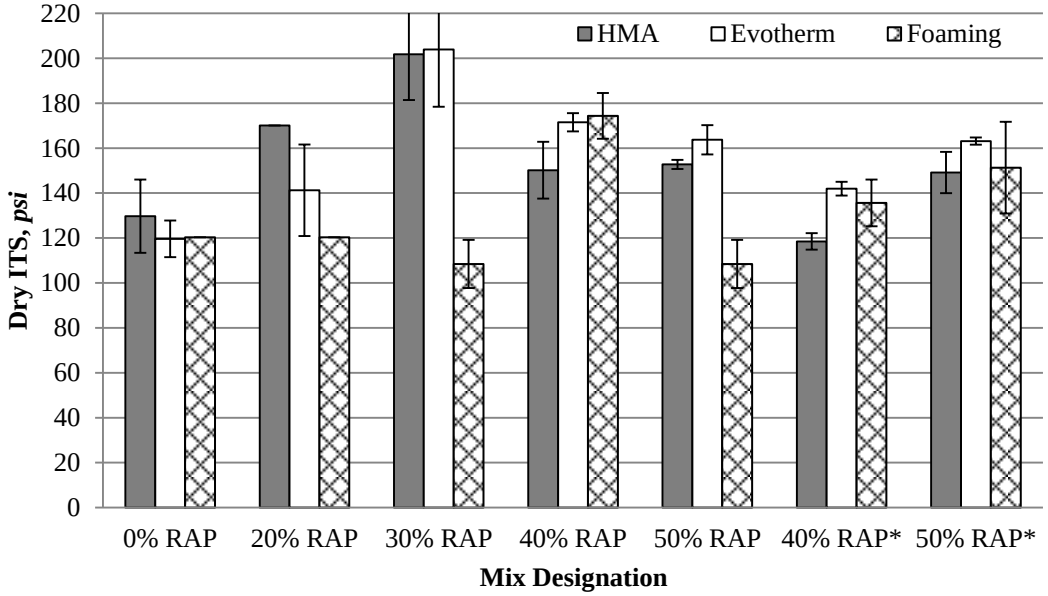
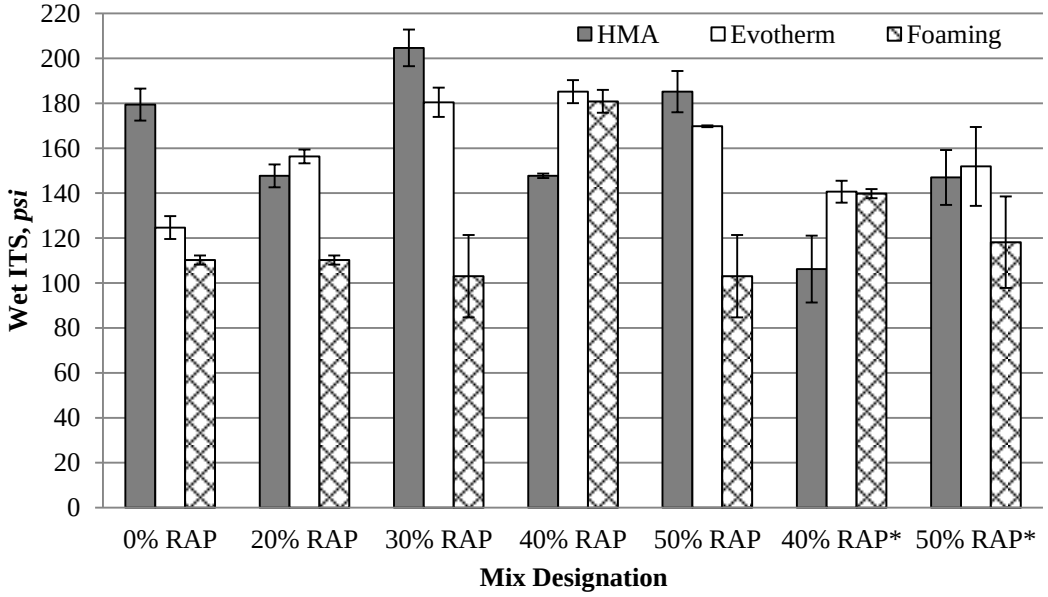


Figure 7.27. Tensile strength ratio (TSR) of HMA and WMA mixtures made with Aggregate C and RAP C using binder from source A.



(a)



(b)

*Figure 7.28. Indirect tensile strength (ITS) of HMA and WMA mixtures made with Aggregate C and RAP C using binder from source B tested at (a) dry conditioning and (b) wet conditioning. * indicates that PG 58-28 binder was used instead of PG 64-22.*

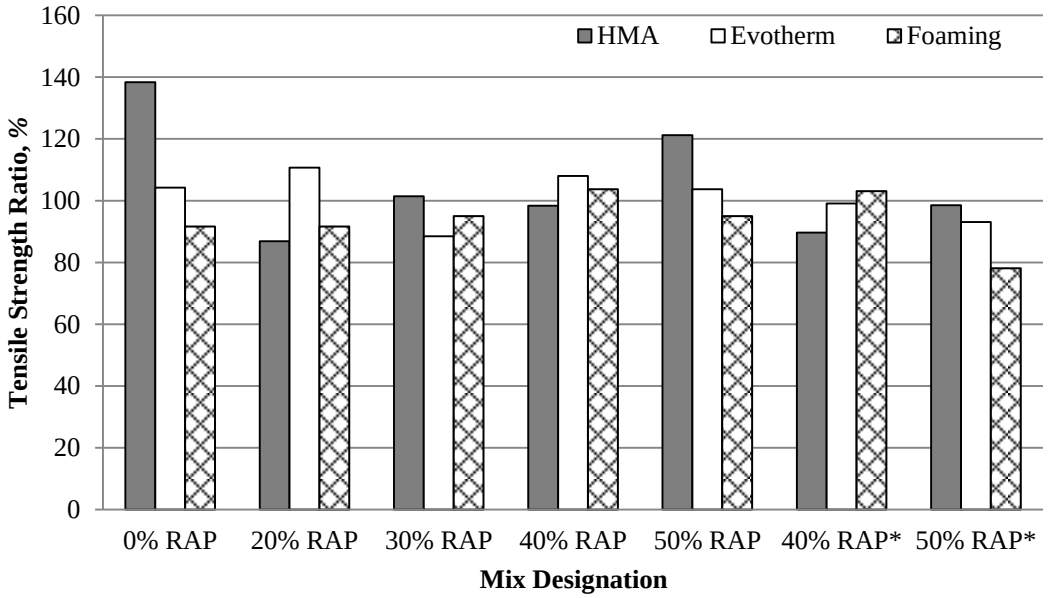


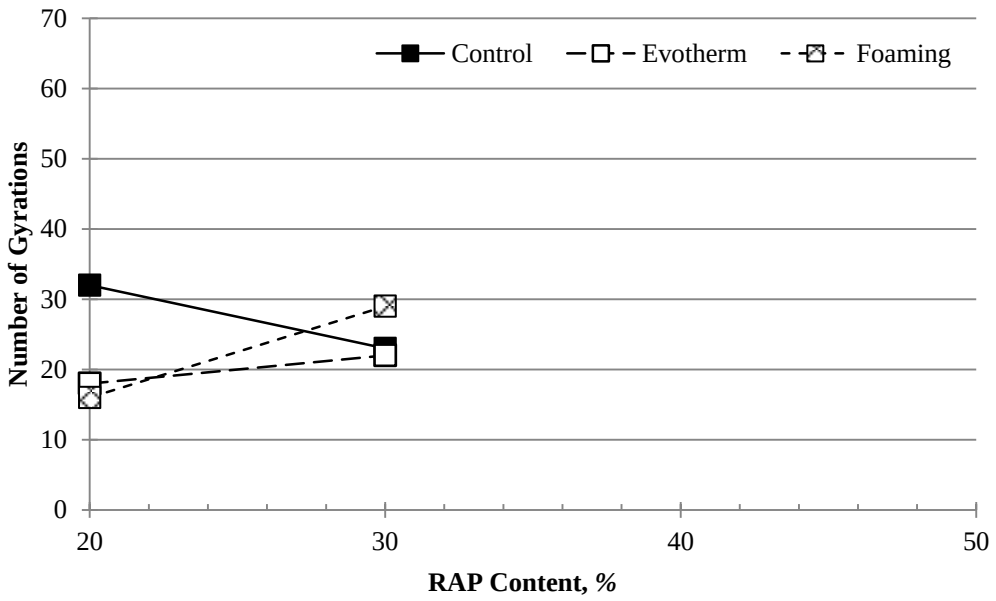
*Figure 7.29. Tensile strength ratio (TSR) of HMA and WMA mixtures made with Aggregate C and RAP C using binder from source B. * indicates that PG 58-28 binder was used instead of PG 64-22.*

EFFECTS OF WMA TECHNOLOGY ON COMPACTIBILITY OF MIXTURES CONTAINING RAP

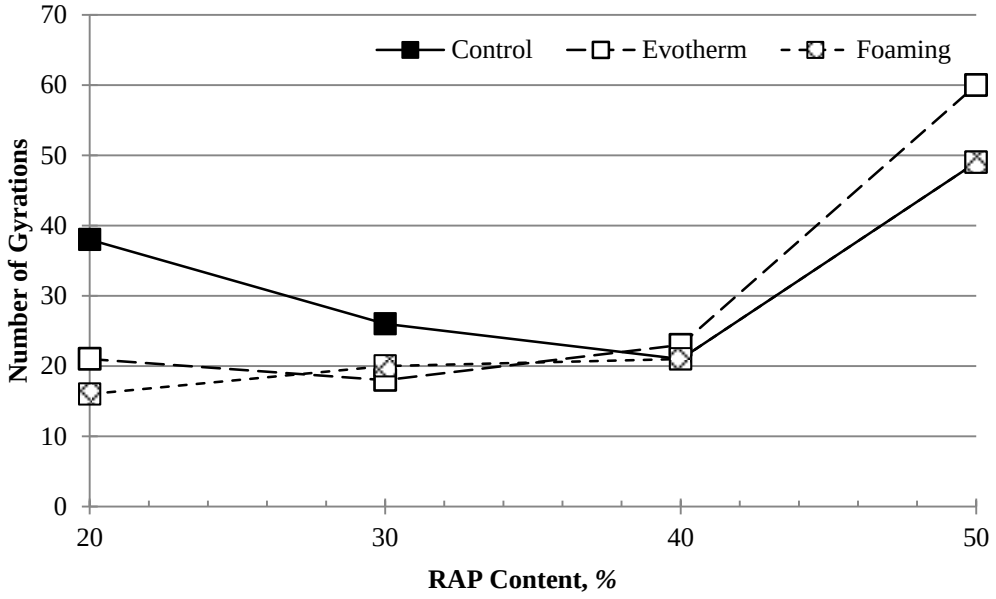
When compacting the specimens used for the ITS testing, the number of gyrations of the gyratory compactor were recorded to compare the relative compactibility of the different mixtures. Each of the specimens was prepared at the respective OBC, had identical aggregate gradations within each RAP and binder content, was compacted to a height of 95 mm, and an air void content of 7 ± 1%.

Based on the results summarized in Figures 7.30 and 7.31, the compactibility is RAP dependent as the stiffness of the RAP binder plays a major role in the overall viscosity of the mixture. For the mixes made with RAP B (Figure 7.30), the compactibility of the HMA appears to improve as the RAP content increases to 40%, then the stiffness of the binder of the 50% RAP mix results in a sharp reduction in the compactibility of the mix. When the WMA technologies were used for the RAP B mixes, the initial compactibility was greater at lower RAP contents, but then became similar to the HMA at RAP contents of 40 and 50%.

The compactibility results of the RAP C mixtures are summarized in Figure 7.31 and indicate that the RAP from source C did not have as significant an impact on the required compaction effort as the RAP from source B did. There was a slight increase in the required number of gyrations when the RAP content increased from 20 to 30% (potentially due the increase in binder stiffness due to the RAP), but then gradually decreased and stabilized as the RAP content increased. The WMA technologies did not have a significant effect on mixture compactibiliy for RAP C.

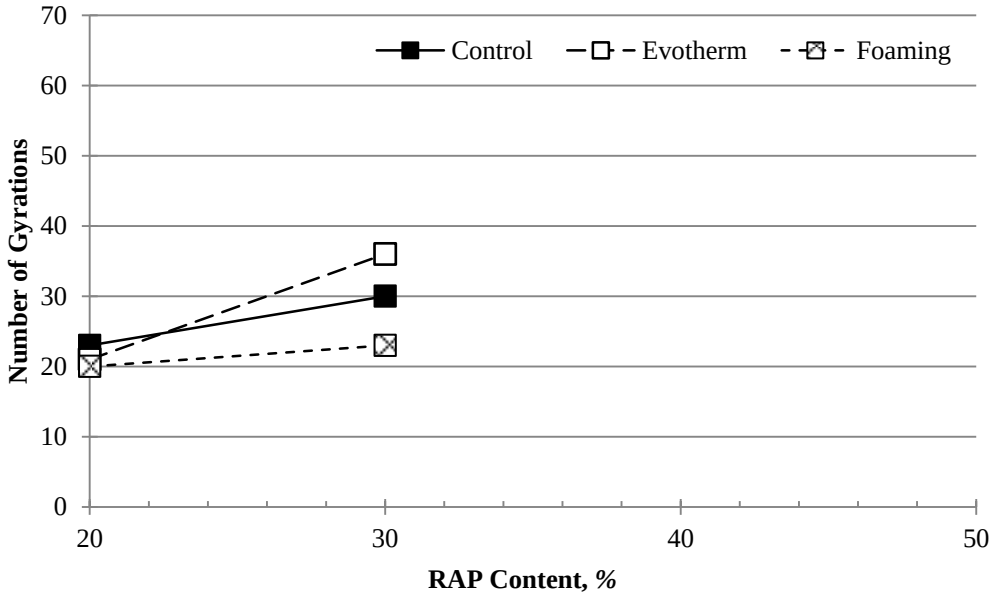


(a)



(b)

Figure 7.30. Relative compactability based on the number of gyrations required to compact the 95mm tall specimens used for ITS testing of HMA and WMA mixtures made with aggregate B and RAP B using binder from (a) source A and (b) source B at optimum binder content.



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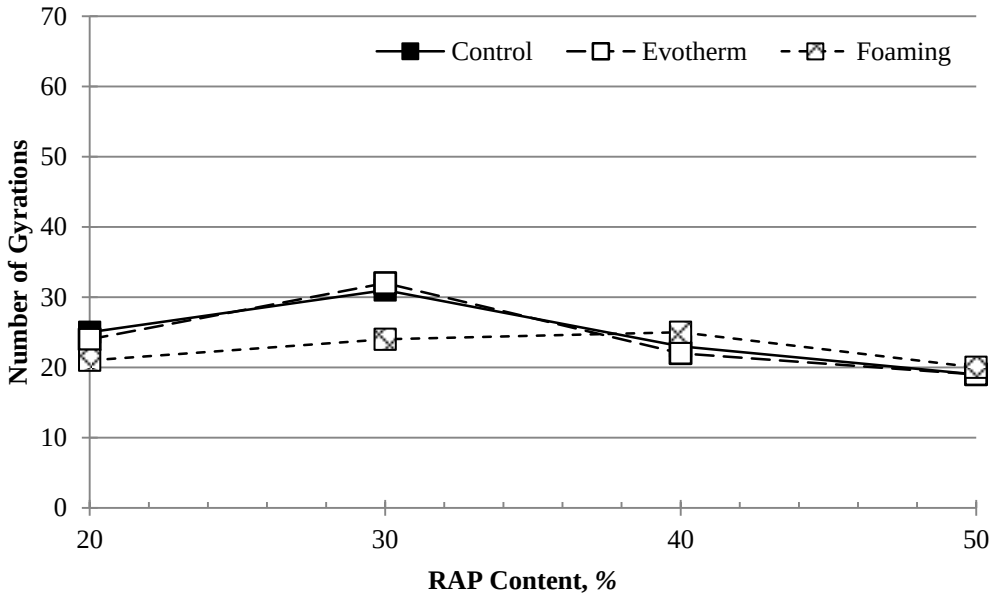


(b)

Figure 7.31. Relative compactability based on the number of gyrations required to compact the 95mm tall specimens used for ITS testing of HMA and WMA mixtures made with aggregate C and RAP C using binder from (a) source A and (b) source B at optimum binder content.

PERFORMANCE CHARACTERISTICS OF WMA MIXTURES CONTAINING RAP

Three performance characteristics of the WMA/RAP mixtures were evaluated in the laboratory phase of the research: Rutting susceptibility (AASHTO T340), resilient modulus (ASTM D4123), and fatigue life (AASHTO T321). All of these properties are critical to ensuring long lasting, functional asphalt pavements. The overall results of the performance evaluation are summarized in Tables 7.7 and 7.8. Additionally, the results are graphically summarized in Figures 7.32 through 7.37.

The results of the rutting resistance in Figures 7.32 and 7.33 indicate that the WMA mixtures follow a similar trend as the HMA—as the RAP content increases, so does the rutting resistance. When comparing the magnitude of the rut depth, the results are dependent on the aggregate source. For the mixtures made with aggregate B, the foamed WMA mixtures had rut depths that were generally similar to the HMA mixes for the same RAP content while the Evotherm™ mixture did not display a consistent trend. In some cases, the Evotherm™ mixes exhibited lower rut depths than the HMA and foamed mixes. In other cases, the values were greater

When considering the rutting results of the mixtures made with aggregate C, Figure 7.33 shows that the WMA mixes generally had higher rut depths than the HMA mixtures at lower RAP contents (0-20%), but as the RAP content increased, the rut resistance of the WMA mixes was equal to or greater than the HMA mixes.

The results of the resilient modulus testing illustrated in Figures 7.34 and 7.35 show that the WMA mixtures generally follow the same trend as the HMA mixtures with regard to RAP content—as the RAP content increases, the resilient modulus also increases. This trend is expected because the addition of greater amounts of stiffer RAP binder should increase the stiffness of the mixture as quantified by the resilient modulus. As with the rutting results, the substitution of PG 58-28 virgin binder reduced the stiffness of the mixtures compared to the mixes made with PG 64-22 virgin binder. In most cases, the WMA mixtures had resilient moduli that were less than or similar to the HMA mixtures for a given RAP content. However, there were some cases were the WMA mixtures were stiffer. For the aggregate B mixtures, the foamed WMA mixtures at higher RAP contents (with PG 64-22 binder) had greater resilient modulus values than the HMA mixes. For the aggregate C mixtures, the Evotherm™ WMA mixes had higher resilient modulus values compared to the HMA at the lower RAP contents (0-20% RAP).

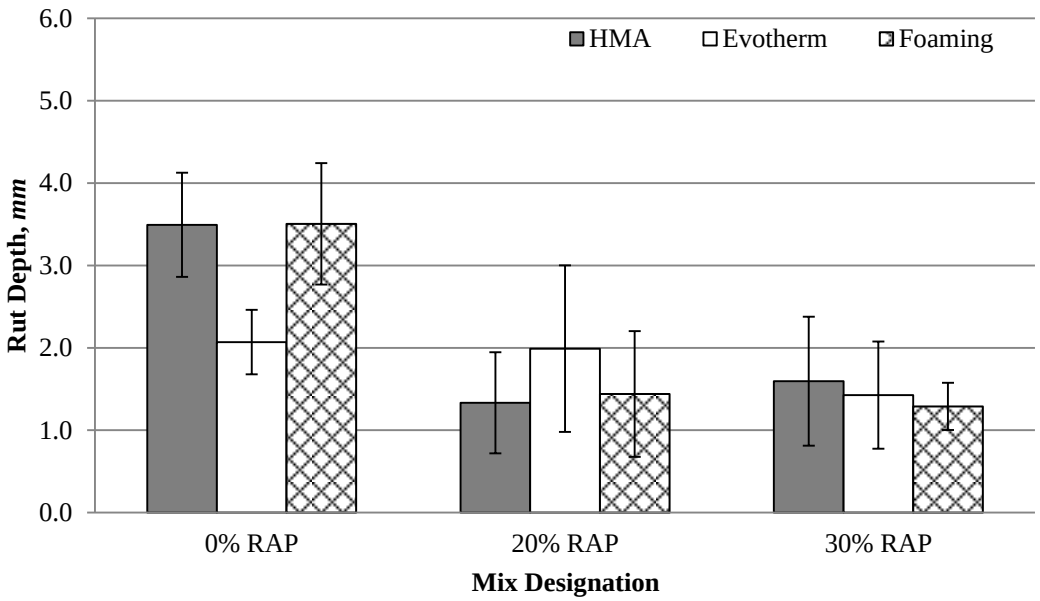
The results of the fatigue testing are illustrated in Figures 7.36 and 7.37. It needs to be stated that the values of this test were highly variable and in many cases contradictory to results reported in the literature. Because of this, the influence of WMA technology on fatigue resistance cannot be quantified in this study. In most cases, the increase in RAP content did not have a significant effect on the fatigue life of the mixtures. However, these values are also suspect.

Table 7.7. Rutting and resilient modulus results of HMA and WMA mixtures made with aggregate B and RAP B.

		% RAP	Rut Depth, *mm*	Resilient Modulus, *ksi*
Binder A PG 64-22	Control	0%	3.5	1491
		20%	1.3	2274
		30%	1.6	2520
	Evotherm	0%	2.1	1705
		20%	2.0	2100
		30%	1.4	2293
	Foaming	0%	3.5	1936
		20%	1.4	1880
		30%	1.3	3094
Binder B PG 64-22	Control	0%	2.9	2076
		20%	1.2	2189
		30%	1.3	2465
		40%	1.0	2614
		50%	0.9	3163
	Evotherm	0%	2.7	1481
		20%	1.1	1698
		30%	2.0	2266
		40%	1.9	2533
		50%	1.2	2192
	Foaming	0%	2.7	3095
		20%	2.3	1912
		30%	1.5	2106
		40%	0.9	3953
		50%	1.0	3851
Binder B PG 58-28	Control	40%	2.0	1607
		50%	1.6	2612
	Evotherm	40%	3.7	2131
		50%	1.4	2252
	Foaming	40%	1.4	1705
		50%	1.2	2429

Table 7.8. Rutting and resilient modulus results of HMA and WMA mixtures made with aggregate C and RAP C.

		% RAP	Rut Depth, *mm*	Resilient Modulus, *ksi*
Binder A PG 64-22	Control	0%	3.4	1556
		20%	2.2	1917
		30%	1.6	2137
	Evotherm	0%	4.9	1859
		20%	3.2	2079
		30%	1.4	2066
	Foaming	0%	4.8	1089
		20%	3.5	1447
		30%	2.2	1892
Binder B PG 64-22	Control	0%	3.1	1511
		20%	2.1	1214
		30%	1.7	1614
		40%	1.6	2457
		50%	2.5	2184
	Evotherm	0%	4.4	2049
		20%	2.7	2475
		30%	1.3	1978
		40%	2.2	2393
		50%	1.5	2542
	Foaming	0%	4.2	
		20%	3.5	1548
		30%	1.9	1367
		40%	1.0	2242
		50%	1.5	2554
Binder B PG 58-28	Control	40%	2.2	1656
		50%	2.1	1407
	Evotherm	40%	2.3	1017
		50%	1.3	1943
	Foaming	40%	3.0	1171
		50%	2.1	1536



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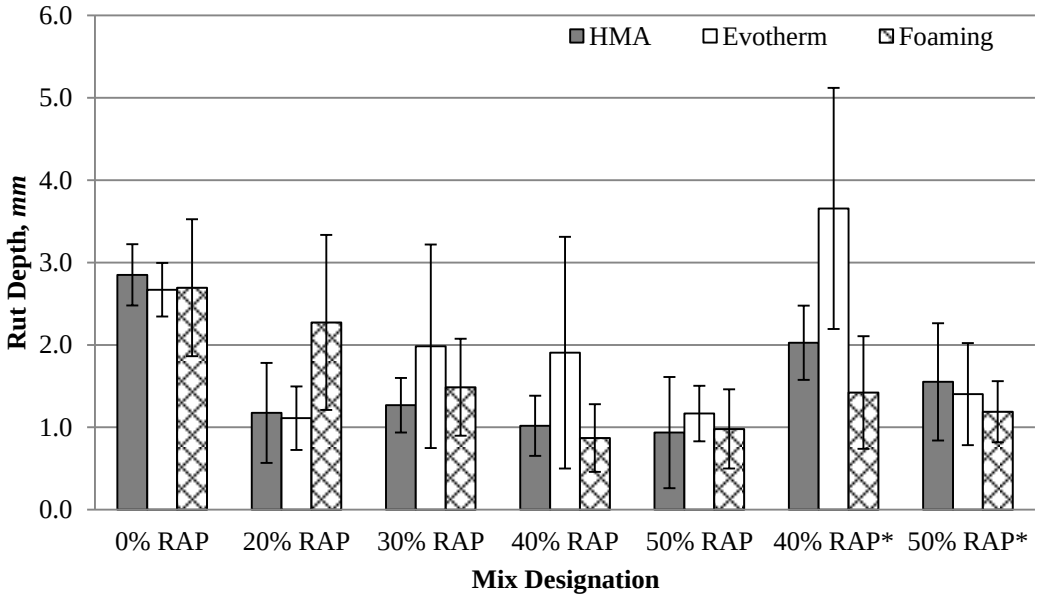
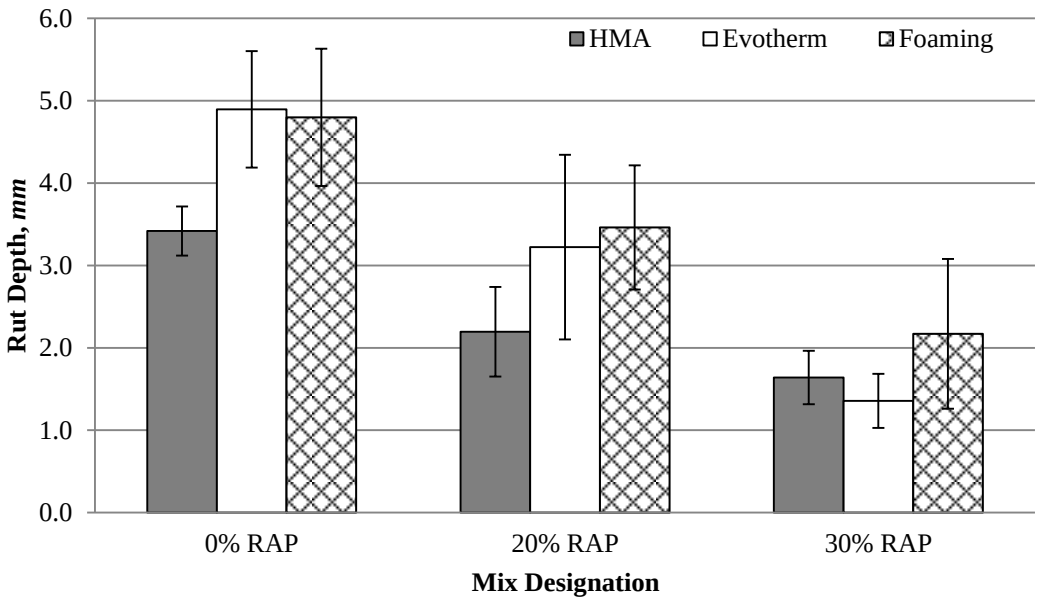


(b)

*Figure 7.32. Rut depth (tested at 64^{o}C) of HMA and WMA mixtures made with aggregate B and RAP B using binder from (a) source A and (b) source B. * indicates that PG 58-28 binder was used instead of PG 64-22.*



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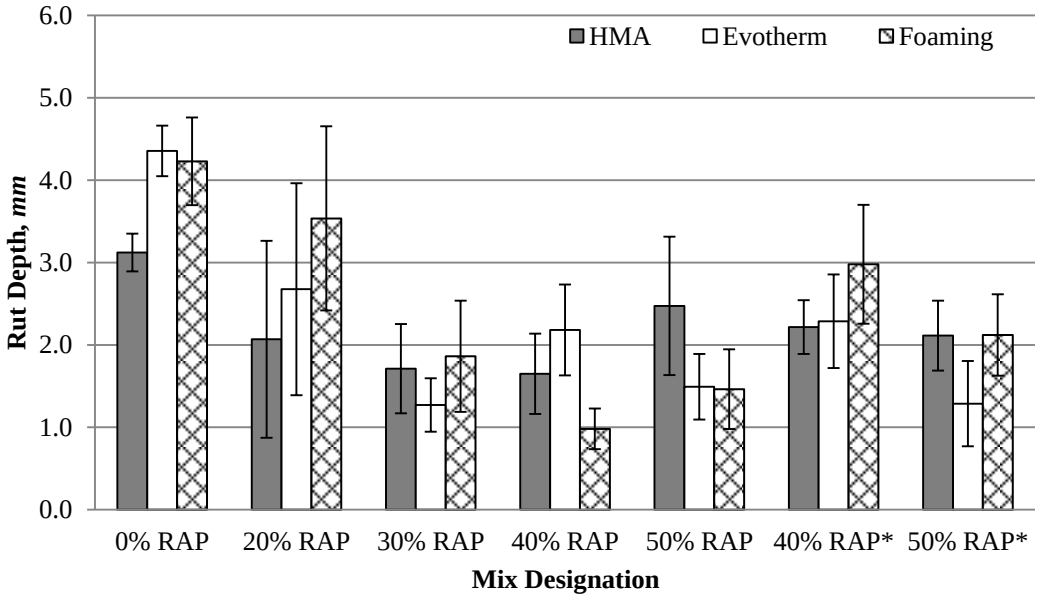
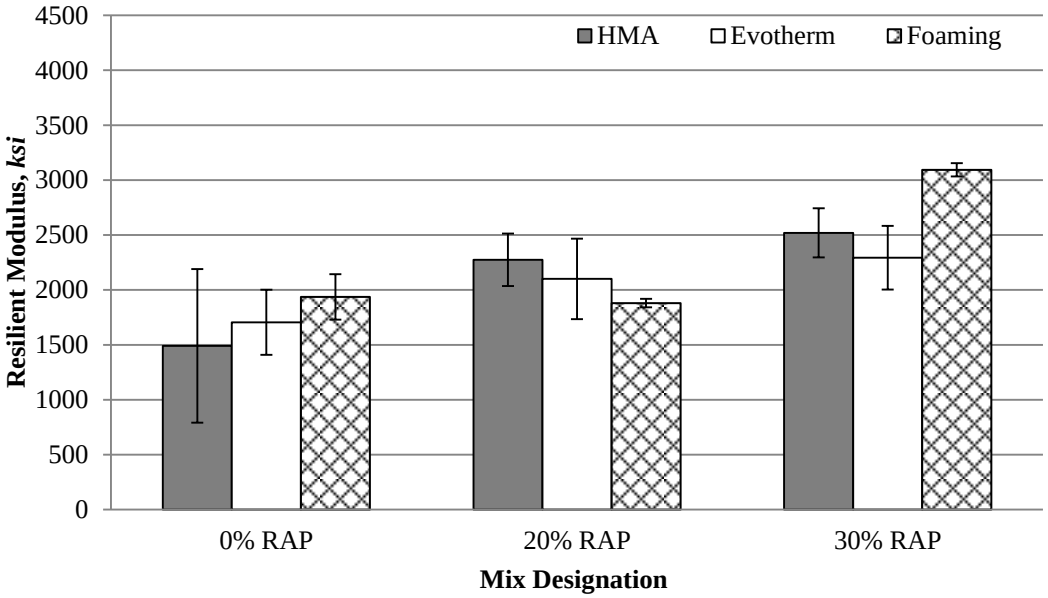


(b)

*Figure 7.33. Rut depth (tested at 64°C of HMA and WMA mixtures made with aggregate C and RAP C using binder from (a) source A and (b) source B. * indicates that PG 58-28 binder was used instead of PG 64-22.*



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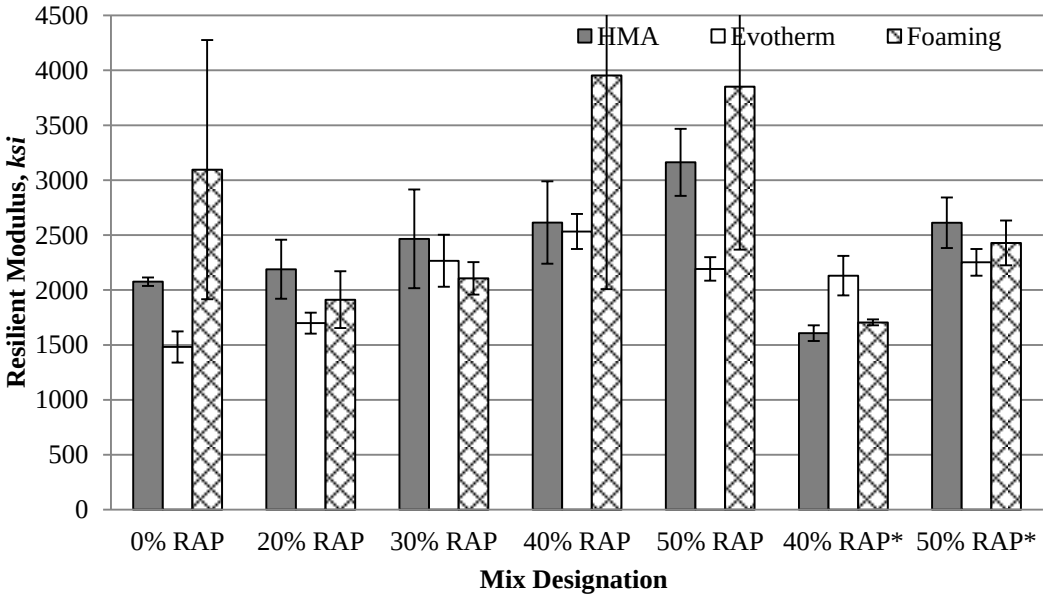
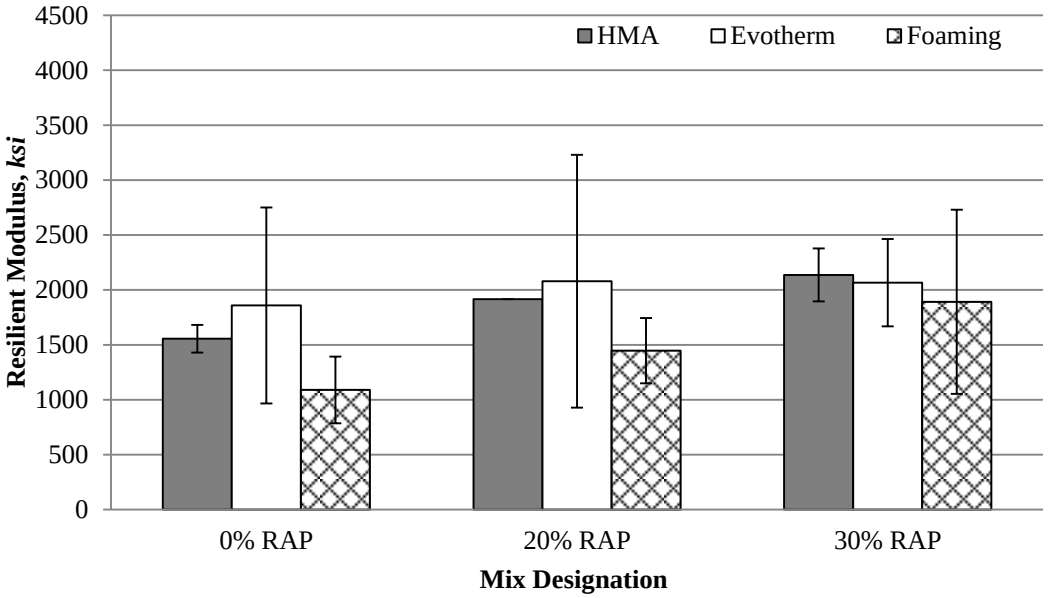


(b)

*Figure 7.34. Resilient modulus (tested at 25°C) of HMA and WMA mixtures made with aggregate B and RAP B using binder from (a) source A and (b) source B. * indicates that PG 58-28 binder was used instead of PG 64-22.*



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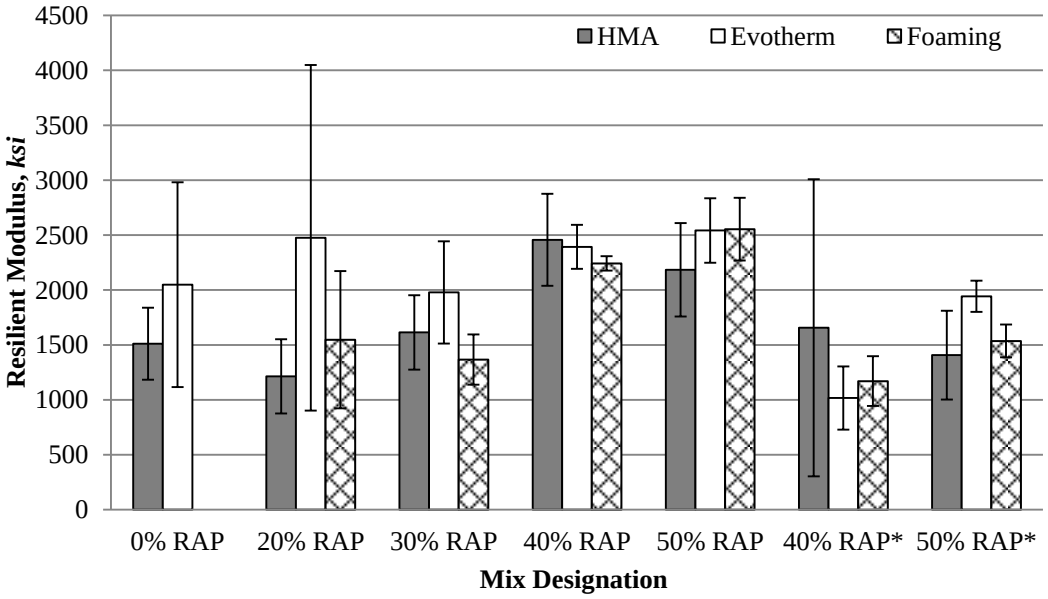
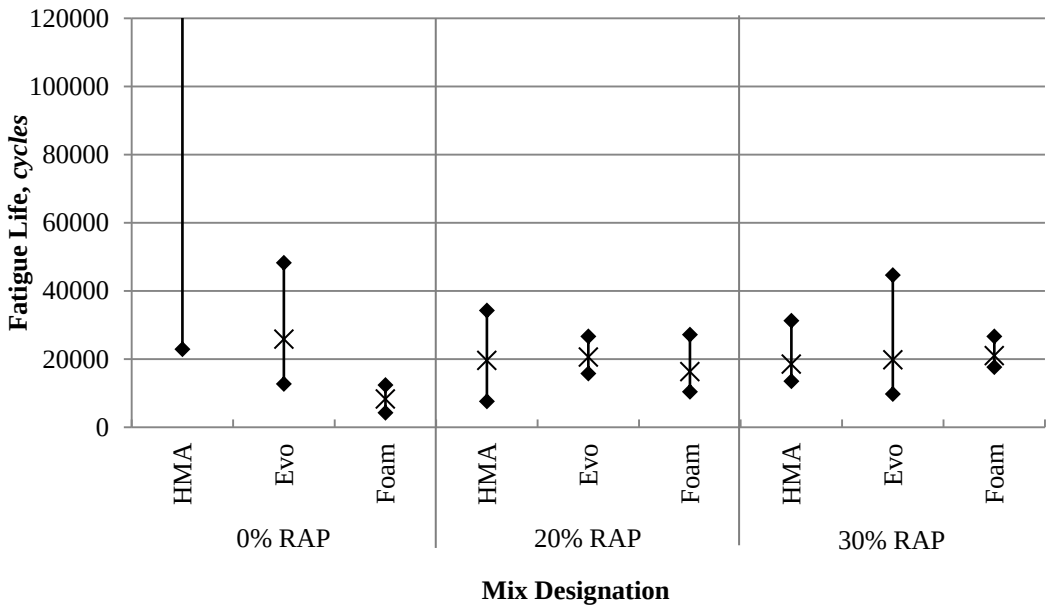


(b)

*Figure 7.35. Resilient modulus (tested at 25^{o}C) of HMA and WMA mixtures made with aggregate C and RAP C using binder from (a) source A and (b) source B. * indicates that PG 58-28 binder was used instead of PG 64-22.*



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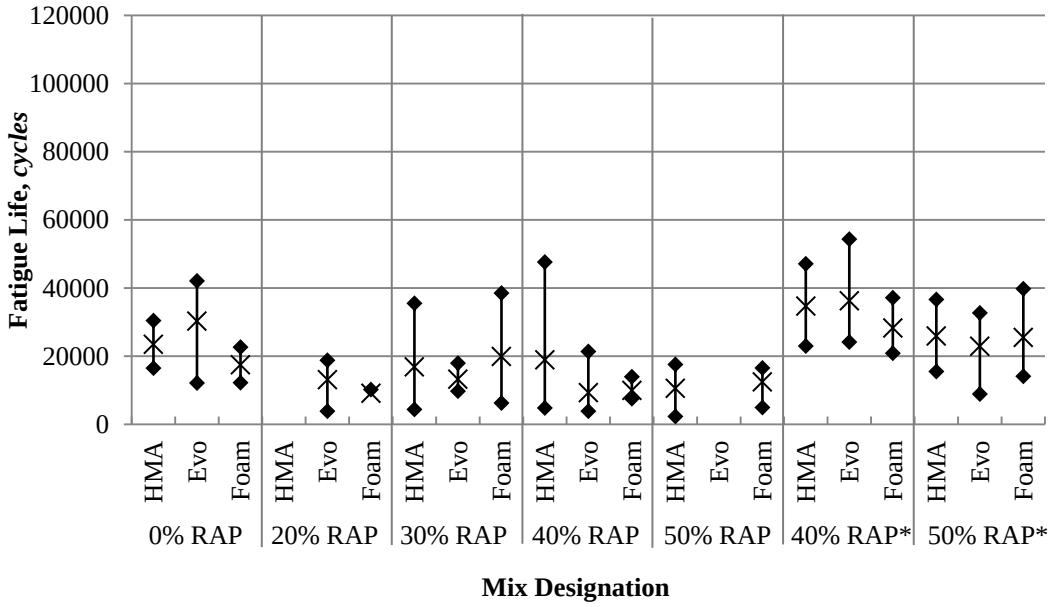
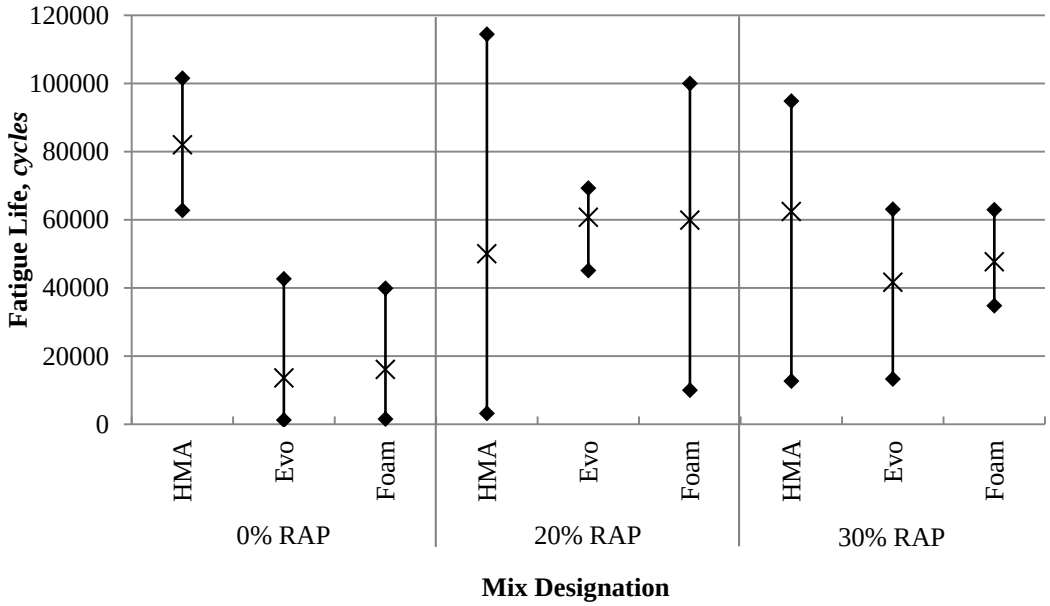


(b)

*Figure 7.36. Fatigue life (tested at 20°C) of HMA and WMA mixtures made with aggregate B and RAP B using binder from (a) source A and (b) source B. Each "×" on the figure represents an average value and the diamonds above and below represent the high and low value measured. * indicates that PG 58-28 binder was used instead of PG 64-22.*



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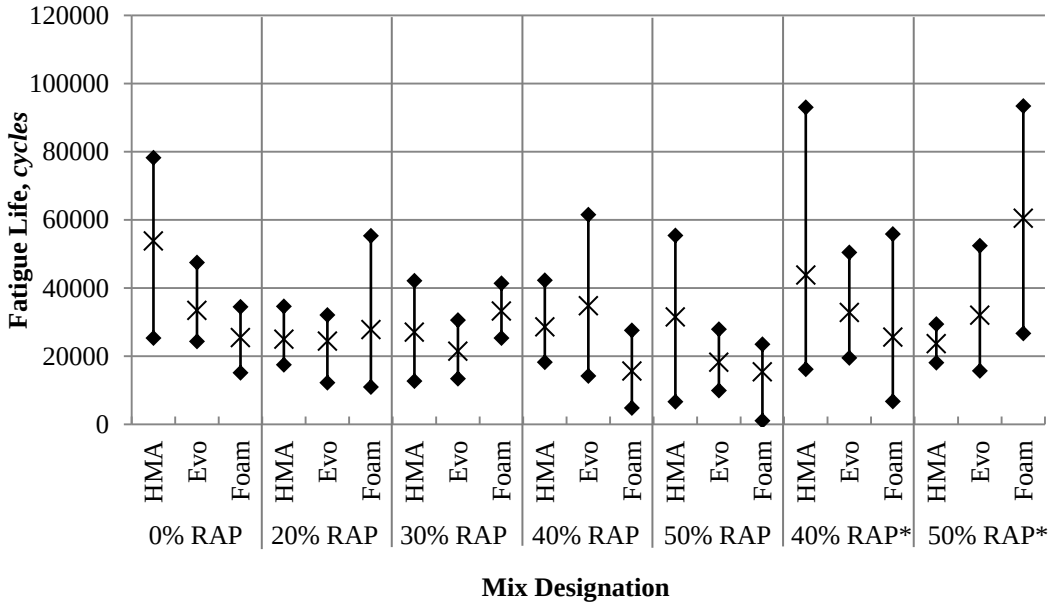


(b)

*Figure 7.37. Fatigue life (tested at 20°C) of HMA and WMA mixtures made with aggregate C and RAP C using binder from (a) source A and (b) source B. Each "×" on the figure represents an average value and the diamonds above and below represent the high and low value measured. * indicates that PG 58-28 binder was used instead of PG 64-22.*

PERFORMANCE PROPERTIES OF PLANT PRODUCED WMA MIXTURES CONTAINING RAP

In addition to the mixtures prepared and compacted in the lab, material was sampled from paving projects utilizing WMA and RAP in the mixtures. The objective of this portion of the research was to determine if reheating WMA mixes prior to specimen compaction had an effect on the volumetric or performance properties. There were four projects using WMA and RAP for this portion of the study. Only foaming WMA technology was utilized by the contractors for SCDOT projects during the duration of this research project, so no plant produced Evotherm™ mixes were evaluated.

Project 1

The plant produced mix for this project was a SCDOT Surface Type B mixture that used foaming WMA technology and included 25% fractionated RAP (12% -No. 4 and 13% +No. 4) and the target compaction temperature in the field was 250°F. The WMA mixture was separated into three sublots. For each sublot, nine specimens (2 for volumetric analysis, 2 for ITS, 2 for resilient modulus, and 3 for APA testing) were compacted at the asphalt plant's lab at 250°F. Additional material was collected from each sublot, bagged, and transported to Clemson where it was reheated several days later and specimens were compacted at 250°F. All compacted specimens were tested in the laboratory to identify any differences between plant compacted and reheated mixture properties.

Project 2

The plant produced mix for this project was also a SCDOT Surface Type B mixture that used foaming WMA technology and included 15% fractionated +No. 4 RAP and the target compaction temperature in the field was 280°F. The WMA mixture was sampled in two sublots. For each sublot, nine specimens (2 for volumetric analysis, 2 for ITS, 2 for resilient modulus, and 3 for APA testing) were compacted at the asphalt plant's lab at 295°F as recommended by the plant QC staff. Additional material was collected from each sublot, bagged, and transported to Clemson where it was reheated several days later and specimens were compacted at 295°F. All compacted specimens were tested in the laboratory to identify any differences between plant compacted and reheated mixture properties.

Project 3

The plant produced mix for this project was a SCDOT Surface Type C mixture that used foaming WMA technology and included 10% unfractionated category 2 RAP and the target compaction temperature in the field was 280°F. The WMA mixture was divided into two sublots. For each sublot, nine specimens (2 for volumetric analysis, 2 for ITS, 2 for resilient modulus, and 3 for APA testing) were compacted at the asphalt plant's lab at 285°F as recommended by the plant QC staff. Additional material was collected from each sublot, bagged, and transported to Clemson where it was reheated several days later and specimens were compacted at 285°F. All compacted specimens were tested in the laboratory to identify any differences between plant compacted and reheated mixture properties.

Project 4

The plant produced mix for this project was also a SCDOT Surface Type C mixture that used foaming WMA technology and also included 10% unfractionated category 2 RAP and the

target compaction temperature in the field was 280°F. The WMA mixture was divided into two sublots. For each sublot, nine specimens (2 for volumetric analysis, 2 for ITS, 2 for resilient modulus, and 3 for APA testing) were compacted at the asphalt plant's lab at 285°F as recommended by the plant QC staff. Additional material was collected from each sublot, bagged, and transported to Clemson where it was reheated several days later and specimens were compacted at 285°F. All compacted specimens were tested in the laboratory to identify any differences between plant compacted and reheated mixture properties.

Results

The results of this comparison are summarized in Figures 7.38 through 7.42. The results gathered during this comparison indicate that the specimens that were reheated several days after production had generally similar volumetric and performance properties compared to the specimens from the same production lot that were compacted immediately after sampling at the plant during production. This should continue to be investigated as WMA becomes more prevalent on SCDOT projects.

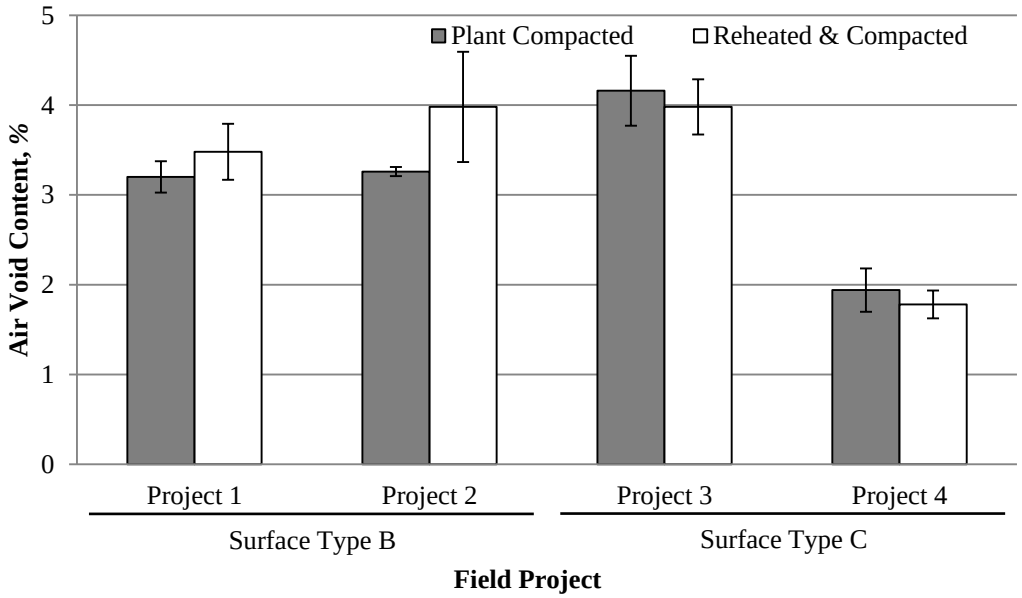
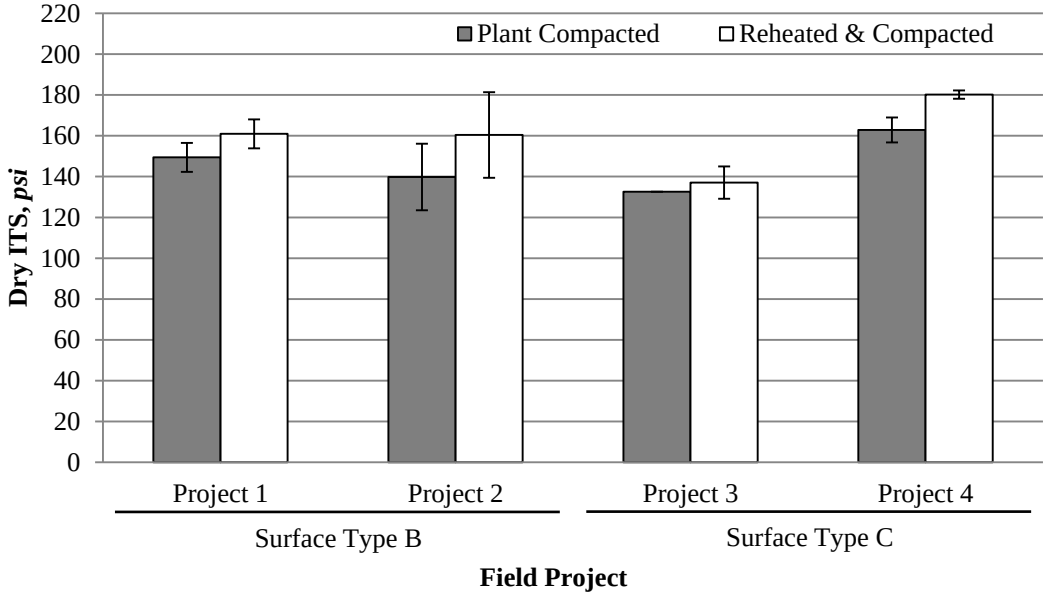


Figure 7.38. Air void content of WMA mixtures compacted at the plant at the time of production and compacted in the lab after reheating.



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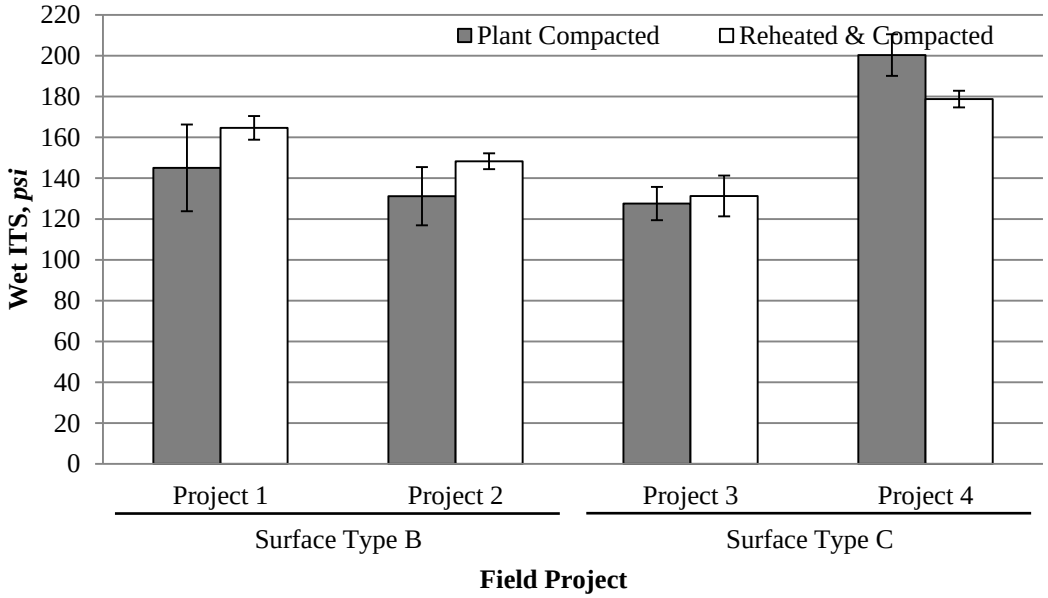

(b)

Figure 7.39. Indirect tensile strength (ITS) of WMA mixtures compacted at the plant at the time of production and compacted in the lab after reheating tested after (a) dry conditioning and (b) wet conditioning.

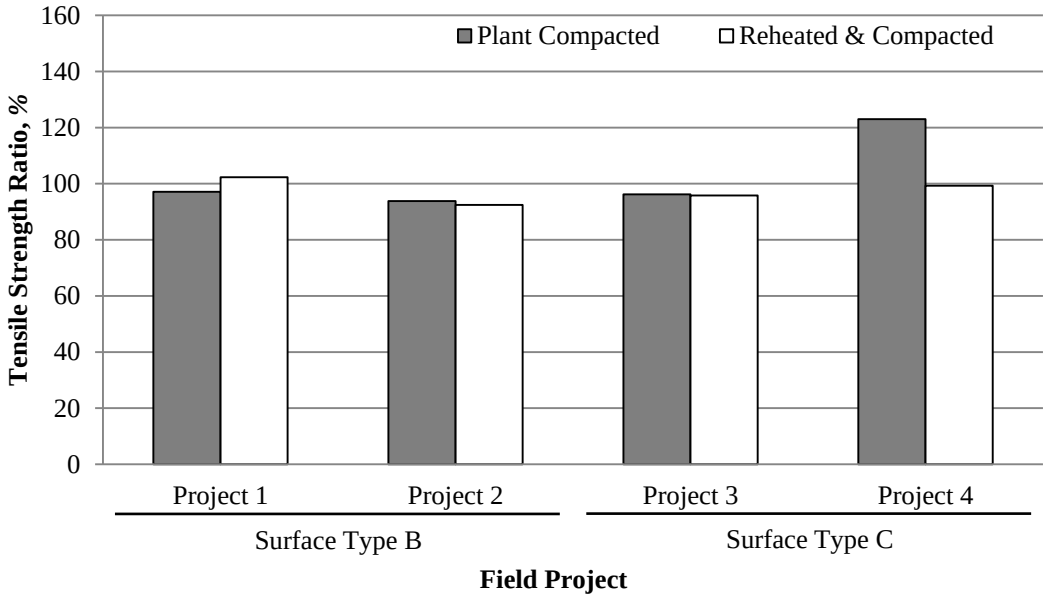

Figure 7.40. Tensile strength ratio (TSR) of WMA mixtures compacted at the plant at the time of production and compacted in the lab after reheating.

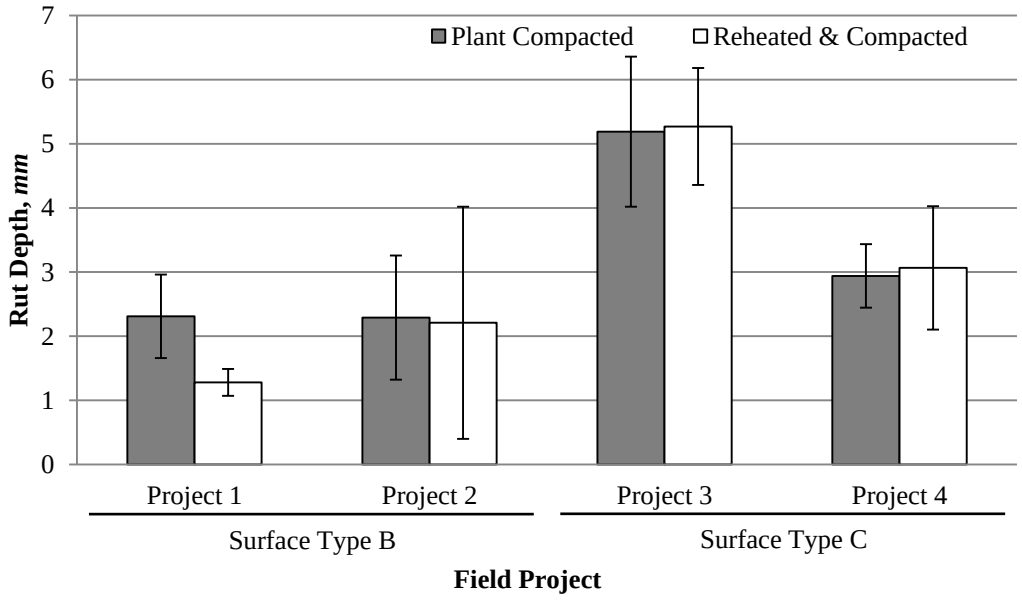

Figure 7.41. Rut depth (tested at 64°C) of WMA mixtures compacted at the plant at the time of production and compacted in the lab after reheating.

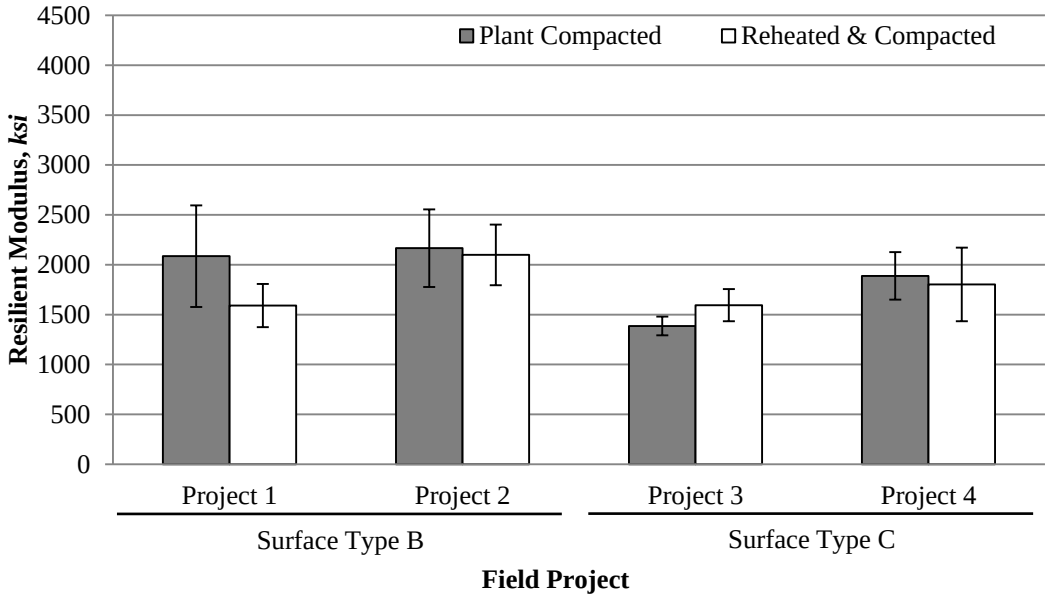

Figure 7.42. Resilient modulus (tested at 25^{o}C) of WMA mixtures compacted at the plant at the time of production and compacted in the lab after reheating.

CHAPTER 8: SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

SUMMARY

The objective of this research project was three-fold:

1. Evaluate the performance of SCDOT mixtures made with WMA technologies.
2. Evaluate the effect of increased RAP contents on SCDOT asphalt mixtures.
3. Evaluate the influence of WMA technologies on SCDOT asphalt mixtures made with RAP.

To accomplish the research objectives, the research was divided in to three separate phases, each addressing one of the three specific objectives. Additionally, an extensive literature review was conducted to establish the state-of-the-practice related to the use of WMA and RAP in asphalt mixtures.

The effects of WMA technologies on asphalt mixtures were evaluated for binders and mixtures. Two different WMA technologies (Evotherm™ and foaming) were selected for this study. Standard binder testing procedures were employed to characterize the effects of Evotherm™ on the binders. Only Evotherm™ was used for the binder portion of the study because Evotherm™ modifies the binder, while foaming does not modify the binder properties—it only adds micro-bubbles which are not a long-term effect on the binder.

Following the binder evaluation, SCDOT Surface Type B mix designs were conducted for HMA and each WMA technology using two binders and two aggregates. Once the mix designs were complete, the performance of each mixture was determined by testing the indirect tensile strength, tensile strength ratio, rutting resistance, and resilient modulus. In addition, the effect of the WMA technologies on the relative compactibiliy of the mixtures was also quantified as the number of gyrations required to achieve the specified height of 95 mm for the ITS specimens.

The effect of RAP content on asphalt mixtures was also investigated by studying the binders and the mixtures. Five different RAP contents were included in this research (0, 20, 30, 40, and 50% by weight of mixture). The properties of composite binders (virgin and RAP blends) were characterized using viscosity and $G^*/\sin\delta$ testing. Mix designs were also conducted for each of the 20 combinations included in the study. The performance properties (indirect tensile strength, tensile strength ratio, rutting resistance, and resilient modulus) of each mix design were then evaluated.

Finally, the combined effects of WMA and RAP were evaluated. This involved the testing 60 different mix designs in the same manner as the previous two phases.

CONCLUSIONS

Based on the results of this multi-faceted study, the following conclusions have been made related to the influence of WMA technologies and RAP on asphalt mixtures.

Warm Mix Asphalt

- The WMA additive Evotherm™, did not have a significant effect on the properties of the virgin binders (PG 58-28, PG 64-22, and PG 76-22) included in this study.
- The use of the WMA technologies included in this study (Evotherm™ and foaming) did not have a significant impact on the optimum binder content determined from the asphalt mix designs. Therefore, a WMA mix can be designed using the same binder content as an equivalent HMA mixture. This has also been concluded by others (Bonaquist 2011). The mixing and compaction temperatures for all WMA mixtures used in this portion of the study were 50°F lower than the HMA mix counterparts. This was based on the manufacturer's recommendation for Evotherm™.
- The WMA technologies generally decreased the indirect tensile strength of the mixtures compared to the HMA mixtures, but all of the mixtures exceeded the minimum allowable wet ITS value of 65 psi.
- The Evotherm™ additive had a compactibility enhancing effect on the mixtures compared to the other mixes.
- The rutting resistance of mixtures made with the WMA technologies included in this study was aggregate source dependent. The WMA mixes exhibited similar rut depths as the HMA mixes for one aggregate, while the WMA mixes had higher rut depths than the HMA mixes for the other.
- The effects of the WMA technologies on the resilient modulus were also aggregate source dependent. The foamed WMA mixtures generally had higher resilient modulus values for one aggregate source and the Evotherm™ WMA mixes generally had higher values for the other aggregate.

Mixtures Made with Reclaimed Asphalt Pavement (RAP)

- The addition of RAP binder to virgin binders had a stiffening effect on each of the binders and the trend was linear with respect to RAB binder content. When the high PG failure temperatures were plotted against RAP content, the slopes of the curves for the two PG 64-22 binders were nearly identical indicating that the RAP binder increased the stiffness of the composite binders in a similar fashion regardless of the virgin binder source. It should be noted, however, that only two binder sources were used in this study. The replacement of the PG 64-22 binder with a softer PG 58-28 resulted in approximately a 4-5°C reduction of the upper PG failure temperature and the slope of this curve was steeper.
- The effects of RAP content on mix design properties are aggregate, binder, and RAP specific meaning that the mixture must be designed for each combination of materials to understand the effect of a particular RAP source on the mix properties. The reason for this is the variable nature of RAP materials, namely the RAP binder properties and the gradation of the RAP. In this research, the addition of higher RAP contents resulted in finer mixes which required a higher binder content to ensure that the dust-to-binder ratio

was kept within the specified range. While this practice could increase the cost of the asphalt mix, it is possible to adjust the virgin fine aggregate contents to control the dust-to-binder ratio without increasing the mix cost.

- As the RAP content increased, the mixing and compaction temperature of the mixtures also increased to ensure adequate mixing and compaction of the mix.
- The RAP content did not have a distinct effect on the indirect tensile strength of the mixtures as the effect appears to be aggregate or RAP specific. When PG 58-28 binder was substituted for the PG 64-22 for the 40 and 50% mixtures, the ITS values did decrease, but the decrease was not detrimental. All of the mixtures had a wet ITS well above the minimum specified value of 65 psi.
- Susceptibility of the RAP mixtures to moisture induced damage was not an issue with the mixtures evaluated in this study as all of the mixes exhibited a TSR of greater than 85%. However, the mixtures with 0% RAP generally had higher TSR values than the RAP mixes. Additionally, no evidence of visible stripping was observed in any specimens.
- The rutting resistance of the mixes improved with the addition of RAP, but not necessarily with increasing RAP contents. The use of PG 58-28 binder in place of PG 64-22 binder in high RAP mixes (40 and 50% RAP) resulted in higher rut depths, but the rut depths were still significantly lower than the virgin mixes.
- An increase in RAP content generally increased the resilient modulus of the asphalt mixtures. The substitution of PG 58-28 for the PG 64-22 binder for the higher RAP mixes reduced the resilient modulus.

Mixtures Made with WMA and RAP

- The Evotherm™ WMA additive generally reduced the stiffness of the composite binders as indicated by the reduction in the upper PG failure temperature. The effect was more pronounced as the RAP content increased for the RTFO aged binders. It should be noted that the Evotherm™ composite binders were conditioned at a lower RTFO temperature (135^{o}C) compared to the HMA binders (163^{o}C), but this change was made to simulate the difference in actual production temperatures.
- The WMA technologies had no significant effect on the mix design properties indicating that the optimum binder content used for HMA mixes could also be used for identical WMA mixes. However, it would be advantageous to conduct the mix design for the WMA mixes and have field verification.
- There was no distinct effect of WMA technology on the indirect tensile strength of the mixtures made with RAP and the results appeared to be aggregate specific. For mixtures from aggregate source B, the Evotherm™ WMA mixtures had 3 out of 10 mixtures that had TSR values below than 85% and for the aggregate C mixtures, the foamed WMA mixes had 2 out of 10 mixes with TSR values below 85%. The lowest TSR value recorded in the study was 78% and there were no visible signs of stripping for any of the mixes. Additionally, all of the wet ITS values were well above the minimum value of 65 psi.
- WMA technologies may improve the compactibility of asphalt mixture at WMA temperatures when RAP is added, but the effect was significant for only one of the two RAP sources included in this study. This effect was quantified using the number of

gyrations of the Superpave gyratory compactor to achieve the desired height and density of ITS specimens in the lab, which has not been correlated to field compaction.

- The effect of WMA technology on the rutting resistance of mixtures containing RAP was dependent on the aggregate source, RAP properties, and binder source. No significant trend was noticed across all mixtures. However, as the RAP content increased, the rut depth of WMA and HMA mixtures generally decreased.
- The resilient modulus of WMA mixtures containing RAP generally followed a similar trend as for HMA mixtures—the resilient modulus increased as the RAP content increased. Additionally, the WMA mixtures generally had similar or lower resilient modulus values than the HMA mixtures for a given RAP content with a few exceptions.

RECOMMENDATIONS

Based on the findings of this investigation, there are several recommendations regarding the implementation of the research findings as well as considerations for further research.

- WMA mix designs could continue to be based off of HMA mix designs. However, it is recommended that this be investigated further because some WMA technologies have the potential to reduce the optimum binder content of a mixture based on the WMA mix design data from this study. The individual mix designs should be designed to meet the SCDOT specifications and the performance properties of the mixtures should be thoroughly investigated to determine if the potential reduction in binder content has any detrimental effects on the longevity of the mixtures. Therefore, it may be advantageous to conduct WMA mix designs when using WMA additives at the respective mixing and compaction temperatures. When foaming is the WMA technology of choice, it is difficult to conduct these mix designs in the laboratory without the investment of laboratory foaming equipment. In this case, the use of HMA mix designs may be preferred.
- When using WMA technologies with the purpose of producing mixtures at lower temperatures, it is important to actually use WMA temperatures at the plant and field to be sure that the benefits of the WMA are realized for this purpose. Alternatively, WMA technologies can be used as compaction aids to improve the quality of a constructed pavement. If this is the case, then it should be allowed, but not considered as "warm mix asphalt" because the mix will still be produced at or near HMA temperatures.
- The QA and long-term performance data for SCDOT WMA projects and similar HMA projects should be collected and compared to evaluate the impacts of WMA throughout the pavement life. Additionally, cost, fuel and energy consumption, and emissions data should be collected to quantify the full benefits of WMA in South Carolina.
- The Qualified Products Policy for Warm Mix Asphalt Additives and Foaming Processes (QPL No. 77) could be revised to include the NTPEP evaluation protocol that is scheduled to be completed in August 2012 (NTPEP 2012). This will be a standard program and could provide SCDOT the ability to compare the results of the NTPEP evaluation with SCDOT requirements. This can also potentially streamline the evaluation/qualification process.

- Field trials should be constructed using HMA and WMA mixtures containing higher RAP contents to fully understand the potential and limitations of the use of asphalt mixtures made with higher RAP contents. These trials should be carefully designed (mix and pavement) and closely monitored during and after construction.
- The potential to incorporate higher RAP contents in strategic locations within a pavement should be considered. For example, the concept of a perpetual pavement includes a thick, rut resistant asphalt sandwiched between a lower fatigue resistant layer and an upper surface course. The rut resistant layer could potentially be produced using high RAP contents that have a stiffening effect on the mixture. Any reduction in fatigue resistance will be accounted for with the use of the fatigue resistant layer beneath this layer. Other potential locations for higher RAP content mixtures could be in asphalt base courses. More research is needed to ensure that surface mixtures are proper location for high RAP content mixes.
- Table 8.1 provides RAP contents for consideration in different SCDOT asphalt mixtures. Table 8.1 is based on fractionated RAP as non-fractionated RAP was not included in the scope of this study. However, the recovered binder will not be affected by fractionation, only the gradation control. It should be noted however, that the properties of the RAP binder should be considered before selecting high RAP contents. This is recommended due to the variability between RAP sources and the potential stiffening effect of higher RAP contents.

Table 8.1. RAP contents (% of aged binder) to be considered based on mixture type.

Type of Mix		% RAP Binder
Surface	A	20
	B	25
	C	35
	CM	35
	D	35
	E	35[1]
	PMTLSC	35[1]
Intermediate	A	20
	B	35[2]
	C	35[2]
Base	A	45
	B	45
	C	45[1, 3]
	D	45[1, 3]

[1] *Fine RAP only (passing the No. 4 seive).*
[2] *Could potentially be increased an additional 10% if using PG 58-28 binder.*
[3] *If used in an application requiring a high endurance limit, the RAP content should be minimized, or the use of a PG 58-22 binder could be used).*

- The economics of the use of increased RAP contents should be studied to quantify any cost savings associated with the use of RAP and the impact of the use of RAP on the life-cycle costs of the pavements.

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APPENDIX A: WARM MIX ASPHALT SURVEY

CONTACT INFORMATION

1. Name:
2. Job Title:
3. Street Address:
4. City:
5. State:
6. Zip Code:
7. Contact Phone:
8. Fax:
9. Email:
10. Would you like to receive a copy of the survey results once we have compiled all of the responses?

THE FOLLOWING QUESTIONS PERTAIN TO YOUR STATE'S WARM MIX ASPHALT USAGE:

11. Has your state used any warm mix asphalt additive or process for producing warm mix asphalt (WMA)? If you select "No", skip to question #27.

PLEASE PROVIDE THE FOLLOWING INFORMATION ABOUT YOUR STATE'S WMA USAGE:

12. Do you have any available reports about the WMA projects your state has completed?

13. If you answered "yes" to Question #12, please provide us with a list of all report titles and the name, telephone number, and email address of a contact person who we may contact to obtain a copy of these reports. If you are able to send the reports by email, please send the reports to mcorley@clemson.edu. If the reports are available online, please provide the web address.

14. Do you have information regarding the use of WMA in your state in projects other than state projects (i.e., city, county, private)?

15. If you answered "yes" to Question #14, please provide us with the contact information for the city/county engineering or consulting engineer.

THIS SECTION PERTAINS TO YOUR STATE'S WMA PROCEDURES AND SPECIFICATIONS:

16. Does your state have a procedure for qualifying WMA additives?
    a. Yes
    b. No
    c. Not currently, but we are in the process of developing one

17. If you answered "yes" to question #16, please provide us with a copy of the procedure (either by email or hard copy). If you are sending by email, please send it to mcorley@clemson.edu and if you are sending by mail, please send to Asphalt Rubber Technology Service, 2002 Hugo Drive, Clemson University, Clemson, SC 29634. If the procedure is available online, please provide us with the procedure number and web address. If you are unable to provide a copy of the procedure, please provide us with the procedure number and let us know how to get a copy of the procedure.

18. If your state has WMA specifications, please check all that apply for your specifications.
    a. Regular/Standard Specifications
    b. Supplemental Specifications
    c. Special Provisions/Project-Specific
    d. Available on Your Website
    e. Available in the National Highway Specifications
    f. Website at http://fhwapap04.fhwa.dot.gov/index.jsp
    g. Other, please specify

19. If you selected any of the specification types in Question #18, please provide us with your specifications either by email or hard copy. If sending by email, please send to mcorley@clemson.edu or if sending by mail, please send to Asphalt Rubber Technology Service, 2002 Hugo Drive, Clemson University, Clemson, SC 29634. If the specs are available online, please provide us with the spec numbers and web address. If you are unable to send us the specs, please provide us with the spec numbers and let us know how to obtain a copy of those specs.

20. Does your state allow for an increase in allowable RAP percentage for WMA compared to HMA?

21. If you answered "yes" to Question #20, what is the increase in percentage of RAP allowed in WMA in your state?

22. How does your state determine the adjustment in the laboratory mixing and compaction temperature ranges for laboratory samples of WMA compared to HMA? What are your typical laboratory mixing and compaction temperature ranges of WMA compared to HMA? If your state uses multiple WMA additives or processes and your temperature ranges or temperature adjustment procedures are different for each of these, please provide information for each type of WMA additive or process.

23. How does your state determine the adjustment in pavement mat compaction temperature ranges for WMA compared to HMA? What is your typical pavement mat compaction temperature range for WMA compared to HMA? If your state uses multiple WMA additives

or processes and your temperature ranges or temperature adjustment procedures are different for each of these, please provide information for each type of WMA additive or process.

24. Has your state completed research or studies about the following issues related to WMA, either alone or compared with HMA (please check all that apply)? If you select any of these issues, please provide us with any available results or reports relating to your analysis of these issues either by email to mcorley@clemson.edu or by mailing them to Asphalt Rubber Technology Service, 2002 Hugo Drive, Clemson University, Clemson, SC 29634. If these reports are available online, please provide us with the web address. If you are unable to send a copy, please provide us with the report titles and let us know how to obtain a copy of these reports.
    a. Emissions of WMA at the plant
    b. Emissions of WMA at the roadway
    c. Energy consumption analysis of WMA production
    d. WMA containing RAP
    e. Lab performance of WMA
    f. Field performance of WMA
    g. Moisture susceptibility of WMA
    h. Fatigue resistance of WMA
    i. Rut resistance of WMA
    j. Life-cycle cost analysis of WMA pavements
    k. Health concerns
    l. Environmental concerns
    m. Other, please specify

25. Please check all that apply regarding your concerns about the use of WMA in your state.
    a. It is too expensive
    b. It is still experimental
    c. Need many equipment changes to make it work
    d. Need new mix design procedures
    e. It is not your typical binder
    f. It does not work
    g. Unsure about recyclability of WMA
    h. Unsure about effect of WMA on emissions
    i. Energy reduction benefits not adequately quantified
    j. We do not know much about the process product
    k. Other, please specify

26. If you have additional comments about issues related to WMA that were not specifically covered in this survey, please list them here.