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The Evaluation and Specification Development of Alternate Modified Asphalt Binders in South Carolina

FINAL REPORT

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16. Abstract

In this research project, asphalt binders containing various polymer modifiers were investigated through examining both binder and mixture properties. Two additional topics were also investigated, including: a) the effects of liquid anti-strip additives on asphalt mixtures; and b) the effects of natural sands in asphalt mixtures. The asphalt binder modifiers in this project included: two plastomers; an elastomer; PPA+SBS; terminally blended ground tire rubber (GTR) binder; and a lab-prepared GTR binder. The binder properties of 16 binder combinations were obtained (e.g., viscosity, DSR, etc.) and compared. In addition, these modified binders were used in mixtures with two aggregate sources, three anti-strip additives, and varying RAP contents. There were 32 different Superpave mix designs conducted for this project. Many engineering properties of the mixtures were obtained, including: indirect tensile strength, tensile strength retained, rutting, and AMPT values. The AMPT testing was conducted at different temperatures and frequencies. The results indicated that, in general, many of the alternate modified binders could be utilized in South Carolina hot mix asphalt (HMA) mixtures. The results also indicated that RAP and natural sand could be utilized, in limited quantities, in many mixtures used on South Carolina secondary roads. In addition, the mixtures made with liquid anti-strip additives in this project in many cases produced moisture susceptibility values (e.g., ITS, TSR) that were compatible with those obtained with mixtures containing hydrated lime.

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Disclaimer

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Chapter 1 - Introduction

The use of polymer-modified binders in hot mix asphalt (HMA) has steadily increased over the past few decades around the country. Over the last three decades, many researchers have investigated the effects of these modifiers on binders and mixtures. In many states, most interstate pavements are paved using these modified mixtures. In addition, these binders are used in mixtures in many additional locations with heavy loading conditions since they provide the required strength for that loading. Most of these modified binders exhibit excellent rutting resistance properties and perform very well under severe climates (e.g., high or low temperatures).

In this research project, asphalt binders containing various polymer modifiers were investigated through examining both binder and mixture properties. Two additional topics were also investigated, including: a) the effects of liquid anti-strip additives on asphalt mixtures; and b) the effects of natural sands in asphalt mixtures. This report has been divided into several sections and chapters to address these issues.

Problem Statement

Alternate Asphalt Binder Modifiers

For many years, polymers have been incorporated into asphalt as a way to mitigate many major causes for asphalt pavement failures, including permanent deformation at high temperatures, cracking at low temperatures, fatigue, and stripping damage (Chen et al. 2002; Li et al. 1998; Wekumbura et al. 2007). These polymer-modified asphalt (PMA) binders also have been used with success at locations of high stress such as interstates, intersections, and airports (Yildirim 2007). For many years, PMA has proven itself to be an essential element in the paving process.

There are several types of polymers used in asphalt binders today. Currently, in the United States, the most commonly-used polymer for asphalt modification is SBS (styrene butadiene styrene) followed by other polymers such as GTR (ground tire rubber), SBR (styrene butadiene rubber), EVA (ethylene vinyl acetate) and polyethylene (Sengoz and Isikyakar 2008). According to a modified asphalt market survey in 2005-2006, 80% of states across the country, including South Carolina, used SBS as a modifier (Casola 2006).

Although they cost more than conventional binders, SBS-modified PG 76-22 asphalt binders have been utilized for many years by the South Carolina Department of Transportation (SCDOT) and many other state DOTs on interstate projects in order to increase the life of asphalt pavements. The high cost associated with the SBS modification process is mostly due to the SBS material. The SBS market was hit with a shortage of Butadiene back in late 2009, which affected both supply and cost of PG 76-22 in SC as well as the entire country. Due to many reasons, it is important to have some alternative modifiers such as elastomers, plastomers, other polymers, GTR (from recycled passenger and truck tires), sulfur additive, and PPA (Polyphosphoric Acid) to substitute for SBS in PG 76-22 asphalt binders in the future.

Most specifications used for binders today, in general, are performance related. Therefore, significant chemistry changes might affect the test behavior and results. In order to obtain a reasonable conclusion before using any new materials, several issues should be considered including the following: a) aging characteristics; b) predictable rheological properties; c) adhesion properties; d) constructability issues; e) odor issues, if any; f) water solubility; g) environmental considerations; h) recyclability of the materials; and i) availability in bulk quantities. Most of the SHRP testing (e.g., DSR, BBR, PAV, etc.) should be conducted in order to characterize the rheological properties of these new additives or polymers. In addition, mixture properties (e.g., volumetric, moisture susceptibility, deformation, etc.) must be initiated and tested. In this research project, many of these characteristics were evaluated for several alternate modifiers. Testing included the modified binders as well as mixtures made with these binders.

Anti-Stripping Additives in Asphalt Mixtures

The phenomenon of breaking the bond between the aggregate and the binder is known as stripping. A typical stripping situation involves the gradual loss of strength over time, which causes various surface manifestations like rutting, corrugation, shoving, raveling, cracking, etc. (Busching et al. 1986, Kim and Amirkhanian 1991). The use of anti-stripping additives (ASAs) is the most common method to prevent stripping in a pavement (Lu and Harvey 2006, Putman and Amirkhanian 2006, Xiao and Amirkhanian 2009, Gandhi et al. 2009). One of the most commonly-used ASAs in the United States is hydrated lime, but there are other ASAs available. Other solid ASAs include Portland cement, fly-ash, and flue dust. Liquid ASAs include amines, di-amines, and liquid polymers. The mechanism by which liquid ASAs work is by reducing the surface tension between the aggregate surface and the asphalt binder. This reduction in surface tension promotes increased adhesion of the binder to the aggregate. For this reason, they are also called surfactants (Putman and Amirkhanian 2006).

Pavement contractors usually prefer liquid ASAs as they are relatively easy to use (Lu and Harvey 2006). However, many DOTs prefer hydrated lime due to its excellent performance and the ease of validating the use of the material. Hydrated lime has been used successfully as an ASA for many years in SC and has a proven track record for increasing asphalt mixture resistance to moisture susceptibility. However, over the last several years, liquid ASAs have gained popularity due to advancements in available liquid ASAs as well as their cost and ease of application. Thus, it is necessary to explore the performance of these new liquid ASAs in conventional mixtures as well as the compatibility of both hydrated lime and liquid ASAs with potential alternate asphalt modifiers. In this research project, some of the effects of liquid ASAs on several mixtures were investigated and compared to the results obtained from samples containing hydrated lime.

Natural Sands in Asphalt Mixtures

The properties of asphalt mixtures are affected substantially by the characteristics of aggregates used in the mix, including shape and surface texture. The effects of natural sands are attributable to their rounded shape and smooth surface texture, which facilitate the rearrangement of larger aggregate particles under the influence of repeated loads (Freeman and Kuo 1999). The presence of excessive natural sand in an asphalt mixture can increase its susceptibility to permanent deformation and other potential problems (Ahlrich 1991). In addition, field investigations have concluded that excessive natural sand is a primary cause of premature rutting (Brown 1983, Anderton 1990, Ahlrich and Anderton 1992). However, the use of natural sand is attractive to some contractors because it is generally less expensive than crushed fines, and it can make mixtures easier to compact.

Due to these factors, it is necessary for agencies that specify pavement construction to limit natural sand contents (Freeman and Kuo 1999). The Federal Highway Administration has issued guidance that limits the proportion of natural sand to 20% by mass of the total fine aggregate. The U.S. Army Corps of Engineers (USACE) limits the natural sand content of heavy-duty pavement mixtures to 15% by mass of all the aggregate (‘‘Asphaltic’’1991).

Although it is necessary to place some limits on the use of natural sand in asphalt mixtures due to performance issues, it is possible that the use of a limited amount of natural sand could provide some cost savings for specifying agencies. This could especially be true with respect to asphalt mixtures that use natural sands in conjunction with recycled asphalt pavement (RAP) materials. However, the performance characteristics of these asphalt mixtures containing natural sands and RAP must be investigated. In this project, performance characteristics were examined for various mixtures containing natural sand and RAP. In addition, the effects of both hydrated lime and liquid ASAs on the performance of these mixtures were also examined.

Chapter 2 – Scope of the Research Project

Research Objectives

There were three major objectives for this study including:

1) Compare the performance of alternate binder modifiers to SBS with respect to rheological properties of the modified binders and engineering properties of the mixtures made with these binders. In these mixtures, recycled asphalt pavement (RAP) materials were also utilized and their effects on engineering properties were investigated.
2) Evaluate the performance of new liquid ASAs in conventional SBS-modified asphalt mixtures as well as to evaluate the compatibility of alternatively-modified binders with both hydrated lime and liquid ASAs. The mixtures were tested and evaluated for moisture susceptibility and other performance properties both with and without RAP materials.
3) Evaluate the moisture susceptibility and other performance properties of asphalt mixtures made with natural sands. For this portion of the project, all of the natural sand mixtures to be tested also included RAP, and the moisture susceptibility testing included hydrated lime as well as liquid ASAs.

1. Alternate Asphalt Binder Modifiers

The first objective was to compare the performance of alternate binder modifiers to conventional SBS with respect to the rheological properties of the modified binders as well as the engineering properties of the mixtures made with these binders. Based on recommendations from the SCDOT Steering Committee, only the following binder modifiers were evaluated for this portion of the project: an elastomer, a plastomer, a PPA, GTR (terminally-blended only), and control SBS. All mixtures to be tested for performance properties were evaluated both with and without RAP. The specific tasks for this portion of the research project included the following:

- Conducting an extensive literature review on the topic of alternate modifiers for PG 76-22 asphalt binders (this task was performed concurrently with the tasks involving testing);
- Conducting a nationwide survey to determine the rate of usage of these materials around the country,
- Determining initial recommendations for terminally-blended GTR mix design guidelines based on the literature review and basic laboratory test results;
- Investigating the effects of various alternate modifiers on the rheological characteristics of asphalt binders at high, intermediate, and low performance temperatures through the performance of AASHTO M 320, TP 70, TP 79, and PP 61;
- Investigating the effects of various alternate modifiers on asphalt mixture volumetric properties such as air voids, %VFA, %VMA, and optimum asphalt

binder content;
- Investigating the effects of various alternate modifiers on various performance properties of asphalt mixtures, including moisture susceptibility, permanent deformation, dynamic modulus, and flow number; and
- Developing recommended specifications for SCDOT regarding the utilization of these materials.

Input was sought from the Steering Committee to select the aggregate sources, binder sources, RAP sources, RAP percentages, and performance characteristics that were used in this portion of the study.

2. Anti-Stripping Additives in Asphalt Mixtures

The second objective of this project was to evaluate the performance of liquid ASAs in conventional SBS-modified asphalt mixtures as well as to evaluate the compatibility of alternatively-modified binders with both hydrated lime and liquid ASAs. HMA mixtures containing various modifiers (SBS and alternate modifiers) as well as either hydrated lime or liquid ASAs were tested for moisture susceptibility. This portion of the study also evaluated all of these mixtures both with and without RAP. The specific tasks for this portion of the research project included the following:

- Conducting an extensive literature review on the usage of liquid ASAs in asphalt pavement surface layers (this task was performed concurrently with the tasks involving testing);
- Determining initial recommendations for mix design guidelines using liquid ASAs based on the literature review;
- Investigating the effects of various liquid ASAs on mixture volumetric properties such as air voids, %VFA, %VMA, and optimum asphalt binder content of various asphalt mixtures (conventional SBS-modified and alternatively-modified);
- Investigating the effects of various liquid ASAs on moisture susceptibility of conventional SBS-modified asphalt mixtures
- Investigating the compatibility of various alternate modifiers with various anti-stripping additives (hydrated lime and liquid ASAs) through moisture susceptibility testing; and
- Investigating the effects of various liquid ASAs on other performance properties, including permanent deformation, dynamic modulus, and flow number of various asphalt mixtures (conventional SBS-modified and alternatively-modified);

Input was sought from the Steering Committee to select the aggregate sources, binder sources, RAP sources, RAP percentages, and performance characteristics that were used in this portion of the study.

3. Natural Sands in Asphalt Mixtures

The third objective of the study was to evaluate the performance of asphalt mixtures made with natural sands. Various HMA mixtures containing natural sands were evaluated to determine the effects on several mixture properties, including deformation/rutting and low-temperature cracking. In addition, the effects of natural sands on moisture susceptibility were examined with respect to the use of both hydrated lime and liquid ASAs. All of the asphalt mixtures tested in this portion of the project utilized conventional PG 64-22 (non-modified) binders and contained RAP in addition to natural sand. The specific tasks for this portion of the research project included the following:

- Conducting an extensive literature review on the usage of natural sand in asphalt pavement surface layers (this was performed concurrently with the tasks involving testing);
- Determining initial recommendations for mix design guidelines using natural sands based on the literature review;
- Determining angularity (based on uncompacted void content) of the natural sands;
- Investigating the effects of natural sands on mixture volumetric properties such as air voids, %VFA, %VMA, and optimum asphalt binder content in asphalt mixes containing either hydrated lime or liquid ASAs;
- Investigating the effects of natural sands on selected performance characteristics, including permanent deformation, dynamic modulus, and flow number of asphalt mixes containing either hydrated lime or liquid ASAs; and
- Investigating the effects of natural sands on moisture susceptibility of asphalt mixes containing either hydrated lime or liquid ASAs.

Input was sought from the Steering Committee to select the aggregate sources, sand sources, binder sources, liquid ASA sources, RAP percentages, and performance characteristics that were used in this portion of the study.

Organization of the Report

The contents of this report have been divided into several sections (chapters). Chapter 3 contains the literature review for many topics studied in this research project. Chapter 4 describes the materials and experimental design used for this work. Chapters 5, 6, and 7 contain the results of the research activities. Chapter 8 contains the conclusions and the recommendations for this research study. Several appendices contain the laboratory or field testing results. The report also includes a partial list of references studied during this investigation.

Chapter 3 – Literature Review

Polymers that have been used to modify asphalt include styrene–butadiene–styrene (SBS), styrene–butadiene rubber (SBR), Elvaloy® (an elastomer), rubber, ethylene vinyl acetate (EVA), polyethylene, and others. Desirable characteristics of polymer-modified binders include greater elastic recovery, a higher softening point, greater viscosity, greater cohesive strength and greater ductility (Yildirim 2007).

Yildirim (2007) points out that for optimal economy, it is desirable to choose an asphalt modifier that resists multiple distresses, such as rutting, fatigue, thermal cracking and water damage. It was found that the choice of polymer may have a significant impact on fatigue properties and that the mixtures boasting the highest fatigue life contained reactive styrene–butadiene crosslinked polymer. Other polymers tested were a chemically-modified crumb rubber, SBR, linear block SBS, and a proprietary modified SBS.

When a polymer and virgin asphalt are blended, the polymer strands absorb part of the low-molecular weight oil fraction of the virgin asphalt and become swollen. When the polymer-rich phase becomes the continuous phase (due to the relatively higher fraction of swollen polymer), the swollen strands connect together and form a three dimensional network. This network provides the physical properties of elasticity, plasticity, and elongation of an asphalt binder (Wekumbura at el. 2007). Ultimately, PMA binders become more viscous and tend to improve the binder coating (i.e., by increasing its film thickness) on aggregates, and this holds the aggregate particles together more effectively. These properties result in better pavement performance.

Of all the polymer modifiers, styrene-butadiene-styrene (SBS), which was originally developed by Shell Chemical Co., is widely used in the majority of the modified asphalt binders (Lavin 2003; Becker et al. 2001). SBS creates a three dimensional network within the virgin asphalt phase, resulting in an excellent bonding strength to aggregates that leads to a durable and long-lasting pavement (Kim 2003; Adedeji et al. 1996).

SBS is a thermoplastic elastomer; thus, it behaves like an elastic rubber at ambient temperatures, and it can be processed like a plastic when heated. Generally, most types of rubber are difficult to process because they are cross-linked; however, SBS and other thermoplastic elastomers can manage to be rubbery without being cross-linked, thus making them easy to process into useful shapes. In structural terms, its backbone chain is made up of three segments. Polystyrene is a hard plastic which provides durability at high temperature, while butadiene is a rubber which contributes to the elasticity of the binder at low temperature. It is envisioned that the SBS network interacts with the asphaltene and resin parts of the binders (Rozeveld et al. 1997).

Sengoz and Isikyakar (2008) found that although the flow values of both SBS and EVA asphalt mixtures are higher than control (virgin) mixtures, modified mixtures reveal more resistance to permanent deformation. Therefore, it can be concluded that the polymer additives contribute to a stronger adhesion of aggregates and binders. The modification agent plays an important role in defining the performance properties of the modified binder. Binders modified with elastomeric modifiers such as GTR, SBS, and SBS-GTR yielded better recoveries than those made with plastomeric modifiers, such as Elvaloy and EVA. The binder modified with both PPA and SBS exhibited properties very similar to the plastomeric binders. Overall, the GTR-modified binder exhibited the least creep, while also demonstrating a very high recovery rate. It also tended to yield the highest percent recoveries over the range of temperatures. The following sections will describe the background of some of the materials tested in this research project.

Elastomer and Plastomer Materials

Polymers, which are long-chain molecules of very high-molecular weight, used by the binder industry are classified based on different criteria. One method classifies polymers into two general categories—elastomers and plastomers. The mechanism of resistance to deformation is the basic difference between these two categories. The load-deformation behavior of elastomers is similar to that of a rubber band such as increasing tensile strength with increased elongation, which may reach 1300% of the original length, and ability to recover to the initial state after removal of load. An elastomer may be defined as an amorphous, cross-linked polymer above its glass transition temperature (Painter and Coleman 1997). When mixed with asphalt binder, elastomers form a two-phase system at the service temperature, with one phase containing nearly all of the polymer and the other phase containing nearly all of the asphaltenes. On the other hand, plastomers exhibit high early strength but are less flexible and more prone to fracture under high strains than elastomers (Painter and Coleman 1997).

Morrison et al (1995) reported that both the chlorinated plastomer and elastomer showed improved compatibility with the asphalt binders after reactive processing at elevated temperatures. This improved compatibility resulted in a significant increase of both the penetration index and penetration-viscosity number over an unmodified binder. This is not an unexpected phenomenon and has regularly been demonstrated in other studies. The results have shown that the addition of only 3% additive to the binder caused the penetration-viscosity number to increase from -2.54 to +0.74. This significant improvement would correspond to enhanced rheological performance of the pavement during hot summer months while also improving performance in cold winter temperatures.

Mostafa et al. (2003) reported that elastomeric modification should be used cautiously and may not be considered a general solution to improve binder performance. Styrene-ethylene/butylene-styrene (SEBS) is mainly suitable for pavements where an increase in the mix elasticity is desired at high service temperatures and/or for slow-moving traffic. SEBS is used for road and roofing applications where high resistance to oxidative and thermal attack is required (Shell 1995). Although the current price of

SEBS is approximately twice that of SBS, the SEBS modified binder may be cost-effective given the enhanced performance it exhibits.

To date, the most common polymer modifier used for asphalt modification has been the elastomer styrene-butadiene-styrene (SBS). While elastomeric polymers have shown the greatest potential for use in asphalt modification, there has also been some use of plastomeric polymers. It has been estimated that approximately 75% of all polymer-modified asphalts utilize elastomeric modifiers, while only 15% of modifiers used are plastomeric. The remaining 10% of modified asphalts use other types of materials, such as sulphur and acid (Diehl, 2000, Thodesen et al. 2009).

Polyphosphoric Acid (PPA)

Asphalt is used in over 200 applications, most of which relate to civil engineering and to paving and roofing in particular (The Asphalt Institute, MS-4). In an attempt to change its characteristics and improve its performance, bitumen is often modified with an elastomer (Kraus 1982; Polacco et al. 2006), a plastomer (Jew et al 1986; Giavarini et al. 1996), a thermoset (Lee et al. 1997; Polacco et al. 2004), sulfur (Fritschy et al. 1981), or a mineral acid (Giavarini et al. 2000). There is now much interest in the use of polyphosphoric acid (PPA) to modify bitumen. By itself or in combination with a polymer, PPA provides a means of bitumen modification usually produced cheaper than one with a polymer alone (Masson 2008).

Kodrat et al. (2007) reported that with the ever-increasing demands on our roads, asphalt producers have been required to increase the operating window of what were previously-acceptable materials. Suppliers are naturally driven to find the lowest-cost modification technology that meets a given specification without any obvious deleterious effects. Hence, the use of polyphosphoric acid (PPA) has increased considerably over the last few years.

The basic compounds for the production of PPA are phosphorus pentoxide (P_2O_5) and phosphoric acid (H_3PO_4), as shown in Figure 3.1. Phosphorus is first oxidized to phosphorus pentoxide, which crystallizes as P_4O_{10}. Upon its reaction with water, phosphoric acid is produced. This route to H_3PO_4 is known as the *dry* process, which is used to provide high-purity material (Averbuch-Pouchot and Durif 1996; Corbridge 1995). A cheaper *wet* process provides H_3PO_4 from the reaction of sulfuric acid on ground apatite phosphate rock, $Ca_3(PO_4)_2CaF_2$ (Averbuch-Pouchot and Durif 1996; Corbridge 1995).

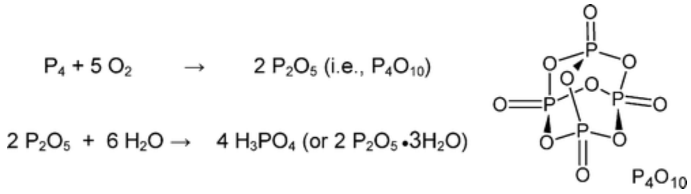


Figure 3-1 Production and reaction of phosphorus pentoxide

PPA is an oligomer of H_3PO_4. High-purity material is produced either from the dehydration of H_3PO_4 at high temperatures or by heating P_2O_5 dispersed in H_3PO_4 (Jameson 1959). Figure 3.2 illustrates the equilibria for these reactions, which produce different chain lengths and distributions. The dehydration method tends to produce short chains, whereas the dispersion method usually produces chains with more than 10 repeat units (Jameson 1959).

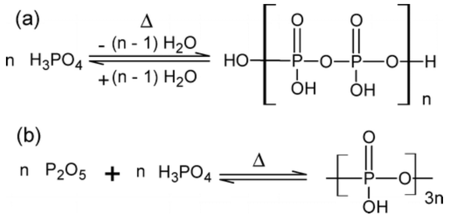


Figure 3-2 Production of PPA from the (a) dehydration and (b) dispersion methods. "n" is an integer.

It is relatively easy to identify the rheological characteristic modifications made to a binder with PPA. However, it is difficult to identify bitumens that react with PPA and to establish the level of PPA required for a given application. This is in great part because the mechanism of PPA action on bitumen, to some part, is unknown. To better understand their reaction or lack thereof, the characteristics of PPA and bitumen are briefly explained. PPA has a high dielectric constant, whereas that of bitumen is low, which renders the dissociation of PPA into its acidic and basic moieties ineffective. PPA is thus a very weak acid in bitumen. It can thus be concluded that PPA can only dissociate and react with bitumen in enclaves of high dielectric constants. This is formed from the aggregation of amphoteric heteroatomic groups into nanodomains.

PPA has found increasing use as a straight additive without the need for air blowing to improve the grade range. Typical results are high-temperature grade improvements of less than 6°C (Giavarini et al. 2000). The increase in grade is thought to occur because of a reaction between the asphaltenes and acid (Giavarini et al. 2000; Baumgardner et al. 2005).

Kodrat et al. (2007) reported: 1) The effect of PPA on the Superpave grading properties was found to be significant, with the high-temperature grade increasing by varying amounts depending on the crude source, and the low-temperature grade remaining largely unaffected for most binders. 2) The effect of PPA on the fracture properties in the brittle state was found to be insignificant. 3) The effect of PPA on the reversible aging process was found to be insignificant. 4) The effect of PPA on the ambient-temperature fracture properties was found to be significant. This result may have a negative impact on long-term fatigue performance. Hence, caution is needed with the use of PPA in areas where fatigue cracking is a concern.

Most recent studies have focused on evaluating the properties of asphalt binder modified with PPA. Bishara et al. investigated the effect of PPA on the high-temperature properties of binder in the absence of and in the presence of ASAs. Results showed that modification with PPA hardens asphalt and can significantly extend its high-temperature application (Bishara et al. 2001). They also showed that although modification with PPA or ASA has benefits, the coexistence of both modifiers limits such benefits. The same team tested mixtures that contained asphalt binders modified with both PPA and ASA using a Hamburg Wheel Tracking Device and an Asphalt Pavement Analyzer and found poor performance in these mixtures with acid–amine binders (King et al. 2002).

Ajideh et al. investigated the effects of several different modifiers (including polymer and PPA) on the rheological and damage properties of asphalt binders and mixtures. The results indicated that asphalt mixtures modified with only PPA exhibited significantly-improved resistance to rutting and fatigue, whereas the effect of aging on rheological properties was noticeably different for mixtures with both modifiers (Ajideh et al. 2004). They also found that the resistance to moisture damage of asphalt mixtures modified with only PPA was not as good as that of those modified with polymer. Baumgardner et al. studied the mechanism of how PPA interacts with asphalt binder and found that the interaction depends on the base (virgin) asphalt (Baumgardner et al. 2005; Li et al. 2011).

The PPA workshop covered extensive laboratory and field evaluations on the use of PPA as a modifier for asphalt binder and reported that: 1) the stiffening effect of PPA on the binder is crude source-dependent with anywhere from 0.5% to over 3% needed to increase the binder grade. 2) PPA works as a stiffener and cross-linker when used with polymers such as SBS and ethylene terpolymers (e.g., Elvaloy®). 3) PPA can significantly improve the delayed elastic response of the polymer-modified binder. 4) There is some indication that hydrated lime can reduce the stiffening effect of PPA, but the increased stiffening from the lime outweighs any loss. Limestone aggregate could not reverse or reduce the stiffening effect of PPA on the binder.

Ground Tire Rubber (GTR)

Ground tire rubber (GTR) is a type of asphalt binder modifier that can improve flexibility and decrease temperature susceptibility of an asphalt mixture. It is formed by the interaction of reclaimed GTR with asphalt binder at elevated temperatures for a certain period of time. This type of modified binder has several advantages. The ground tire rubber not only increases the binder's elasticity but also increases its resistance to aging due to anti-oxidants contained in tires. It is broadly used as a sustainable material in improving the long-term performance of asphalt pavements.

GTR modifier is a general type of asphalt modifier that consists of crumb rubber produced from scrap tires. GTR asphalt binder pavement products are produced by several techniques including wet process and dry process. These GTR-modified asphalt binders may contain additional additives or modifiers (i.e., rubber polymers, diluents, and aromatic oils) besides scrap tire rubber.

The primary uses of GTR-modified asphalt binders in pavement applications include crack sealants, joint sealants, chip seals, interlayers, hot-mix asphalts (HMA), and membranes. The life cycle cost analysis presented in this paper is limited to wet-processed GTR asphalt binders used for chip seals, interlayers, and HMA, including dense-, gap-, and open-graded mixtures.

GTR modifiers have been used in asphalt binders for hot-mixes since the 1960s (Epps, 1994). They have contained binders prepared from both the wet process and the dry process. The dry process was a patented process called PlusRide. This process is no longer being utilized in the United States. Dense-, open-, and gap-graded aggregates have been used and field-tested in various states with GTR modifiers.

Currently, the majority of GTR binder used in hot mix asphalt (HMA) is placed in the states of Arizona, California, Florida, and Texas. ASTM defines "asphalt rubber" as materials consisting of a virgin binder and a minimum of 15% crumb rubber. Arizona DOT (ADOT) and local governments in Arizona primarily use asphalt rubber binder in open-graded and gap-graded HMA. The use of asphalt rubber binder in open-graded friction courses is now the most popular use of this type of binder by ADOT. Arizona first placed HMA containing asphalt rubber in 1975. California DOT uses asphalt rubber binders in dense-, gap-, and open-graded HMA. Local governments in southern California utilize asphalt rubber binders in gap- and open-graded mixtures. Texas DOT uses asphalt rubber binders primarily in gap-graded mixtures identified as coarse matrix, high binder (CMHB) (Hicks et al. 1995). Florida DOT (FDOT) uses GTR-modified binders containing fine crumb rubber at percentages typically between 6-12% by weight of asphalt binder in dense- and open-graded hot mixtures. These binders are not asphalt rubber as defined by ASTM (Hicks et al. 1995).

Crumb rubber produced from scrap tires consists mainly of natural and synthetic rubber, carbon black, sulphur, zinc oxide and coloring agents. It is well known to absorb asphalt binder and swell. The amount of swelling is dependent on the nature, temperature and viscosity of the base asphalt binder. This swelling of the crumb rubber is a diffusion process and increases the dimension of the rubber network until the concentration is uniform and equilibrium swelling is achieved. This complex process significantly affects the performance grade (PG) of GTR-modified asphalt binders, especially as rubber size, type, amount, and blending process differ.

There are several benefits of using GTR-modified asphalt mixtures including the following (Hicks 2002):

- Improved resistance to surface-initiated cracking due to higher binder contents
- Improved aging and oxidation resistance due to higher binder contents
- Improved resistance to fatigue and reflection cracking due to higher binder contents

- Improved resistance to rutting due to higher viscosity and softening points
- Increased night-time visibility due to contrast in the pavement and striping
- Reduced tire noise due to increased binder film thickness and open texture
- Reduced splash and spray during rain storms due to open texture
- Reduced construction times because less material is placed
- Lower pavement maintenance costs due to improved pavement performance
- Better chip retention due to thicker films of asphalt
- Lower life cycle costs due to improved performance
- Savings in energy and natural resources by using waste products

The limitations of GTR-modified binders include the following (Hicks 2002):

- Higher initial unit costs compared to conventional virgin mixes, although this can be offset by using reduced thicknesses, resulting in lower life cycle costs (as such, they are primarily used for surface courses only)
- In the past, variable performance due mainly to poor construction practices or construction during inclement weather (these issues have been corrected through improved specifications)
- More challenging construction due to more restrictive temperature requirements
- Potential odor and air quality problems
- Difficult to handwork

Ground tire rubber doesn't combine with asphalt binders in quite the same way as a polymer, but it offers many of the same benefits when used as a modifying agent. The increased viscosity in polymer-modified binders results from the swelling of polymer molecules. Similarly, crumb rubber particles also swell and cause an increase in viscosity when combined, or "reacted", with asphalt (ARTS 2002). In addition, ground tire rubber facilitates an increase in elasticity similar to that seen in polymer-modified binders. Thus, GTR-modified binders also increase resistance to rutting and cracking. In addition to offering advantages similar to those gained with polymers, crumb rubber can also extend pavement life in a different way. During the process of manufacturing tires, items such as carbon black and anti-oxidants are added to the rubber to prevent the aging. When GTR is used as an asphalt modifier, the anti-aging benefits provided by these anti-oxidants are passed on to the asphalt binder.

Specifying GTR is normally done in terms of physical and/or chemical properties. Commonly specified properties include: size/gradation, specific gravity, acetone extract, ash, carbon black, rubber hydrocarbon, and natural rubber content. The size/gradation of the GTR can influence the interaction of the rubber-asphalt blend; for example, a coarser GTR gradation generally requires a longer time to react than a fine grind.

Chemical properties of the rubber are important and have also been established to define the GTR material. These requirements insure the proper use of auto/truck tires in GTR materials. The inclusion of specification requirements for ash, carbon black, and rubber hydrocarbon insures that unacceptable materials (e.g., conveyor belts, etc.) are not used.

Asphalt binder can affect the final GTR-modified binder product in several ways. The base binder must be compatible with the GTR. Compatibility is controlled by the chemical composition of both the asphalt binder and the GTR as demonstrated by an increase in the viscosity of the GTR-modified asphalt binder with time. Most of the crumb rubber produced today is a homogenous blend of different rubber polymers; hence, compatibility is primarily dependent on the properties of the asphalt binder rather than the composition of the GTR material.

Terminally-Blended GTR-Modified Asphalt Binder

Terminally-blended (TB) GTR-modified binder materials use finely ground (nominal #30 or #40 mesh) crumb rubber and are typically blended at the asphalt refinery or the "terminal". Historically, the primary differences between TB and asphalt rubber (AR) binders were the amount of GTR used in the binder (TB: <10%; AR: 15-20%), the size of the crumb rubber used, and the use of specialized mixing equipment for AR due to larger crumb rubber sizes and amounts. However, in recent years, the rubber content in some TBs has been increased to 15-20 % or more (Hicks et al. 2010).

TB GTR-modified binder has been used since the mid-1980's beginning with Florida and Texas. Since then, it has been used in several other states, including California, Colorado, Louisiana, Arizona, and Nevada. TBs are produced at the refinery (or terminal) like any other polymer-modified asphalt. The asphalt is heated in a tank to an elevated temperature, and crumb rubber is introduced into the tank and is digested into the asphalt. During this process, the operator takes samples and runs a solubility test to ensure the rubber is completely digested. Most producers use a high-shear process to make sure the tire rubber is completed digested. The solubility of the finished product is generally above 97.5 %.

TB GTR-modified binders can be stored just like other asphalts. According to the industry, they are storage-stable binders because the tire rubber is fully digested into the asphalt. The material is delivered to the hot mix plant by tanker trucks just like virgin and SBS-modified binders. It is then mixed and shipped to the job just like any other asphalt binder.

TB GTR-modified binders have been used in both hot mix and chip seal applications. They are usually the preferred choice for dense-graded mixes, but they are also used in gap-and open-graded mixtures. The field-blended AR is usually used only in gap- or open-graded mixes. TB GTR-modified binders are also routinely used in hot applied chip seals and have been emulsified for use in emulsion chip and slurry seals (Hicks et al. 2010).

TB GTR-modified binders are produced in a closed-system plant which prevents particulates from entering the atmosphere. Crumb rubber is delivered to the processing plant and in some cases is introduced into the SBS polymer-modified asphalt in a wetting vessel, where both products are precisely blended by weight with the use of computer-controlled scales. The material is then "cooked" for approximately 16 hours under great pressure at temperatures as high as 425ºF. This method of blending the materials produces a more consistent and homogenous blend, assuring the complete breakdown of the crumb rubber into the asphalt. By contrast, in the field-produced "wet process", crumb rubber and asphalt binders are only blended for approximately 45 minutes at 425ºF.

In the next step in the process, the TB material is loaded into tanker transports and shipped directly to the contractor's storage tanks, where the material is required to be heated to 325ºF and constantly agitated until it is ready to be introduced into the aggregates at the asphalt plant.

Additional advantages of using the TB process in lieu of the "wet" or "dry" methods at the contractor's plant include:

1. No need for specialized equipment.
2. No portable plants required for blending of crumb rubber with asphalts.
3. No additional holding areas for storing the crumb rubber product.
4. Easiest for the contractor to incorporate into their traditional manufacturing process.
5. Completely eliminates potential problems with heating and blending of crumb rubber and asphalt products.
6. Eliminates smoke and particulates from entering the atmosphere.

Despite the many advantages of these systems, there are situations where these technologies, like most polymer binders and mixes, should not be used:

1. During cold or rainy weather with ambient temperatures below 13°C.
2. Over pavements with severe cracks.
3. Where considerable handwork is required.
4. Where traffic and deflection data are unknown.
5. Where haul distances are too long to maintain sufficient mix temperature for placement and compaction. (Warm Mix technology may eventually alleviate this problem.)

Liquid Anti-Stripping Additives in Asphalt Mixtures

Liquid anti-stripping additives (ASAs) in the form of cationic surface-active agents, principally amines, have been used for many years. In 1964, Mathews (1964) reviewed the use of amines as cationic additives in bituminous road materials and explained the problems associated with each of the materials. At the time of his research, heat-stable agents were not available, and the development of a heat-stable agent that could be kept in hot storage was essential to the future usage of the liquid ASAs. The difficulty of determining the quantity of additive present was expressed. The results from the immersion wheel tracking test, which was the best available test method at that time, and full-scale experiments did not correlate. However, this study found that cationic additives helped to bind bitumen to wet stone and prevented stripping. Some additives were more effective than others in specific applications because of differences in asphalt binder composition and aggregate surface condition.

In addition, hydrated lime has been widely used as an ASA to reduce the problem of stripping in HMA. Currently, the South Carolina Department of Transportation (SCDOT) specifies the use of hydrated lime as an ASA. This was based on a research conducted in the 1980s, which indicated that hydrated lime was very effective as an ASA (Busching et al 1986). Also, the heat stability of liquid ASAs was still an issue at that time. However, in the last 20 years, new liquid ASAs have been developed that are reported to be as effective as hydrated lime. Thus, a new evaluation of ASAs is needed to select the most effective ASA properties for use in South Carolina.

Recently, with the advent of new liquid ASAs in the market and because of their cheaper cost and ease of application, liquid ASAs are gaining popularity. The mechanism by which liquid ASAs work is by reducing the surface tension between the aggregate and the asphalt binder. When surface tension is reduced, increased adhesion of the binder to the aggregate is promoted. For this reason, liquid ASAs are also called surfactants.

Liquid ASAs are normally added in doses between 0.5 and 1.5% by weight of the binder (as recommended by the manufacturer). For example, in many cases this dose is determined by the actual mix design or in some states there is a specified minimum rate (SCDOT: 0.7%). The liquid ASA may be added either to the aggregate or to the heated binder. Both of these procedures have certain concerns. If added directly to the aggregate, uniform coating of all the aggregates is not ensured due to such a small quantity of the ASA. If added to the heated binder, care should be taken to ensure that the liquid ASA is heat stable and will not disintegrate at such high temperatures.

In response to a need to measure the amount of liquid ASA in either asphalt binders or mixtures for assurance testing or forensic investigation, the StripScan instrument was developed by InstroTek, Inc. The StripScan method involves three major steps. In the first step, the binder or mixture containing the liquid ASA is heated, which causes the ASA to vaporize. The vapor then flows through a measurement chamber where it reacts with a litmus paper. This reaction results in a change in color of the litmus paper. Finally, the color of the litmus paper is analyzed with a spectrophotometer to measure the change in color. A greater color change indicates the presence of a higher quantity of additive (InstroTek 2002).

Researchers have indicated that of the states surrounding South Carolina (Alabama, Florida, Georgia, North Carolina, Tennessee, and Virginia), all of these allow the use of liquid ASAs in all asphalt mixes except for Georgia (Putman and Amirkhanian 2006). Georgia DOT only allows the use of liquid ASAs on off-system roads, and hydrated lime (1% by weight of aggregate) is required in all other mixes. In the other states, it is the contractor's decision whether to use hydrated lime or liquid ASA. The contractor almost always selects a liquid ASA due to the reduced cost of liquid ASA and the simplicity of incorporating it into the mix compared to hydrated lime. Putman and Amirkhanian also found that in 2004, Virginia, Tennessee, and North Carolina all had ongoing research projects evaluating liquid ASAs in asphalt mixtures. Tennessee was interested in evaluating the "shelf life" of liquid ASAs, while Virginia and North Carolina were both evaluating the StripScan.

Each state uses some version of AASHTO T 283 to test the moisture susceptibility of their asphalt mix designs. The required tensile strength ratio (TSR) varies from state to state but remains in the range of 75 to 85%. Tennessee is the only state that currently uses a boil test in addition to TSR to evaluate moisture susceptibility.

The project completed in South Carolina (Putman and Amirkhanian 2006) indicated that:

1. All of the ASAs (liquid ASA and hydrated lime) evaluated in this study improved the moisture susceptibility over the control mixes containing no ASA. However, hydrated lime was the most effective in raising the TSR of the mixes above the SCDOT minimum design value of 85% for the ASA percentages evaluated in this study.
2. All of the ASAs were effective in producing mixtures with wet ITS values above the SCDOT minimum design value of 65 psi. This was not always the case with the control mixes containing no ASA.
3. The aggregate and binder sources both affect the effectiveness of ASAs.
4. The effect of storing binders containing liquid ASAs did have an effect on the moisture susceptibility of the mixes, but all of the mixes performed similarly. Additionally, the mixtures containing stored binder with hydrated lime also had increased moisture susceptibility.
5. The effect of the liquid ASAs on the properties of the asphalt binders was not significant in either the fresh or stored conditions. All binders met the criteria of a PG 64-22 in accordance to AASHTO M 320.

The project completed by National Lime Association (Sebaaly et al. 2010) pointed out that:

1. In the case of thermal cracking, both the lime and liquid additives improved the fracture temperature of the HMA mixtures from all five sources. However, the lime-treated mixtures showed significantly higher fracture stresses for all sources. This indicates that if thermal cracking occurs, the lime-treated mixtures will have significantly fewer cracks per mile than the non-treated and liquid-treated mixtures. Fewer cracks per mile translate directly into lower maintenance cost and time for repair.
2. Lime either maintained or improved the fatigue resistance of four out of the five sources of HMA mixtures. On the other hand, the impact of the liquid additives on the fatigue resistance of the HMA mixtures was source-dependent and very inconsistent. In most cases the liquid additive resulted in a significant change in the slope of the fatigue curve of the mix indicating an unbalanced impact on the low and high strains regions. This behavior contributed to the poor performance of the liquid-treated mixtures in the MEPDG fully mechanistic structural design.

3. Lime either maintained or improved the rutting resistance of the HMA mixtures from all five sources. The impact of liquid additives on the rutting resistance of the HMA mixtures was source dependent; for the non-moisture sensitive mixtures from Alabama and Illinois, the liquid additives reduced their rutting resistance compared to the non-treated mixtures.
4. The life cycle cost data for new construction projects revealed that the use of lime in HMA mixtures resulted in significant savings, which in some cases were more than 45%. The use of liquid anti-strip additives in HMA mixtures may result in additional cost, which in some cases could be as high as 50%. The data generated on the four mixtures from Alabama, California, Illinois, and South Carolina show that lime is highly compatible with asphalt binders and will generally result in life cycle cost savings in the order of 13-34%.

Natural Sands in Asphalt Mixtures

Natural sand can be defined as fine aggregates that are obtained from natural deposits rather than from aggregate crushing operations. Natural sand generally has rounded particles, excessive clay and organic materials, and when used in hot mix asphalt (HMA), it tends to lower its resistance to permanent deformation (rutting). As such, many highway agencies now limit the amount of natural sand in HMA for heavy duty pavements in order to minimize rutting potential. However, the use of generic terms such as natural or manufactured sand in specifications is not rational. It is the shape and texture of these sands that actually determines the rutting resistance of the HMA mixes in which they are used. There are some natural sands which are sub-angular rather than rounded, and on the other hand, some crushed or manufactured sands are sub-rounded rather than completely angular. There is a definite need to quantify the shape and texture of the fine aggregate in order to specify in a more rational manner rather than in a generic fashion (Shklarsky and Livneh 1964).

Shklarsky and Livneh (1964) completed a very extensive study of the difference between natural gravel and crushed stone aggregates in combination with natural sand and crushed stone fine aggregates. Several variables were studied, including the Marshall stability and flow, resistance to moving wheel loading, resistance to splitting, immersion compression strengths, permeability, and angle of internal friction and cohesion as measured in triaxial shear. They reported that replacement of the natural sand with crushed fines improves incomparably the properties of the product, increases its stability, reduces rutting, improves moisture susceptibility resistance, reduces bitumen sensitivity, increases the void ratio, and brings the mixture (with gravel coarse aggregate) to the quality level of one with crushed coarse and fine aggregates. On the other hand, replacement of the coarse material with crushed coarse aggregate entails no such decisive effect (Kandhal et al. 1991).

Significant increases in stability were reported by Wedding and Gaynor (1961) when using crushed gravel (CG) in place of natural gravel. They concluded that the use of crushed gravel sand in place of natural sand is nearly equal in effectively raising stability as the use of 25% CG in the coarse aggregate (Kandhal et al. 1991).

Maupin (1970) has reported a laboratory investigation of the effects of particle shape on the fatigue behavior of an asphalt surface mixture. He used three aggregates: round gravel, crushed limestone, and slabby slate. Constant strain mode fatigue tests were conducted, and it was shown that the mixture containing round gravel had longer fatigue life than the other mixtures (Kandhal et al. 1991).

A particle index value of 14 seems to divide the natural and manufactured sands when using ASTM D3398. This value can probably be used for specification purposes when ASTM D3398 is used. All manufactured sands except one exhibited higher particle index values than 14, and all natural sands exhibited lower particle index values (Kandhal et al. 1991).

The rutting resistance for 12.5-mm mixtures containing natural sand was greater than that of mixtures with manufactured sand. But for 9.5-mm gradations, mixtures with natural sand showed a reduced performance compared to the same mixtures containing manufactured sand. In other words, certain amounts of natural sand could be used in these mixtures without any significant effect on the rutting potential. However, the TSR test results revealed that mixtures with natural sands are relatively more moisture susceptible. An increase in thickness of 9.5-mm mixtures containing natural sand may improve the fatigue life to a desired level.

Chapter 4 – Materials and Experimental Design

A work plan was prepared, in coordination with SCDOT officials, for a coordinated series of laboratory experiments to assess the rheological and engineering properties of mixtures made with alternate binders. In addition, the examination of engineering properties of mixtures made with liquid ASAs and natural sands was included in the plan in order to determine the effectiveness of most asphalt designs used by SCDOT with and without modified binders. The plan provides specific information on and justification for the above-mentioned areas of research including the following:

- Rheological property assessments of various alternate modified asphalt binders in terms of various aging states;
- Assessment of mixture volumetric properties as well as engineering properties (including moisture susceptibility, permanent deformation, dynamic modulus, and flow number) for mixtures containing alternate modified asphalt binders.
- Assessment of compatibility of ASAs (lime and liquid ASAs) with alternate binder modifiers
- Recommendations on the use of various alternate modified asphalt binders in South Carolina
- Recommendations on the use of liquid ASAs in asphalt mixtures; and
- Recommendations on the use of natural sand in selected mix types in South Carolina.

Alternate Asphalt Binder Modifiers: Binder Testing (Objective 1)

The objectives of this research were achieved through the completion of the following tasks. A detailed flowchart of the full potential range of testing (prior to possible selective sample reduction) is shown in Figures 4.1, 4.2, and 4.3. Any recommended changes to evaluation procedures for alternate modified asphalt binders are provided to SCDOT in this report. Based on recommendations from SCDOT, only two base binder sources were used in this study.

- Study the high-temperature rheological properties of original alternate modified asphalt binders. As not much is known about the properties of alternate modified asphalt binders and how they behave under different stress conditions, rheological testing of alternate modified asphalt binders was conducted before using them in various mixtures. The testing plan is shown in Figure 4.1.
  - Rotational viscometer – AASHTO T 316
  - Dynamic shear rheometer (DSR) – AASHTO T 315

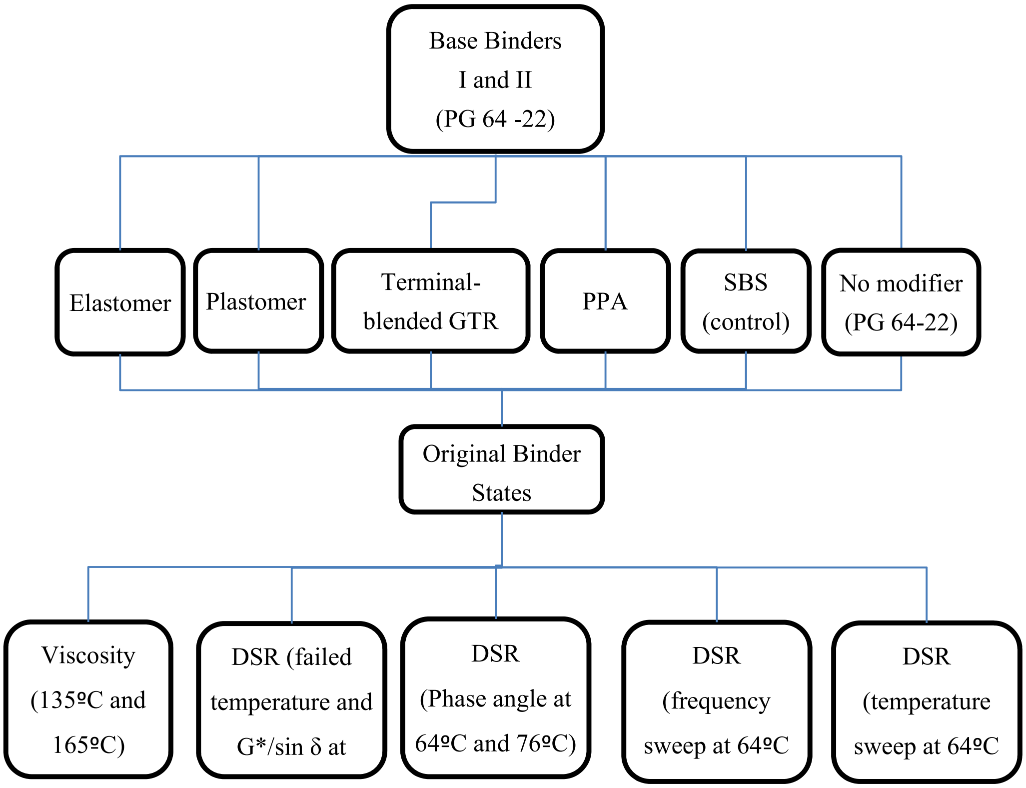


Figure 4-1 Rheological properties of alternate modified binders at Original state

- Study the high-temperature rheological properties of alternate modified asphalt binders after rolling thin film oven (RTFO) aging procedure. This investigated the effects of a short-term aging procedure on rheological properties of these selected alternate modified binders. The testing plan was as per Figure 4.2.
  - Dynamic shear rheometer (DSR) – AASHTO T 315
  - Multiple stress creep recovery (MSCR) – AASHTO T350

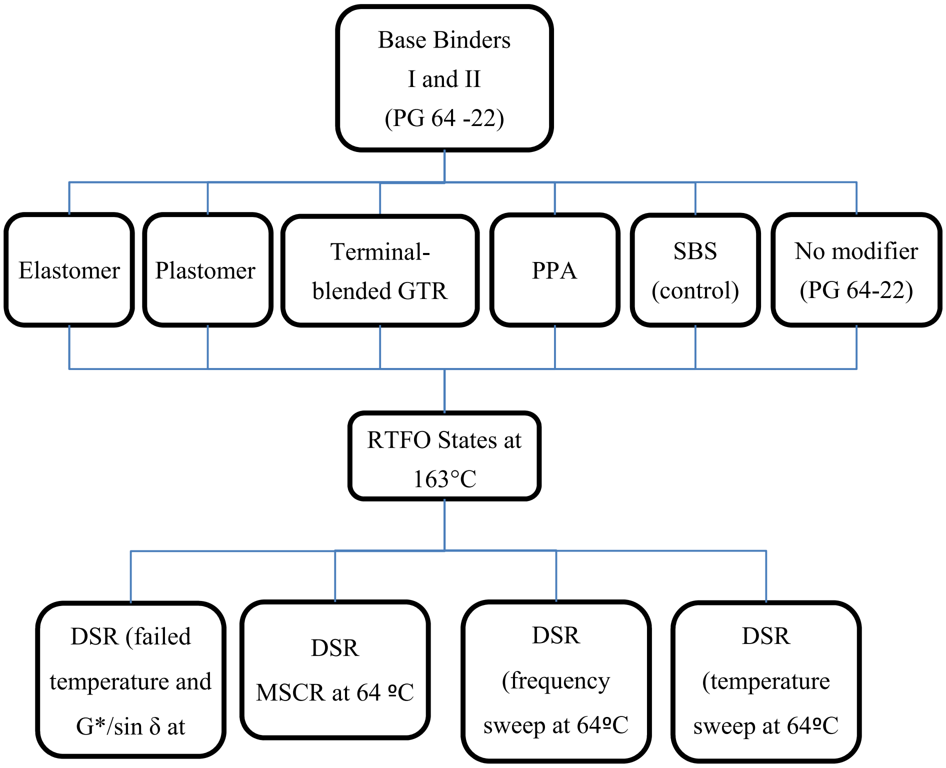


Figure 4-2 Rheological properties of alternate modified binders at RTFO state

- Study the intermediate- and low-temperature rheological properties of alternate modified asphalt binders after RTFO and pressure aging vessel (PAV) aging procedures. This investigated major effects of a long-term aging procedure on rheological properties of these selected alternate modified binders. The testing plan was as per Figure 4.3.
    - Dynamic shear rheometer (DSR) – AASHTO T 315
    - Bending beam rheometer (BBR) – AASHTO T 313.
    - Multiple stress creep recovery (MSCR) – AASHTO T350

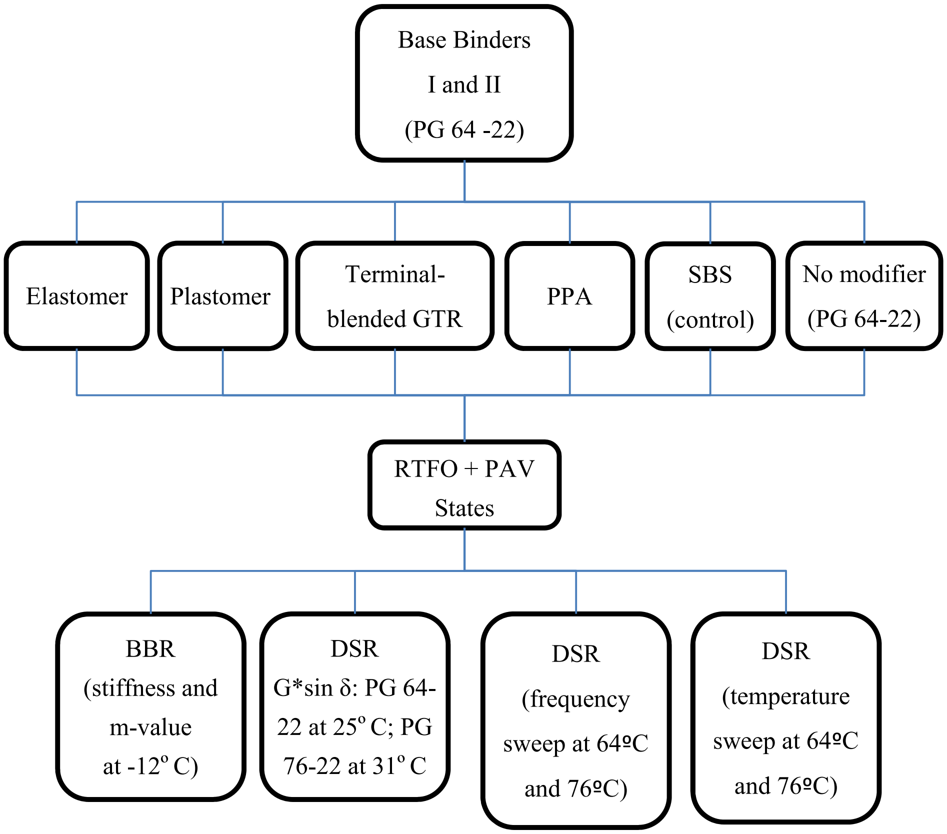


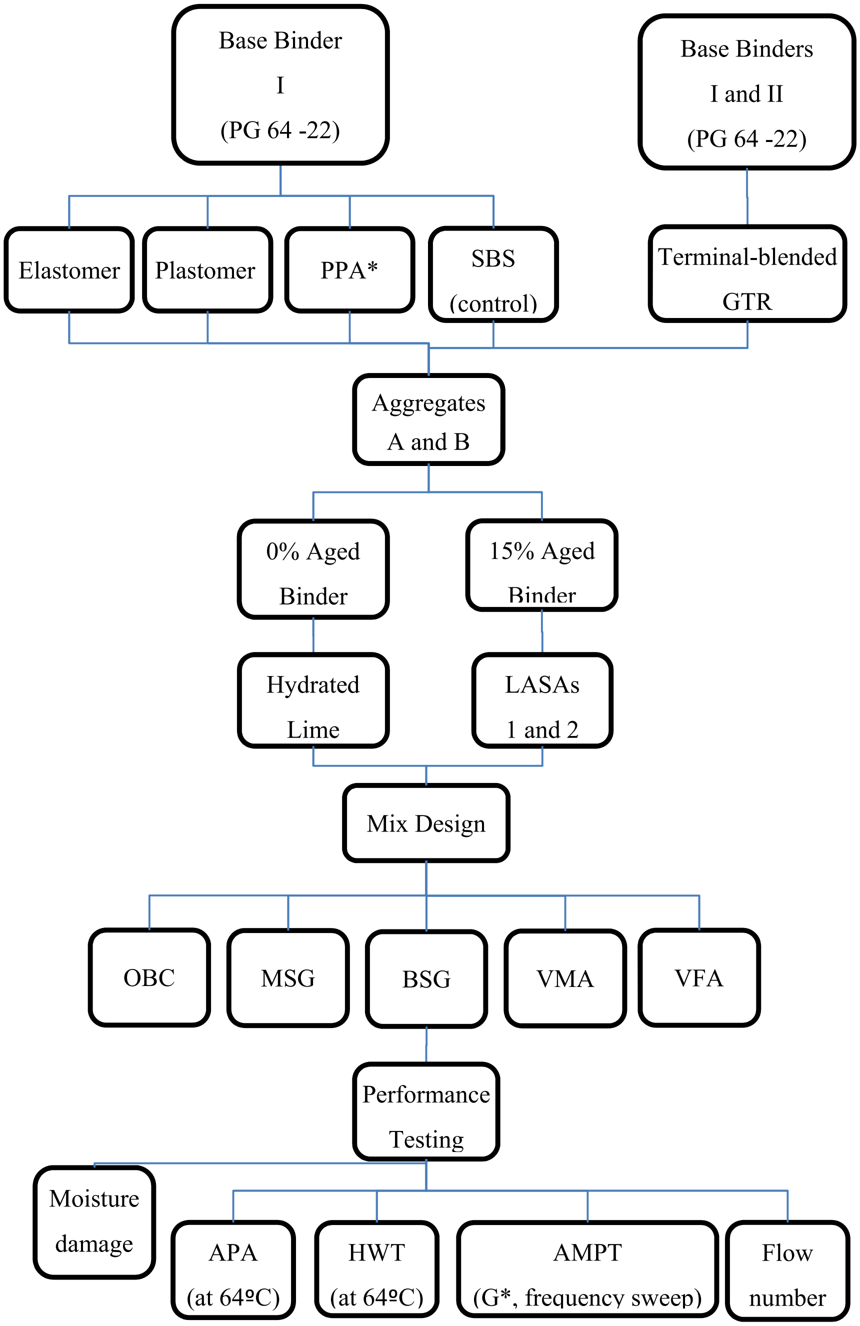
Figure 4-3 Rheological properties of alternate modified binders at RTFO + PAV state

Alternate Asphalt Binder Modifiers and Liquid ASAs: Mix Design and Testing (Objectives 1 and 2)

Mix designs were performed according to SCDOT procedures and specifications for alternate modified mixtures using selected aggregate sources, selected binder sources, hydrated lime and selected liquid ASAs. Two binder sources, two aggregate sources, one lime source, two liquid ASA sources and two reclaimed asphalt pavement (RAP) concentrations were selected based upon input from the Steering Committee. As shown in Figure 4.4, the effects of alternate modified binders on mix design (VMA, VFA, optimum binder content, etc.) as well as engineering properties (moisture susceptibility, permanent deformation, dynamic modulus, and flow number) were investigated. Any recommended changes to mix design and evaluation procedures for alternate modified mixes and liquid ASAs are provided to SCDOT in this report. The following testing procedures were used for all the mixtures.

- Moisture susceptibility (without freeze-thaw resistance) – AASHTO T 283
- Rut resistance – AASHTO TP 63 (APA) / AASHTO T 324 (HWT)

- Dynamic modulus and flow number - AASHTO TP 79
- Dynamic modulus master curves - AASHTO PP 61



*Note: Use only 1 aggregate source

Figure 4-4 Properties of modified mixtures

Natural Sands and Liquid ASAs: Mix Design and Testing (Objectives 2 and 3)

The effects of using natural sand in selected mixes were investigated. The effects of liquid ASAs on these same mixtures were also investigated. Two aggregate sources, one asphalt binder source, one binder grade (PG 64-22), one concentration of natural sand (20%), one RAP source, two liquid ASA sources, and one hydrated lime source were selected based upon input from the Steering Committee. Also based on the input from the Steering Committee, testing was performed on samples made from mixtures meeting Surface Type C and Surface Type B design requirements from SCDOT. For the Surface Type C mixtures, 30% aged binder was used, and for the Surface Type B mixtures, 25% aged binder was used. The angularity of the sand sources was also tested. Any recommended changes to mix design and evaluation procedures for the use of natural sands and liquid ASAs are provided to SCDOT in this report. The tests shown in Figure 4.5 were included in this study.

- Fine aggregate angularity (uncompacted void content) – AASHTO T 304
- Moisture susceptibility (without freeze-thaw resistance) – AASHTO T 283
- Rut resistance – AASHTO TP 63 (APA) / AASHTO T 324 (HWT)
- Dynamic modulus and flow number - AASHTO TP 79
- Dynamic modulus master curves - AASHTO PP 61

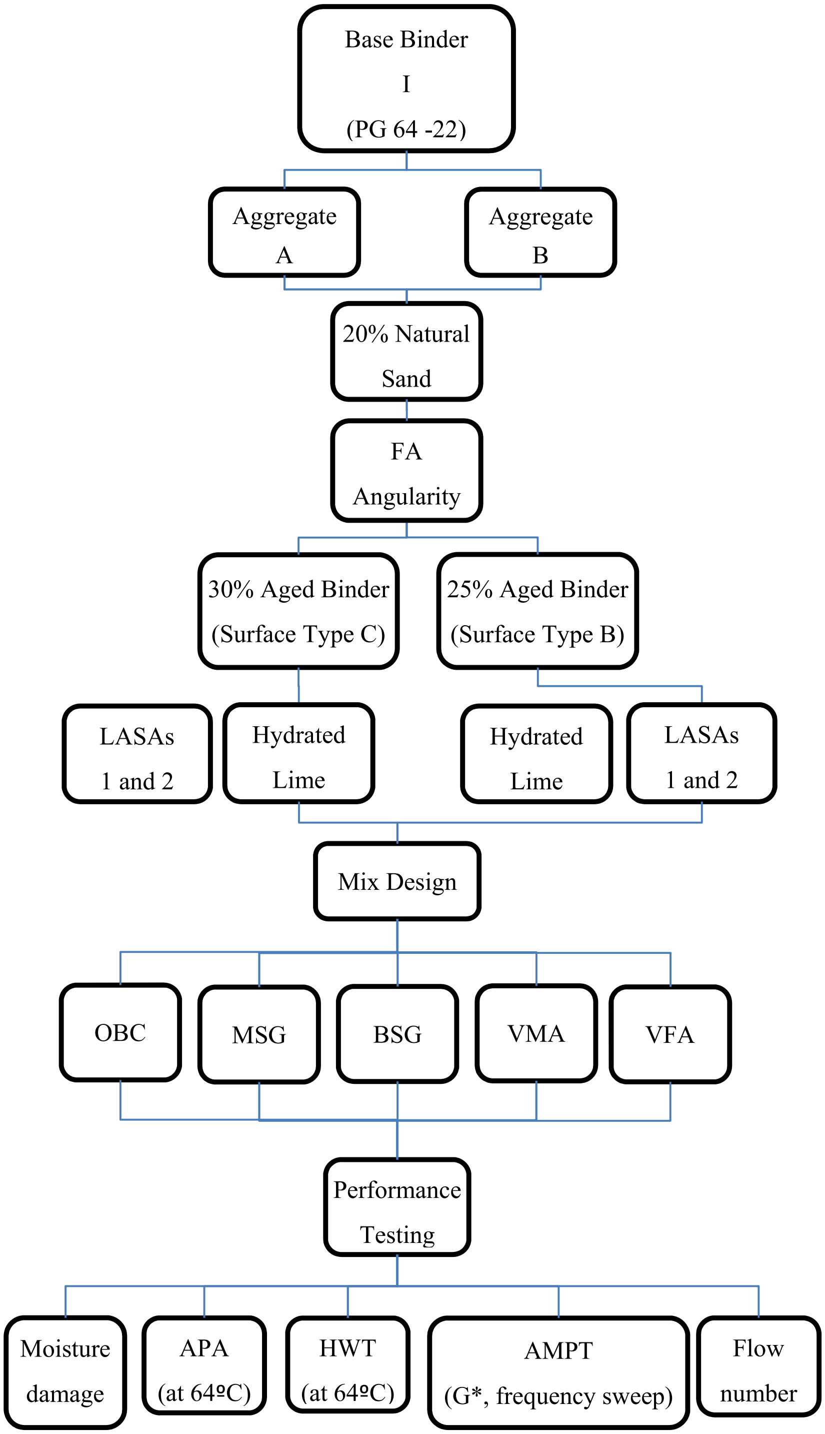


Figure 4-5 Properties of mixtures containing natural sands

Chapter 5 – Results: Alternate Modified Binders

Introduction

In this section of the report, the results of various binder tests for different binder sources and polymers are presented. In addition, the moisture susceptibility of various mixtures using different aggregate sources and anti-strip additives are discussed. The results of dynamic modulus and flow number tests of the mixtures tested are also shown in this section. The engineering properties of the two aggregate sources are shown in a later chapter of this report in Table 7.1. The mix designs from this portion of the research are shown in Appendix A.

Binder Testing

Two binder sources were selected as base binders (PG 64-22, referred to as polymer 0 in this section of the report). One of the sources (A) is a Venezuelan source while binder source B is a mix of several sources. Several polymers were used to modify these binders. Polymer 1 refers to SBS binder obtained from the suppliers. These binders contain approximately 3.5% SBS, by weight of the binder. Polymer 2 is a plastomer that acts as a warm mix additive and as an anti-strip additive agent. Polymer 3 is a plastomer-based material (similar to polymer 2), which is added at a rate of 1-3% by weight of the binder. It is Ethylene-based (5,000-15,000 MW) polyolefin polymer. For these two polymers, no butadiene is required or added to the binders. Polymer 4 is a laboratory-prepared ground tire rubber (GTR) binder where 10% of crumb rubber (passing #30 mesh) was added to the base binder (PG 64-22) producing a modified binder (PG 76-22). The crumb rubber was mixed at 800 rpm for at least 30 minutes. Polymer 5 is a combination of SBS and PPA (Acid modified binder). Polymer 6 is an elastomer. Polymer 7 is a terminally-blended GTR binder, which was obtained from a source outside of the state (Florida).

There were a total of 16 binder combinations. All of these binders were tested using various Superpave binder testing procedures. All testing procedures were conducted according to the AASHTO, ASTM or SCDOT testing procedures. The viscosities of all binders were obtained, and the results are shown in Table 5.1. The viscosities were measured at three temperatures: 135, 150 and 165 C (AASHO T 316). The results indicated that, in general, binder source A is more viscous than binder source B. In general, ground tire rubber (GTR) binders, either lab-produced (A4 or B4) or terminally-blended (TB), produced the highest viscosity values compared to all other binders. The TB and lab-produced GTR binders produced approximately 25% and 20% higher viscosity values compared to SBS binders for binder sources A and B, respectively. Figures 5.1 to 5.4 show the results of viscosity for all combinations graphically. Figure 5.2 indicates that SBS binder for source A produced viscosity values that were lower than the two GTR binders, the elastomer binder and the PPA+SBS binder.

Table 5-1 Viscosity Values of Various Alternative Binders

Binder Type	Binder Source A			Binder Type	Binder Source B		
	135°C (c.p.)	150°C (c.p.)	165°C (c.p.)		135°C (c.p.)	150°C (c.p.)	165°C (c.p.)
A0	550.4	270.8	150.8	B0	435.0	210.8	125.8
A1	1620.7	810.8	429.2	B1	1510.0	714.2	375.2
A2	697.5	335.8	186.7	B2	525.8	260.0	145.0
A3	629.2	311.7	170.8	B3	494.2	250.0	140.8
A4	2188.3	1061.7	558.3	B4	1870.0	960.0	488.3
A5	1816.3	841.7	433.3	B5	1216.3	556.7	277.5
A6	1911.7	865.0	465.0	B6	1685.0	625.0	325.0
TB**	2140.7	1044.3	575.8	TB**	2140.7	1044.3	575.8

*Notes: 0~Control (PG 64-22); 1~SBS; 2~Plastomer 1; 3~Plastomer 2; 4~Lab-blended 10% GTR; 5~PPA+SBS; 6~Elastomer; TB**~Terminally-blended GTR from Binder Source C*

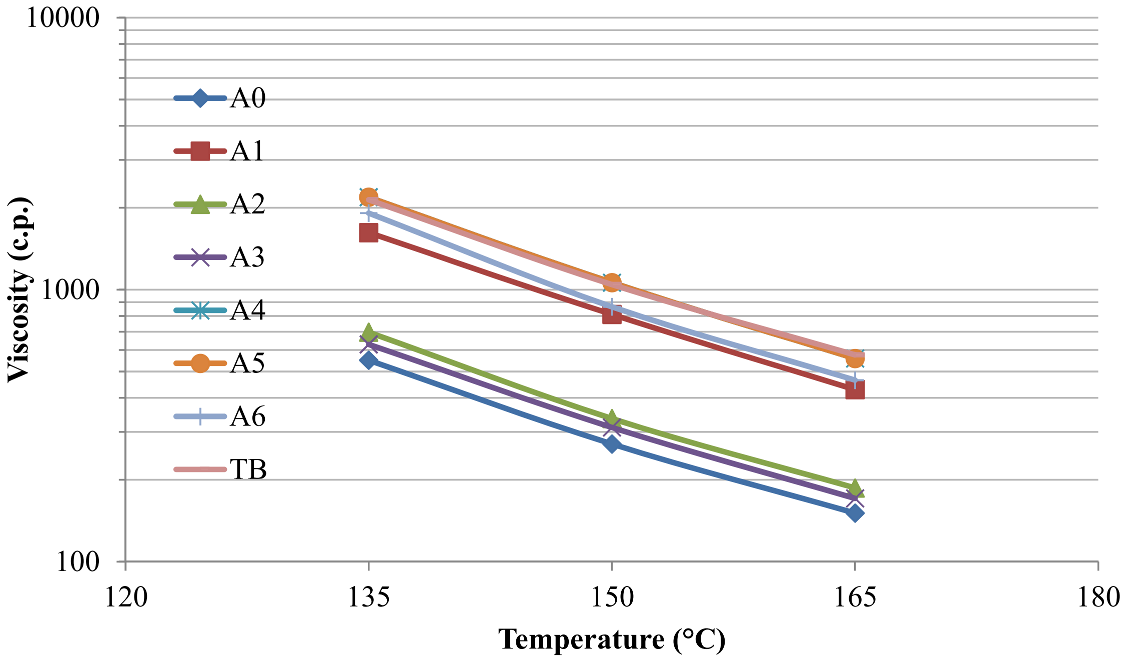


Figure 5-1 Viscosity Values of Binder Source A with Various Alternative Modifiers

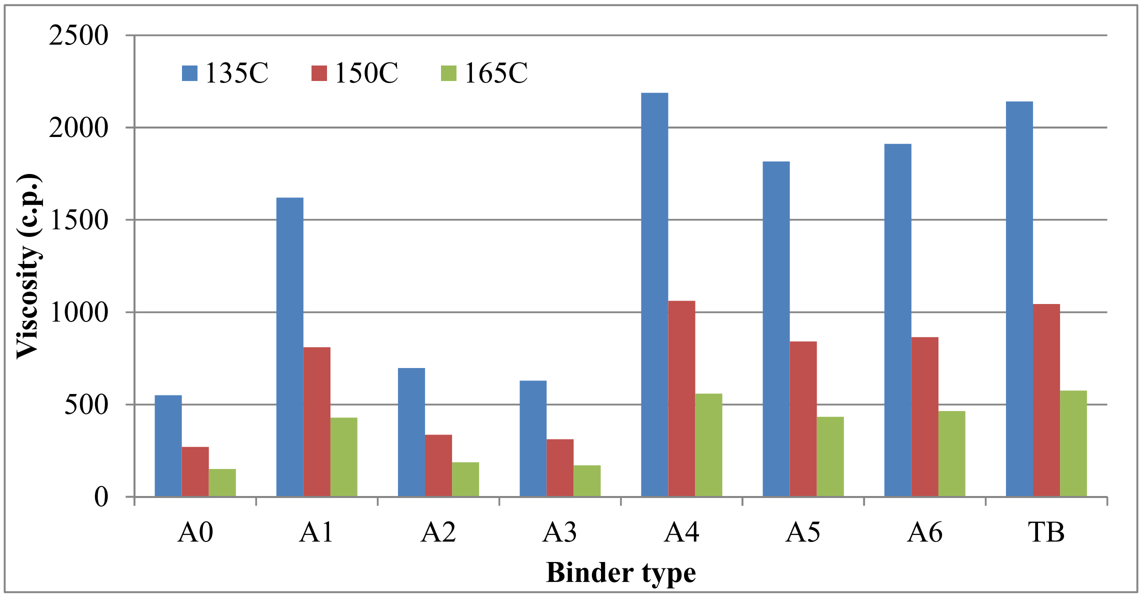


Figure 5-2 Viscosity Values of Binder Source A with Various Alternative Modifiers

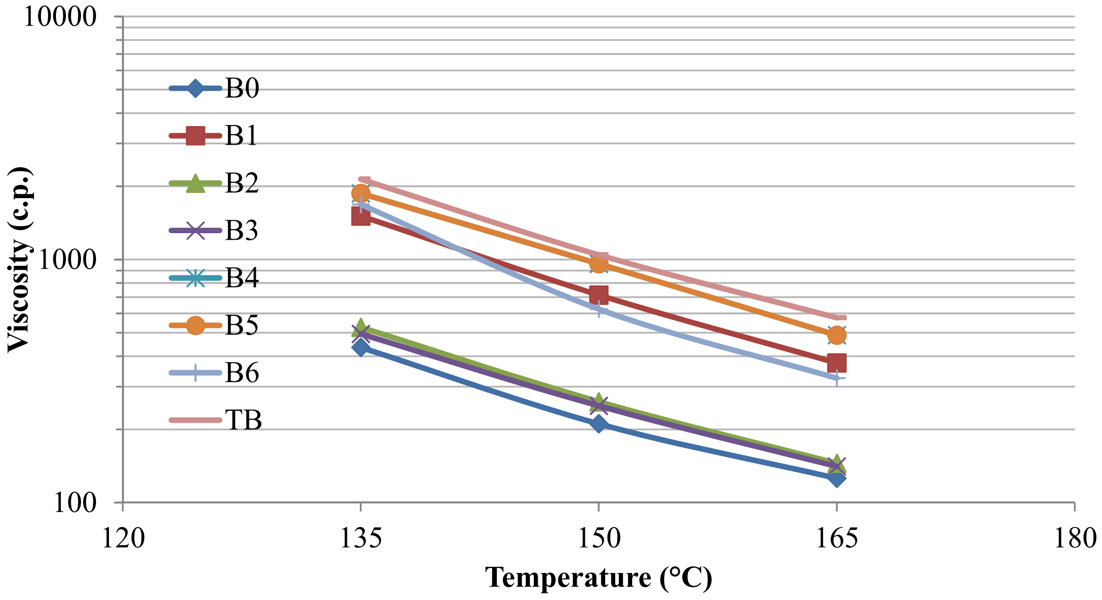


Figure 5-3 Viscosity Values of Binder Source B with Various Alternative Modifiers

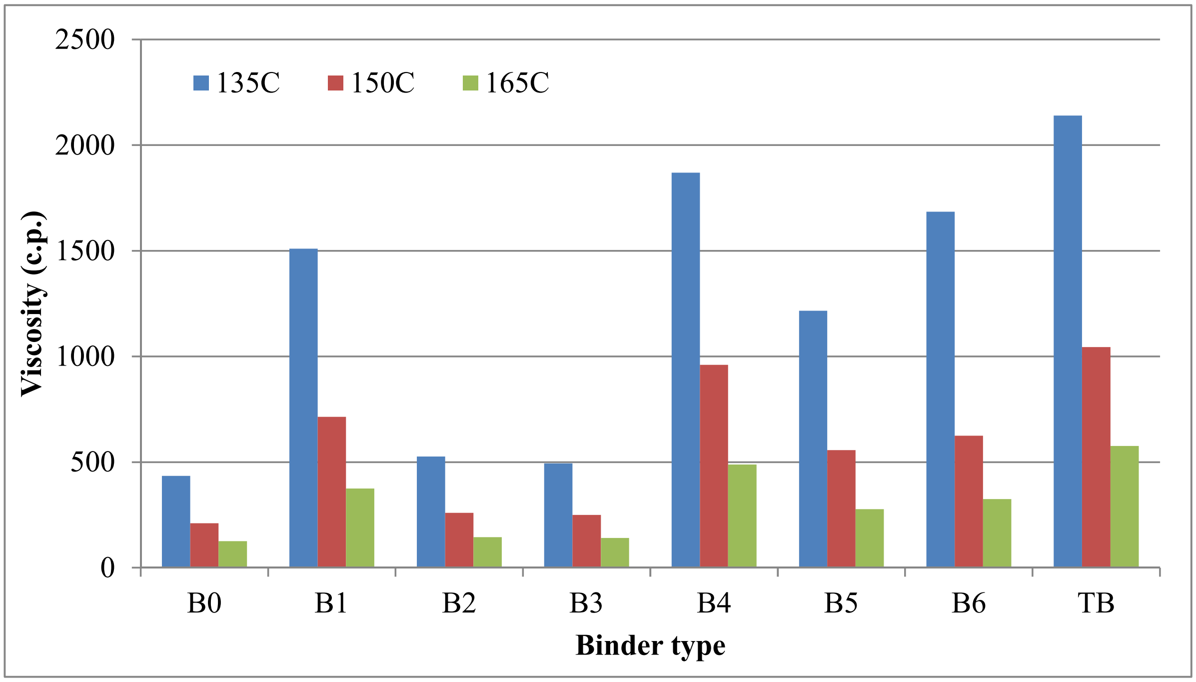


Figure 5-4 Viscosity Values of Binder Source B with Various Alternative Modifiers

The high failure temperatures of all binders were measured according to AASHTO T 315 testing procedures and the results are shown in Table 5.2 and Figures 5.5 and 5.6. The results in Table 5.2 indicate that base binder source A has a higher high failure temperature than binder source B. All of the binders, except the lab-prepared GTR binder with source B, produced a PG 76-22 binder after the modifications with various modifiers. TB binder produced the highest high failure temperature compared to all other binders, regardless of the binder source. The statistical analysis of the differences between different binders is shown on each graph. If there is no statistically-significant difference between two binders, the same letter (lower case) is used. For example, Figure 5.5 indicates that, statistically, there are no differences between polymer 1 (SBS) and polymer 2 (a plastomer) when considering the high temperature failure of binder source A. However, considering binder source B, the same binders produced statistically different results. The results of phase angle of all binder combinations are also shown in Table 5.2. In general, the phase angle of TB binder was the lowest among all binders, regardless of the binder source. The highest phase angle value for both sources was the base binder (PG 64-22). The phase angle results for binder sources A and B are shown graphically in Figures 5.7 and 5.8, respectively.

Table 5-2 Failure Temperatures and Phase Angles of Binders with Various Modifiers

Binder Type	Binder Source A				Binder Type	Binder Source B			
	Failure temp. (°C)		Phase angle (degree) at 76°C			Failure temp. (°C)		Phase angle (degree) at 76°C	
	Mean	Std. Dev.	Mean	Std. Dev.		Mean	Std. Dev.	Mean	Std. Dev.
A0	68.8	0.4	85.0*	0.1	B0	66.4	0.4	86.7*	0.1
A1	78.7	0.1	71.9	0.1	B1	77.9	0.2	71.9	0.1
A2	78.7	0.5	80.8	0.4	B2	81.2	0.1	75.4	0.5
A3	80.7	0.1	72.4	0.4	B3	81.5	0.4	71.0	0.3
A4	77.1	0.1	84.8	0.2	B4	75.7	0.1	83.6	0.2
A5	80.3	0.1	78.8	0.0	B5	79.0	0.5	78.2	3.2
A6	77.8	0.1	80.4	0.0	B6	78.2	0.1	76.0	0.2
TB**	82.8	0.0	71.5	0.1	TB**	82.8	0.0	71.5	0.1

*Notes: * ~Test at 64°C; 0~Control (PG 64-22); 1~SBS; 2~Plastomer 1; 3~Plastomer 2; 4~Lab-blended 10% GTR; 5~PPA+SBS; 6~Elastomer; TB**~Terminally-blended GTR from Binder Source C*

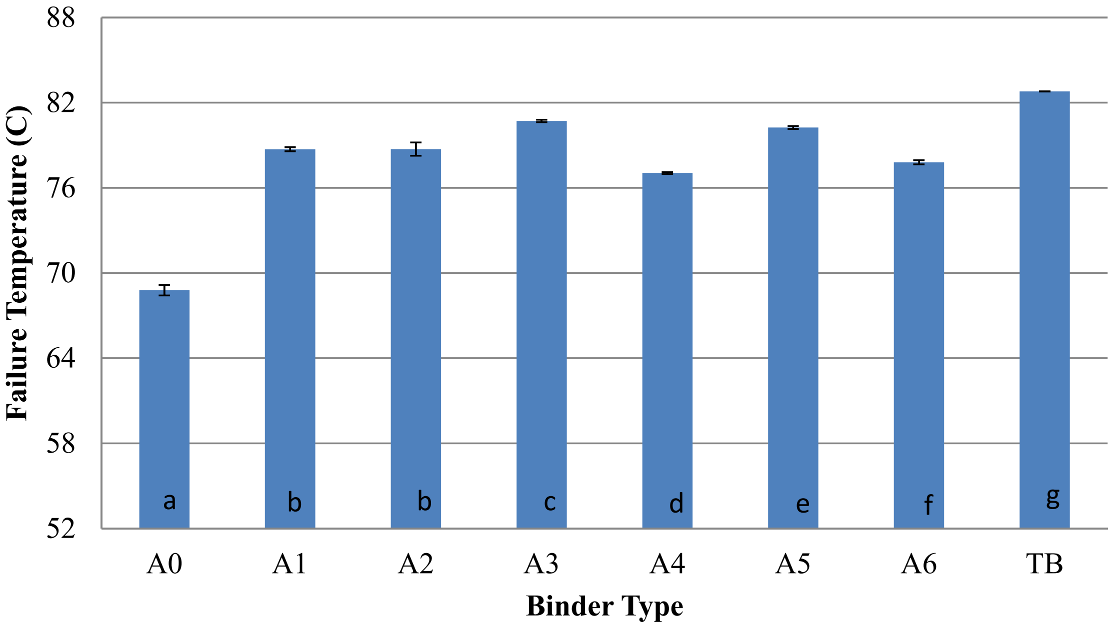


Figure 5-5 Failure Temperatures of Binder Source A with Various Alternative Modifiers

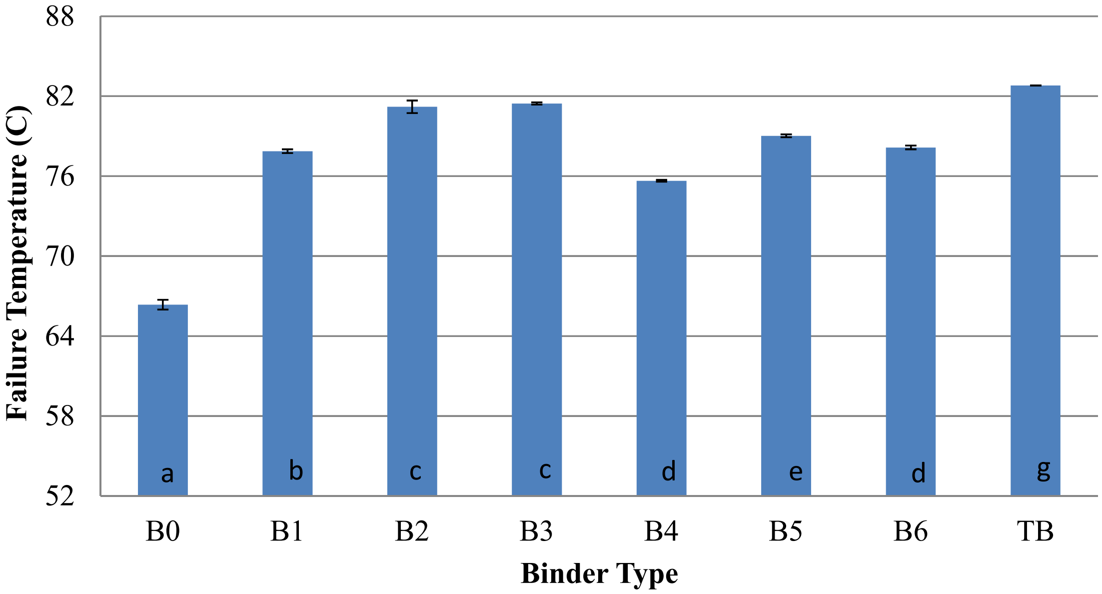


Figure 5-6 Failure Temperatures of Binder Source B with Various Alternative Modifiers

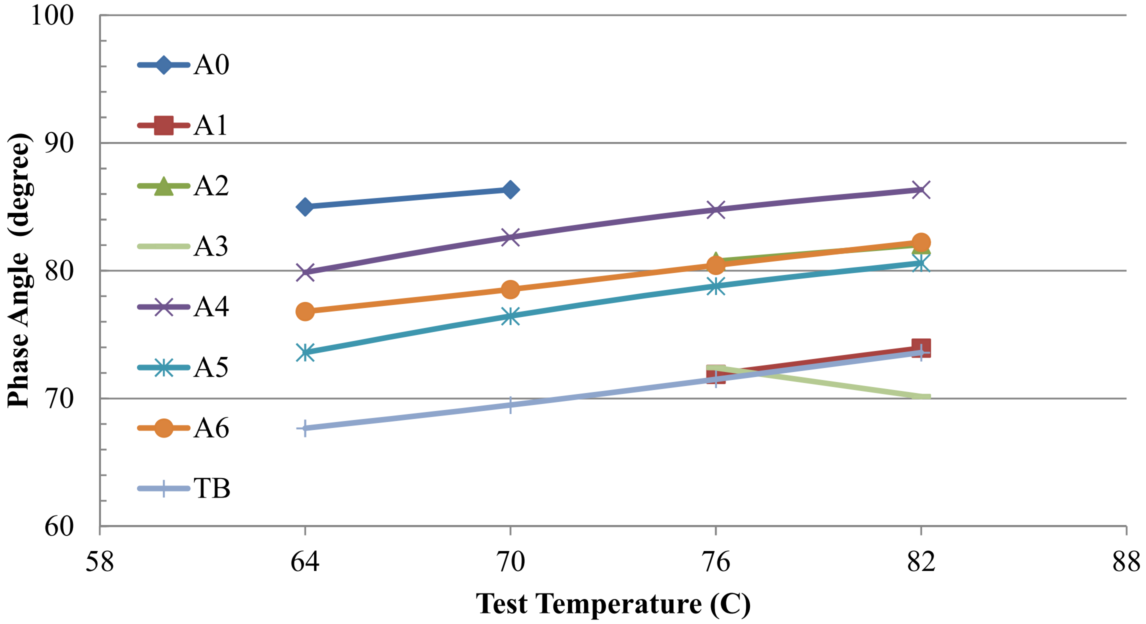


Figure 5-7 Phase Angle Values of Binder Source A with Various Alternative Modifiers

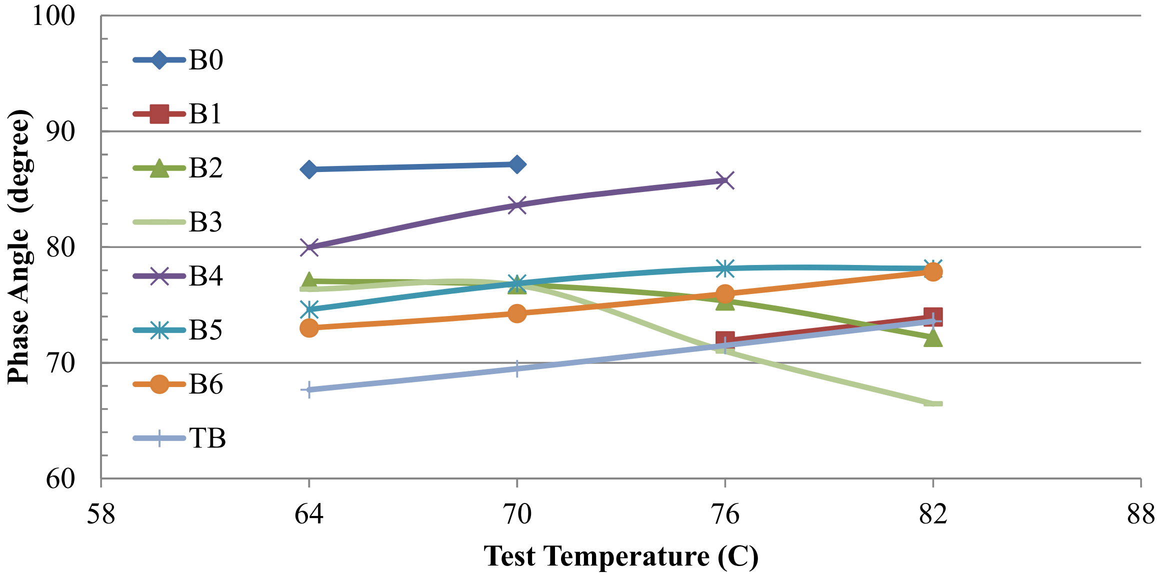


Figure 5-8 Phase Angle Values of Binder Source B with Various Alternative Modifiers

The G*/sin δ values of binder sources A and B are shown in Figures 5.9 and 5.10, respectively. The TB source produced the highest G*/sin δ values compared to all binder combinations. As expected, the virgin base binders produced the lowest values of G*/sin δ.

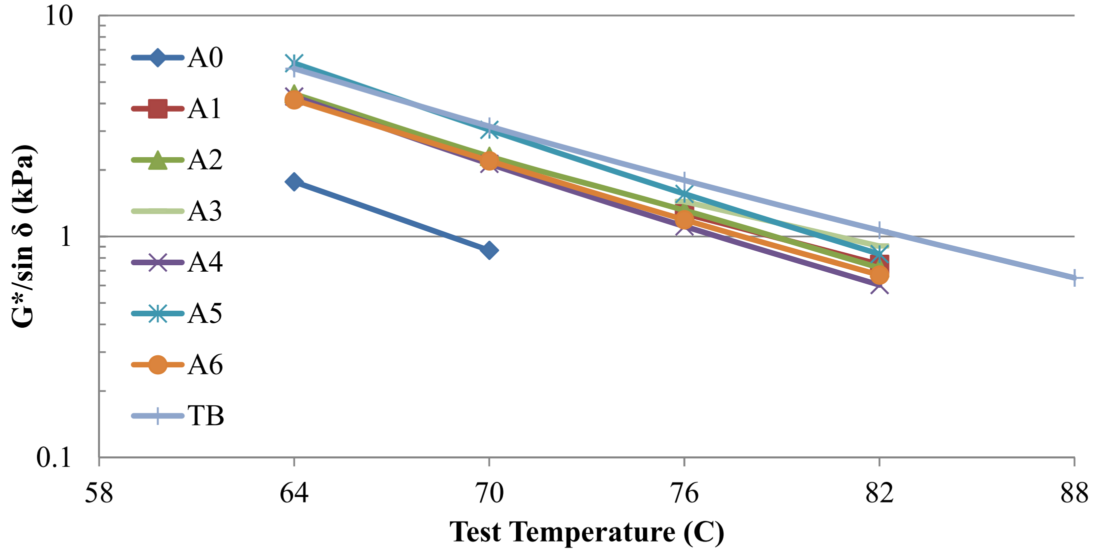


Figure 5-9 G*/sin δ of Binder Source A with Various Alternative Modifiers

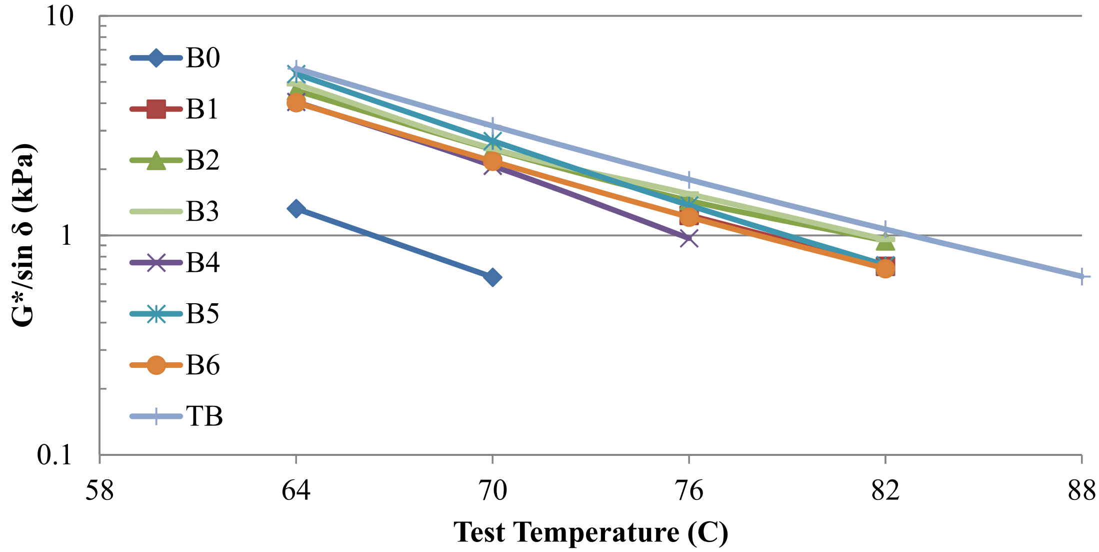


Figure 5-10 G*/sin δ of Binder Source B with Various Alternative Modifiers

The high-temperature rheological properties of alternate modified asphalt binders after completing the rolling thin film oven (RTFO) aging procedure were investigated. This phase of the research project investigated the effects of a short-term aging procedure on rheological properties of alternate modified binders using the testing procedures described in AASHTO T 315 (DSR) and AASHTO T 350, the multiple stress creep recovery. Table 5.3 shows the results of the failure temperature and phase angle of the modified binders after RTFO aging.

The failure temperatures of binder sources A and B after the RTFO aging process are shown in Figures 5.11 and 5.12, respectively. For binder source A, the results indicate that binders containing polymer 1 (SBS) and polymer 4 (lab-blended GTR) produced the highest failure temperatures. However, for binder B, polymers 1 and 6 (elastomer) produced the highest failure temperatures. The statistical analyses indicate that there are statistical differences among the modifiers.

G* and δ are used as predictors of HMA rutting and fatigue cracking. Rutting is a concern in early years of the pavement life; however, in later years, fatigue cracking becomes a major concern. An asphalt binder should not deform too much (i.e., should be stiff), but should also be somewhat elastic.

Therefore, the complex shear modulus elastic portion, G*/sinδ (Figure 5.6), should be large. When rutting is of greatest concern (during an HMA pavement's early and mid-life), a minimum value for the elastic component of the complex shear modulus is specified. Intuitively, the higher the G* value, the stiffer the asphalt binder is (able to resist deformation), and the lower the δ value, the greater the elastic portion of G* is (able to recover its original shape after being deformed by a load).

The G*/sin δ of binder sources A and B binders are shown in Figures 5.13 and 5.14, respectively. In addition, the phase angles of these binders are depicted in Figures 5.15 and 5.16. The results of the multiple stress creep recovery (MSCR) testing are shown in Figures 5.17 to 5.20. This test provides a more accurate indicator of rutting performance of a typical binder. The major benefit for this test is that it eliminates other testing procedures designed to indicate polymer modification to an asphalt binder (e.g., elastic recovery, toughness and tenacity, force ductility, etc.).

Table 5-3 Failure Temperatures and Phase Angles of Binders with Various Modifiers, RTFO Aged

Binder Type	Binder Source A				Binder Type	Binder Source B			
	Failure temp. (°C)		Phase angle (degree) at 76°C			Failure temp. (°C)		Phase angle (degree) at 76°C	
	Mean	Std. Dev.	Mean	Std. Dev.		Mean	Std. Dev.	Mean	Std. Dev.
A0	74.3	0.0	79.5*	0.1	B0	70.6	0.4	86.7*	0.2
A1	85.4	0.1	65.1	0.2	B1	82.0	0.7	61.5	0.3
A2	83.2	0.8	76.0	0.8	B2	75.3	1.9	77.5	2.3
A3	82.6	1.6	76.0	0.5	B3	78.0	0.4	77.3	0.1
A4	85.6	0.7	62.4	0.7	B4	78.3	0.8	66.9	0.2
A5	80.8	0.1	71.2	0.2	B5	79.0	0.3	69.9	0.5
A6	78.4	0.2	74.9	0.0	B6	83.9	3.5	64.9	1.9
TB**	78.3	0.8	67.9	0.2	TB**	78.3	0.8	67.9	0.2

*Notes: * ~Test at 64°C; 0~Control (PG 64-22); 1~SBS; 2~Plastomer 1; 3~Plastomer 2; 4~Lab-blended 10% GTR; 5~PPA+SBS; 6~Elastomer; TB**~Terminally-blended GTR from Binder Source C*

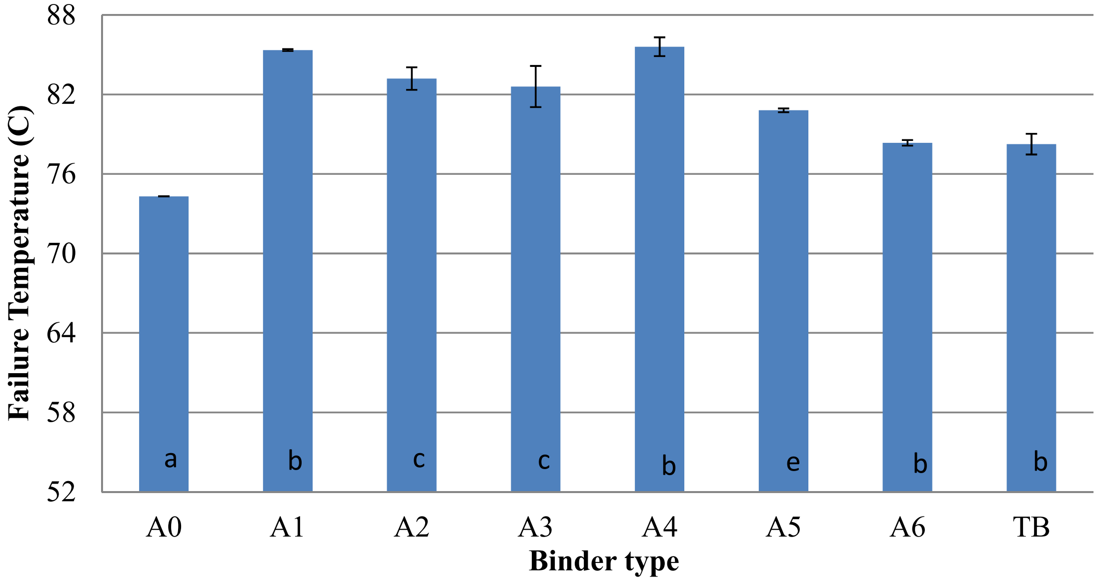


Figure 5-11 Failure Temperatures of Binder Source A with Various Alternative Modifiers, RTFO Aged

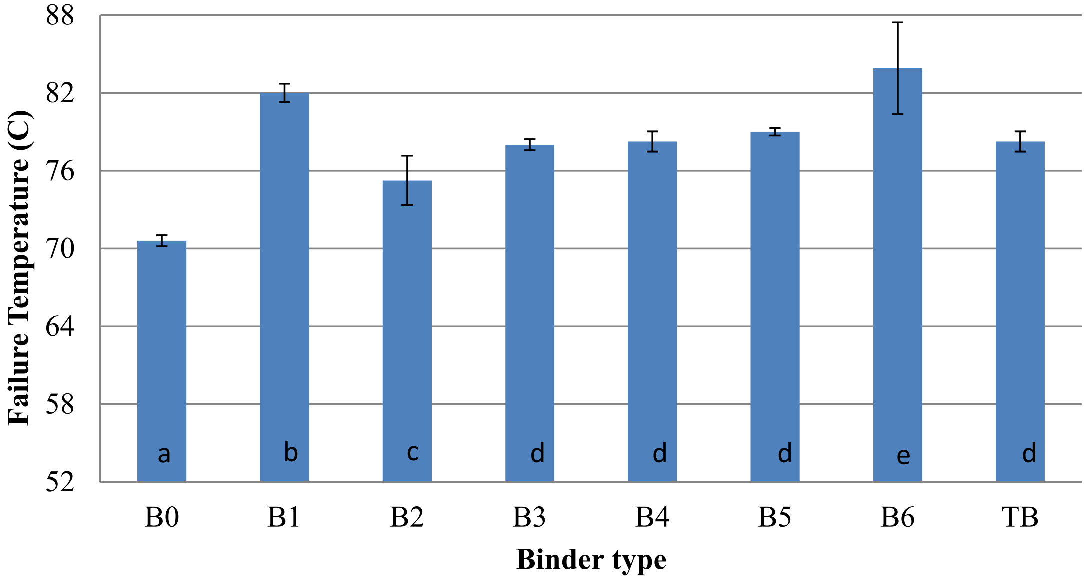


Figure 5-12 Failure Temperatures of Binder Source B with Various Alternative Modifiers, RTFO Aged

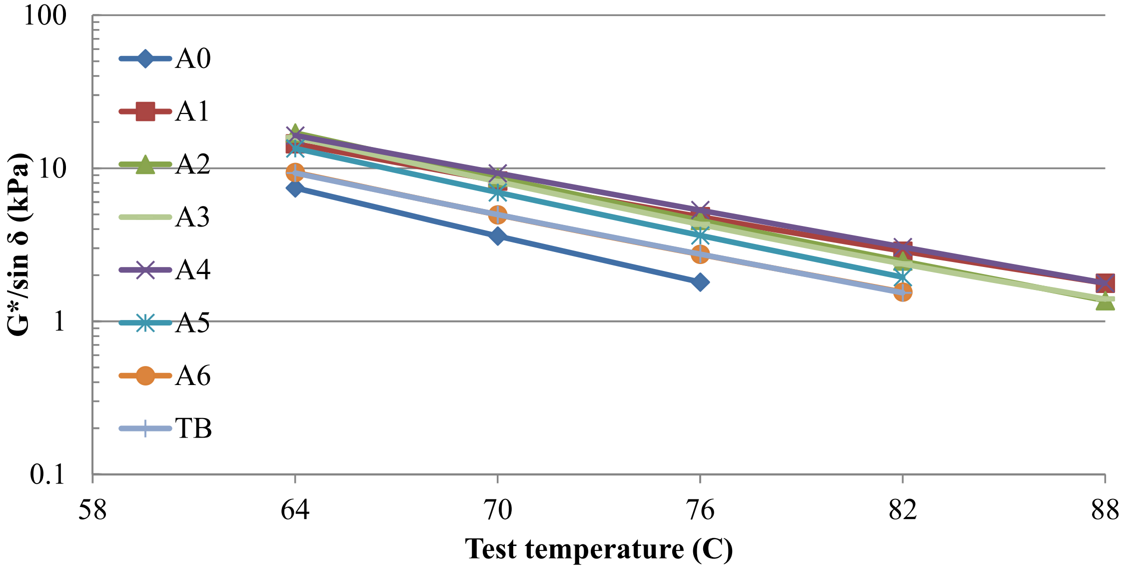


Figure 5-13 G*/sin δ Values of Binder Source A with Various Alternative Modifiers, RTFO Aged

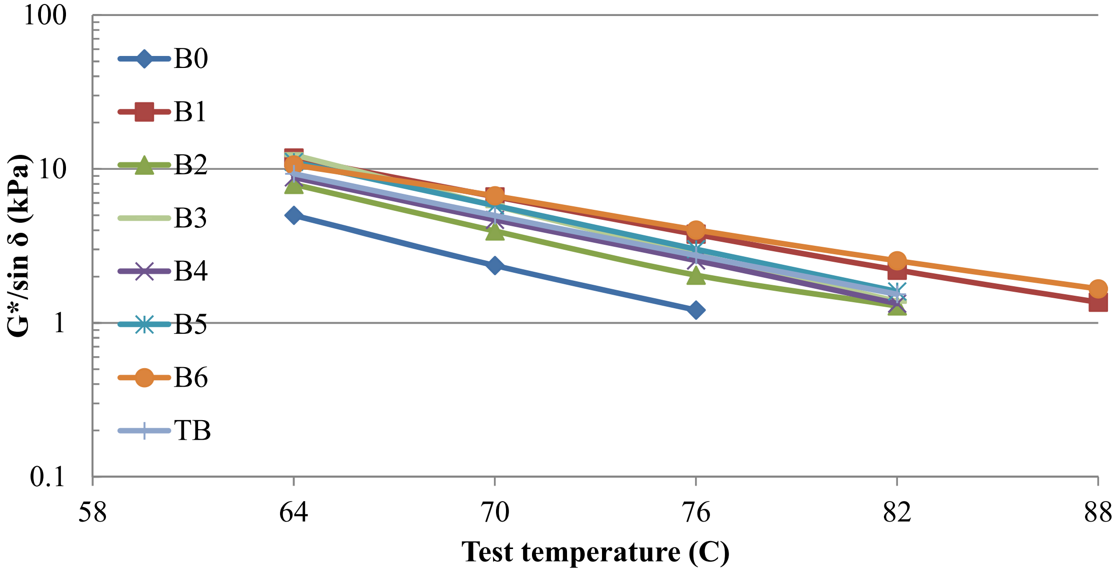


Figure 5-14 G*/sin δ Values of Binder Source B with Various Alternative Modifiers, RTFO Aged

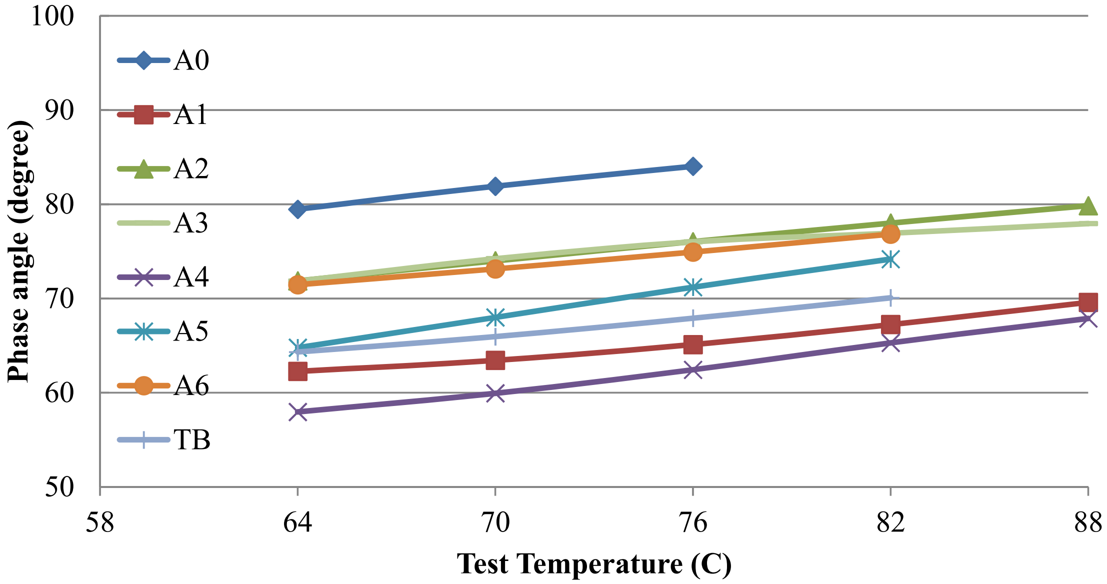


Figure 5-15 Phase Angle Values of Binder Source A with Various Alternative Modifiers, RTFO Aged

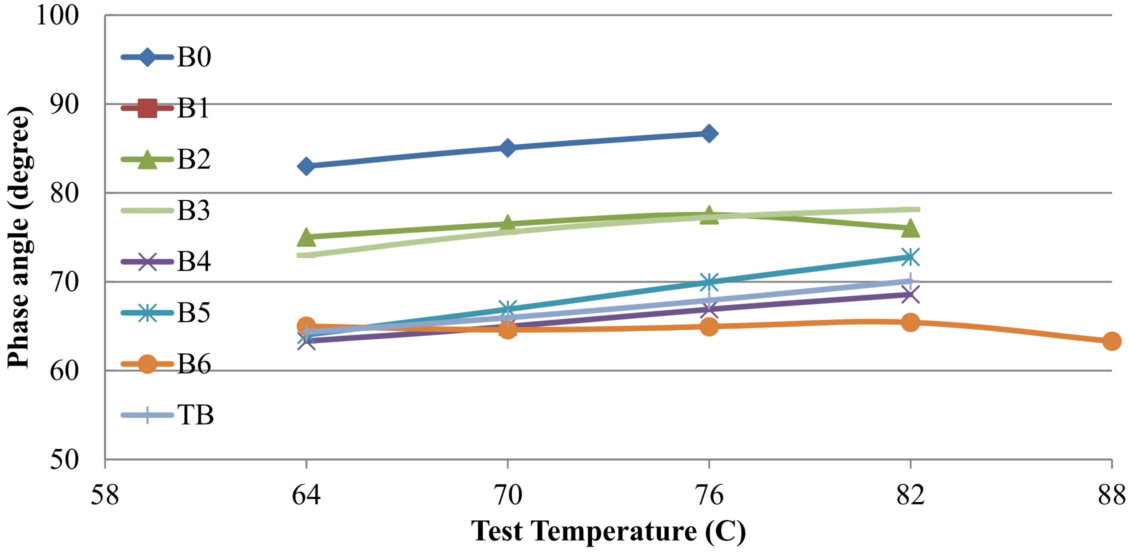


Figure 5-16 Phase Angle Values of Binder Source B with Various Alternative Modifiers, RTFO Aged

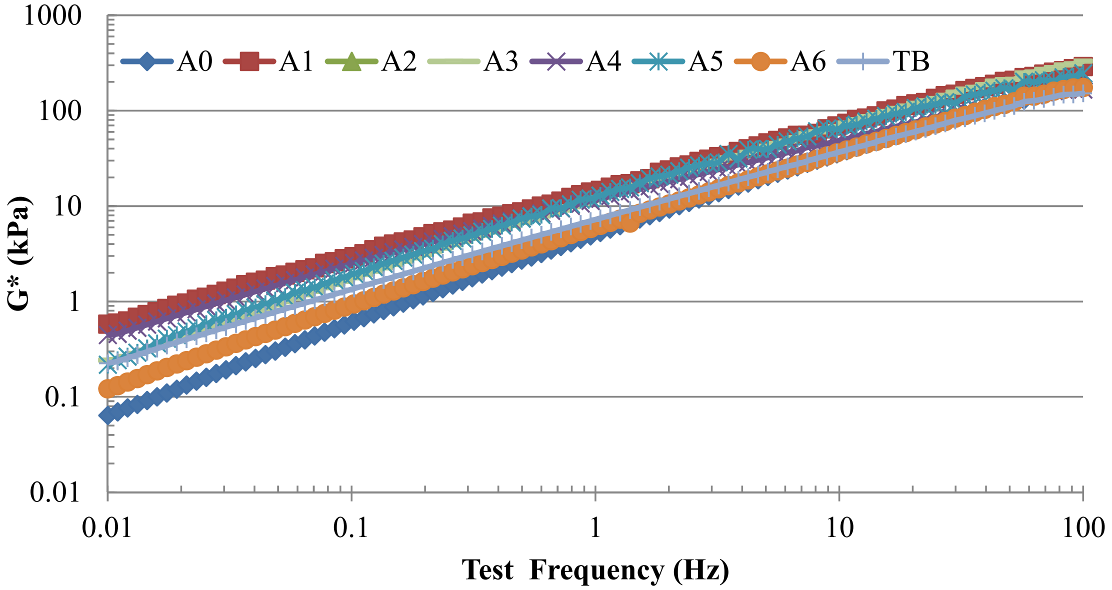


Figure 5-17 G* Values of Binder Source A with Various Alternative Modifiers in Terms of Frequency Sweep, RTFO Aged

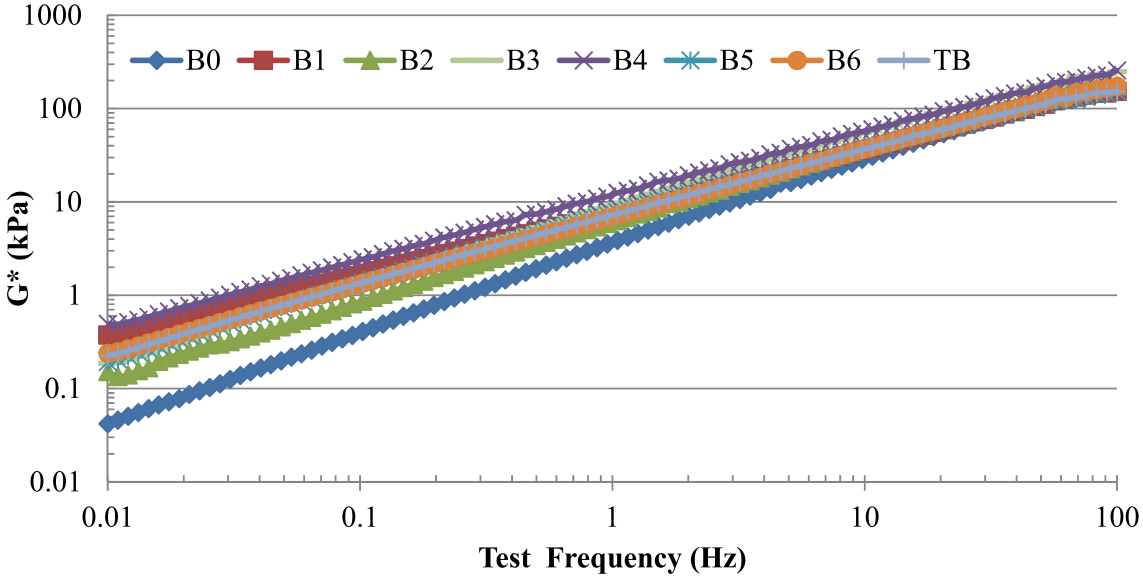


Figure 5-18 G* Values of Binder Source A with Various Alternative Modifiers in Terms of Frequency Sweep, RTFO Aged

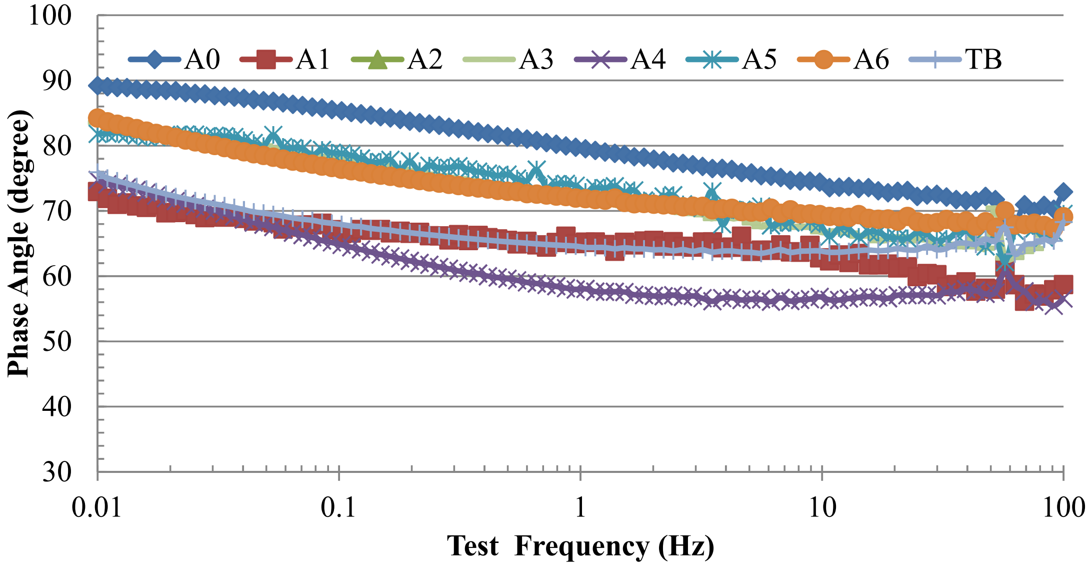


Figure 5-19 Phase Angle Values of Binder Source A with Various Alternative Modifiers in Terms of Frequency Sweep, RTFO Aged

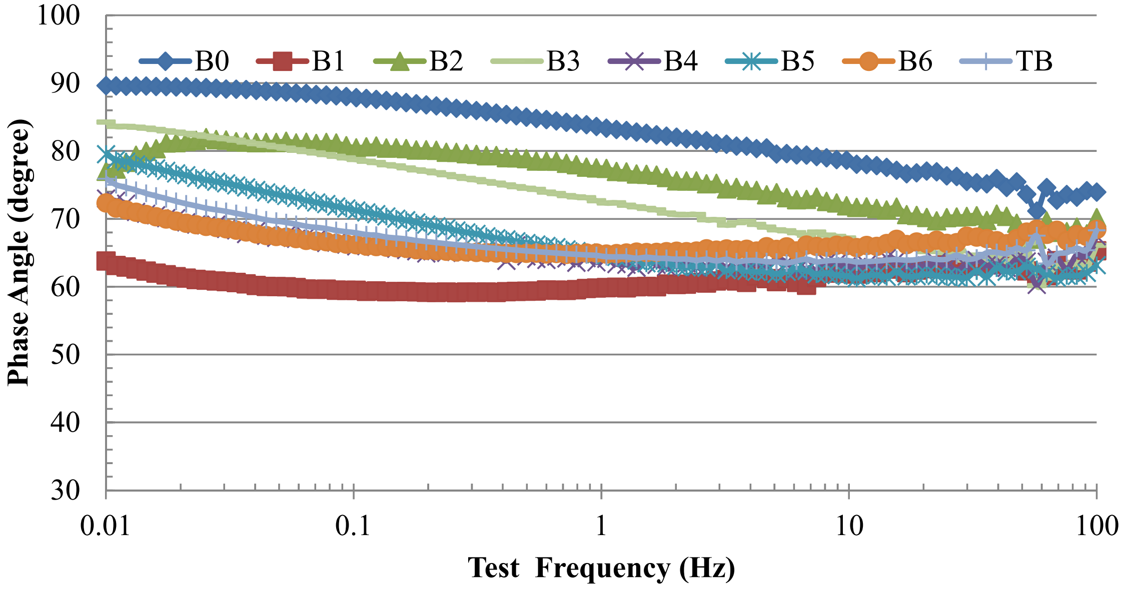


Figure 5-20 Phase Angle Values of Binder Source B with Various Alternative Modifiers in Terms of Frequency Sweep, RTFO Aged

Multiple Stress Creep Recover (MSCR) Test Results

In this study, the multiple stress creep recovery (MSCR) test is used to characterize the rheological properties of various asphalt binders after a short term aging process (RTFO). This test covers the determination of percentage recovery and non-recoverable creep compliance of asphalt binders by means of the MSCR test, which is conducted using the DSR at a specified temperature. The percentage recovery value is intended to provide a means for determining the elastic response and stress dependence of polymer-modified and unmodified asphalt binders.

In this study, two testing temperatures of 64°C and 76°C were used to test PG 64-22 and PG 76-44 (polymerized binders) according to AASHTO T 350. The test results are shown in Tables 5.4 and 5.5. The testing showed that the PG 64-22 binders (unmodified binders) generally had a lower recoverable creep compliance compared to the modified binders. In addition, various modified binders generally had different recoverable creep values regardless of binder source and test temperature. In general, the SBS-modified PG 76-22 binders exhibited the highest recovery percentage.

Table 5-4 MSCR data results of various binders after RTFO aging at 64C

(a)

Binder type	100Pa				3200Pa				Difference (%)
	Average creep strain	End. strain	Average recovery strain	Percentage recovery (%)	Average creep strain	End. strain	Average recovery	Percentage recovery	
A0	0.1229	0.1085	0.0143	11.7	0.1321	0.1276	0.0044	3.4	8.3
A1	0.0415	0.0160	0.0255	61.4	0.0426	0.0177	0.0249	58.5	2.9
A2	0.0381	0.0207	0.0174	45.8	0.0456	0.0359	0.0097	21.2	24.6
A3	0.0524	0.0353	0.0171	32.7	0.0585	0.0501	0.0084	14.3	18.3
A4	0.0325	0.0131	0.0194	59.8	0.0345	0.0174	0.0172	49.7	10.1
A5	0.0362	0.0228	0.0133	36.9	0.0498	0.0366	0.0132	26.6	10.3
A6	0.0796	0.0518	0.0277	34.9	0.0848	0.0622	0.0226	26.6	8.2
TB	0.0713	0.0311	0.0402	56.4	0.0741	0.0378	0.0364	49.1	7.4

(b)

Binder type	100Pa				3200Pa				
	Average creep strain	End. strain	Average recovery strain	Percentage recovery (%)	Average creep strain	End. strain	Average recovery strain	Percentage recovery (%)	Difference (%)
B0	0.2034	0.1884	0.0150	7.4	0.2211	0.2183	0.0028	1.2	6.1
B1	0.0482	0.0142	0.0340	70.6	0.0452	0.0137	0.0315	69.7	0.9
B2	0.0713	0.0448	0.0265	37.1	0.1248	0.1111	0.0137	10.9	26.2
B3	0.0534	0.0347	0.0187	35.0	0.0636	0.0531	0.0106	16.6	18.4
B4	0.0412	0.0149	0.0263	63.8	0.0429	0.0174	0.0255	59.4	4.4
B5	0.0571	0.0284	0.0286	50.2	0.0592	0.0366	0.0226	38.2	11.9
B6	0.0599	0.0197	0.0402	67.1	0.0636	0.0291	0.0345	54.2	12.9
TB	0.0713	0.0311	0.0402	56.4	0.0741	0.0378	0.0364	49.1	7.4

Table 5-5 MSCR data results of various binders after RTFO aging at 76C

(a)

Binder type	100Pa				3200Pa				
	Average creep strain	End. strain	Average recovery strain	Percentage recovery (%)	Average creep strain	End. strain	Average recovery strain	Percentage recovery (%)	Difference (%)
A0	0.5180	0.4960	0.0220	4.2	0.5883	0.5868	0.0015	0.3	4.0
A1	0.1358	0.0678	0.0679	50.0	0.1581	0.1098	0.0483	30.5	19.5
A2	0.2016	0.1409	0.0607	30.1	0.3125	0.3048	0.0077	2.5	27.6
A3	0.1864	0.0973	0.0891	47.8	0.3302	0.3238	0.0064	1.9	45.9
A4	0.1239	0.0770	0.0469	37.8	0.1502	0.1262	0.0239	15.9	21.9
A5	0.1981	0.1472	0.0510	25.7	0.2578	0.2413	0.0165	6.4	19.3
A6	0.3037	0.2313	0.0724	23.8	0.3673	0.3315	0.0358	9.8	14.1
TB	0.2863	0.1475	0.1388	48.5	0.3353	0.2723	0.0629	18.8	29.7

(b)

Binder type	100Pa				3200Pa				
	Average creep strain	End. strain	Average recovery strain	Percentage recovery (%)	Average creep strain	End. strain	Average recovery strain	Percentage recovery (%)	Difference (%)
B0	0.8648	0.8395	0.0254	2.9	0.8860	0.8861	0.0000	0.0	2.9
B1	0.1623	0.0583	0.1040	64.1	0.1459	0.0719	0.0740	50.7	13.4
B2	0.5006	0.3544	0.1462	29.2	0.8015	0.7926	0.0089	1.1	28.1
B3	0.3015	0.1948	0.1067	35.4	0.4629	0.4560	0.0069	1.5	33.9
B4	0.1311	0.0646	0.0665	50.7	0.1472	0.0998	0.0474	32.2	18.6
B5	0.2542	0.1511	0.1031	40.5	0.3236	0.2661	0.0575	17.8	22.8
B6	0.1972	0.0921	0.1051	53.3	0.2140	0.1279	0.0861	40.2	13.0
TB	0.2863	0.1475	0.1388	48.5	0.3353	0.2723	0.0629	18.8	29.7

Rheological Characteristics of PAV-Aged Binders

The modified binders were also subjected to a long-term aging process in the laboratory using a pressure aging vessel (PAV). G* sin δ and phase angle values are shown in Table 5.6 and Figures 5.21and 5.22. In according with the specification, PG 64-22 and PG 76-22 binders were tested at 25°C and 31°C, respectively. All G* sin δ values were less than 5,000 kPa and thus satisfied the requirements of the PAV specification.

Table 5-6 G*sin δ and Phase Angle Values of Binders with Various Modifiers, PAV Aged

Binder Type	Binder Source A				Binder Type	Binder Source B			
	G* sin δ (kPa) at 31°C		Phase angle (degree) at 31°C			G* sin δ (kPa) at 31°C		Phase angle (degree) at 31°C	
	Mean	Std.	Mean	Std.		Mean	Std.	Mean	Std.
A0	1972	233	50.1*	0.0	B0	2375	7	46.2*	0.4
A1	767	93	53.1	0.0	B1	1858	130	43.8	0.8
A2	1255	19	50.2	0.1	B2	1854	288	43.7	0.0
A3	1146	59	49.7	0.1	B3	2028	170	40.4	0.2
A4	955	33	47.0	1.2	B4	661	7	53.2	0.0
A5	1052	65	46.8	0.4	B5	1217	126	42.3	0.1
A6	736	4	53.9	0.1	B6	752	14	49.6	0.2
TB**	782	126	48.9	0.2	TB**	782	126	48.9	0.2

*Note: *~test at 25°C; 0~Control (PG 64-22); 1~SBS; 2~Plastomer 1; 3~Plastomer 2; 4~Lab-blended 10% GTR; 5~PPA+SBS; 6~Elastomer; TB**~Terminally-blended GTR from Binder Source C*

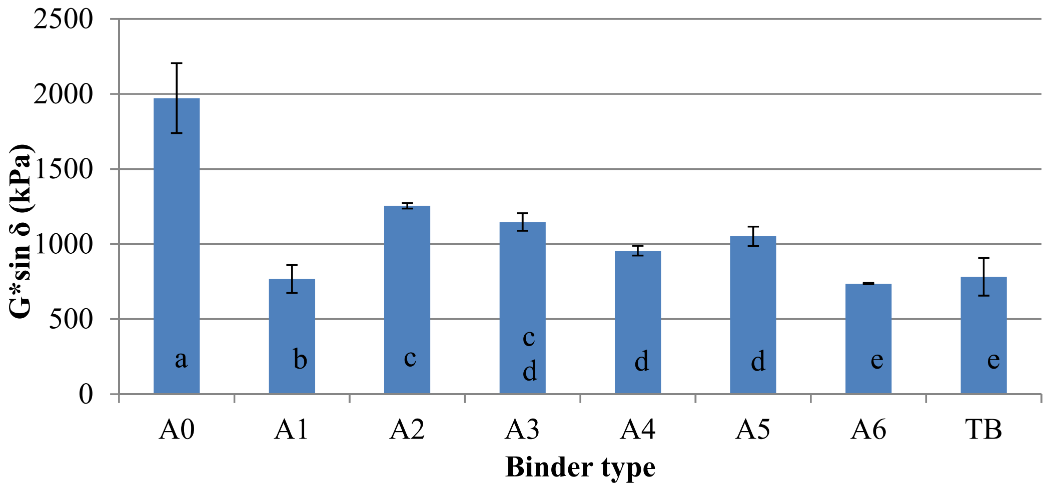


Figure 5-21 G*sin δ Values of Binder Source A with Various Alternative Modifiers, PAV Aged

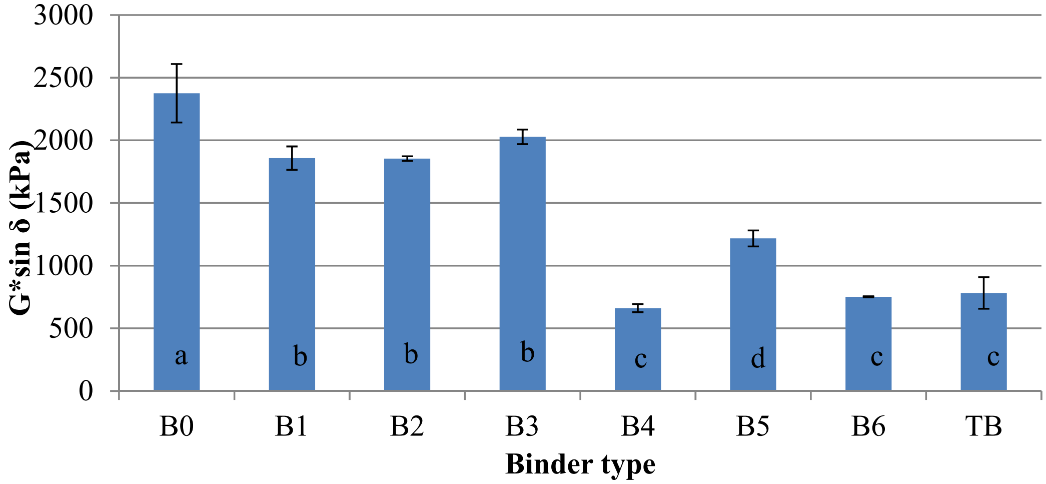


Figure 5-22 G*sin δ Values of Binder Source B with Various Alternative Modifiers, PAV Aged

The binders were also tested with the bending beam rheometer (BBR) at -12°C, which covers the determination of the flexural creep stiffness or compliance of asphalt binders. The test results are shown in Table 5.7. It can be noted that all m-values of binders from binder source A were greater than 0.3, the minimum values set by the specification. However, the modified binders from binder source B containing polylmers 2 and 3 (both plastomers) had m-values less than 0.3, which indicates that they may not exhibit favorable long-term performance. Some other studies to characterize the long-term performance may be needed.

Table 5-7 Deflection, stiffness and m values of various alternative binders at -12°C after PAV aging

Binder type	Binder source A					
	Deflection (mm)		Stiffness (Mpa)		m value	
	Mean	Std.	Mean	Std.	Mean	Std.
A0	0.50	0.06	158.0	17.0	0.355	0.004
A1	0.58	0.02	137.5	4.9	0.355	0.003
A2	0.40	0.01	202.0	2.8	0.334	0.011
A3	0.52	0.10	155.0	32.5	0.345	0.008
A4	0.57	0.05	139.0	12.7	0.328	0.003
A5	0.48	0.05	168.0	15.6	0.328	0.003
A6	0.46	0.03	174.0	9.9	0.336	0.025
TB	0.71	0.03	132.0	35.4	0.331	0.004
	Binder source B					
B0	0.48	0.07	165.0	24.0	0.314	0.001
B1	0.38	0.01	206.5	3.5	0.303	0.002
B2	0.36	0.04	220.5	27.6	0.273	0.003
B3	0.37	0.03	218.0	19.8	0.278	0.011
B4	0.41	0.02	181.5	7.8	0.320	0.002
B5	0.53	0.03	151.5	7.8	0.308	0.007
B6	0.47	0.01	169.0	7.1	0.328	0.007
TB	0.71	0.03	132.0	35.4	0.331	0.004

*Note: Std. ~ Standard deviation; 0~Control (PG 64-22); 1~SBS; 2~Plastomer 1; 3~Plastomer 2; 4~Lab-blended 10% GTR; 5~PPA+SBS; 6~Elastomer; TB**~Terminally-blended GTR from Binder Source C*

Moisture Susceptibility

For this phase of the research project, the moisture susceptibility of several mixtures was investigated. The anti-strip additives (ASAs) used included the following: lime (a0), liquid ASA 1 (a1) and liquid ASA2 (a2). In addition, two aggregate sources (sources I and II) were used to determine the effects of the aggregate source.

Aggregate source II is known to be a strip-prone aggregate, while aggregate source I is known to be a strip-resistant source. The mixtures were prepared with several different modified binders. The modified binders included SBS (0), a plastomer (1), a terminally-blended GTR binder (2), a lab blended GTR binder containing 10% crumb rubber (passing #30 mesh) (3) and an elastomer (4).

Table 5.8 shows the results of dry and wet ITS as well asTSR values for several mixtures made with aggregate source I and either hydrated lime or one of the two liquid ASAs. The modifiers used in the mixtures made with aggregate source I included SBS, a plastomer, a terminally blended GTR, a lab blended GTR, and an elastomer. The results indicate that the mixture made with SBS containing hydrated lime produced the highest dry and wet ITS values. However, the mixture containing the lab-prepared GTR and hydrated lime produced the highest TSR value. The mixtures containing terminally-blended GTR and liquid ASAs 1 and 2 produced the second and third highest TSR values, respectively. All of the TSR values, with exception of the lab-prepared GTR-modified binder used with liquid ASA 1, were greater than 85%. It should be noted that the mixture made with the lab-prepared GTR and lime produced the second-highest wet ITS value.

Figures 5.23 to 5.25 show the results in a graphical format with the statistical analysis for dry ITS, wet ITS and TSR values for all mixtures made with aggregate source I tested for this phase of the research work. In most cases, the lime mixtures produced dry ITS and wet ITS values that were statistically higher than the samples containing the liquid ASAs. However, the mixtures prepared with terminally-blended GTR and both liquid ASAs produced statistically higher TSR values than the terminally-blended GTR samples containing hydrated lime. In many cases, the mixtures made with liquid ASA 2 (a2) produced dry and wet ITS and TSR values that were greater than those of a1.

Table 5-8 Moisture Susceptibility Testing Values of Aggregate Source I Mixtures with Various Modified Binders and Anti-Stripping Additives (ASAs)

Mix Type	ASA Type	Dry ITS (kPa)		Wet ITS (kPa) (min 448 KPa)		TSR (%) (min 85%)
		Mean	Std. Dev.	Mean	Std. Dev.	
I0	a0	1588.8	54.8	1778.6	295.1	111.9
	a1	1248.0	42.2	1316.6	7.0	105.5
	a2	990.6	46.4	869.4	91.3	87.8
I1	a0	1321.5	28.1	1245.0	32.3	94.2
	a1	1348.3	46.4	1167.5	7.0	86.6
	a2	1038.3	77.3	944.4	93.4	91.0
I2	a0	1199.5	4.5	1215.0	16.3	101.3
	a1	1027.9	129.7	1195.0	58.9	116.3
	a2	1125.2	120.6	1296.0	130.8	115.2
I3	a0	1173.8	164.5	1447.3	110.7	123.3
	a1	888.0	13.1	735.4	23.7	82.8
	a2	861.9	43.6	909.6	65.5	105.5
I4	a0	1312.2	2.8	1315.5	52.7	100.2
	a1	1266.6	22.6	1048.8	5.2	82.8
	a2	1319.7	113.3	1274.7	39.2	96.6

Notes: 0~SBS; 1~Plastomer 2; 2~ Terminally-blended GTR from Binder Source C; 3~Lab-blended 10% GTR;4~Elastomer; a0~hydrated lime; a1~liquid ASA 1; a2~liquid ASA 2; ITS~Indirect Tensile Strength; TSR~tensile strength ratio

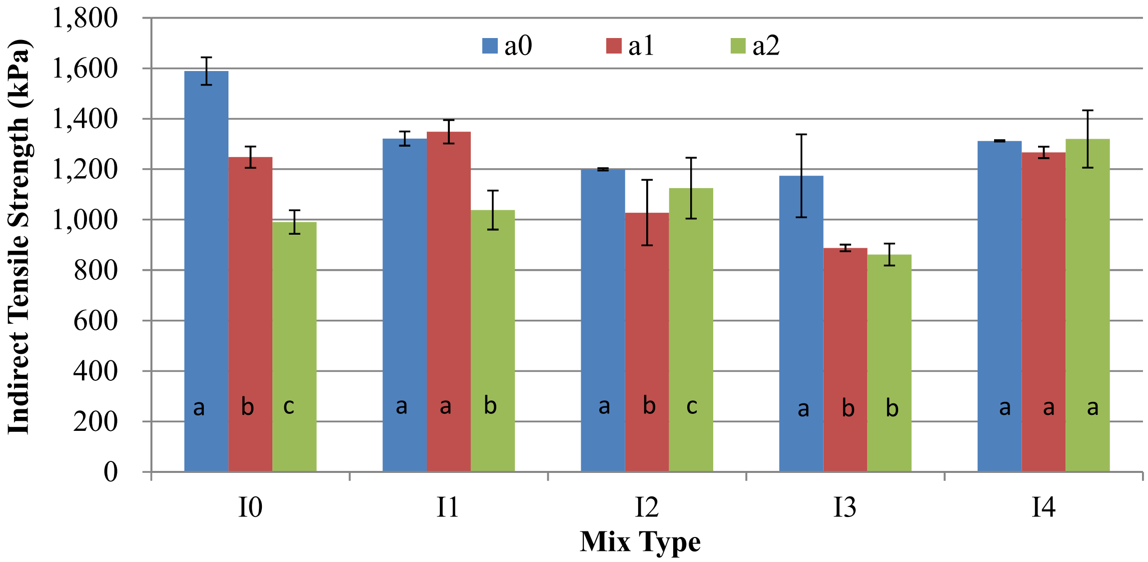


Figure 5-23 Dry Indirect Tensile Strength (ITS) Values of Aggregate Source I Mixtures with Various Modified Binders and ASAs

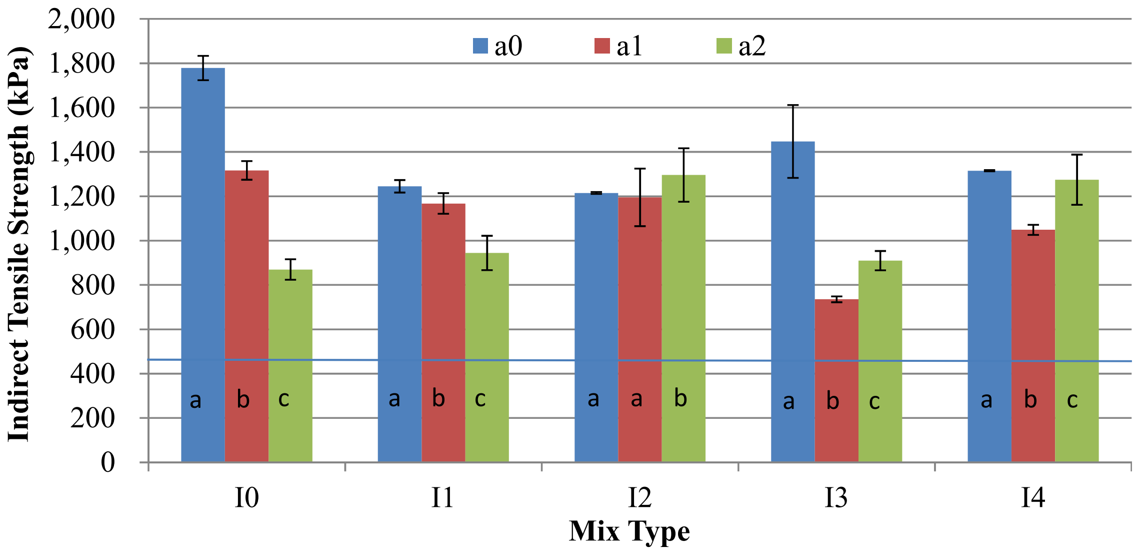


Figure 5-24 Wet ITS Values of Aggregate Source I Mixtures with Various Modified Binders and ASAs

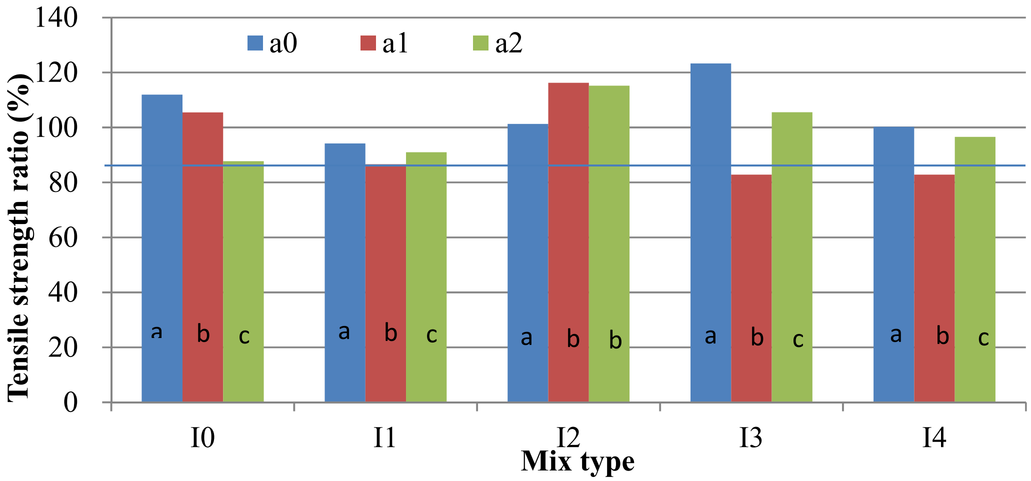


Figure 5-25 Tensile Strength Ratio (TSR) Values of Aggregate Source I Mixtures with Various Modified Binders and ASAs

Table 5.9 shows the results of dry and wet ITS and TSR values for several mixtures made with aggregate source II (a strip-prone aggregate) and either hydrated lime or one of two liquid ASAs. The modifiers used in the mixtures made with aggregate source II included SBS, a plastomer, a terminally blended GTR, a lab blended GTR, an elastomer and PPA+SBS. The results indicate that the mixture made with SBS and containing hydrated lime produced, in most cases, the highest dry ITS, wet ITS and TSR values. The mixture containing the elastomer-modified binder and hydrated lime produced the second highest TSR value. All of the TSR values, with exception of the mixtures containing elastomer and PPA+SBS modified binders and liquid ASAs 1 and 2, were greater than 85%. The results, in general, indicate that even though this aggregate is a strip-prone source, the use of ASAs (hydrated lime or liquid) is an effective method to minimize stripping in various mixtures.

Figures 5.26 to 5.28 show the results in a graphical format with the statistical analysis for dry, wet ITS and TSR values for all mixtures made with aggregate source II tested for this phase of the research work. In several cases, the results indicate that the wet ITS values of samples made with various modified binders and liquid ASAs were the same or higher than mixtures containing hydrated lime.

Table 5-9 Moisture Susceptibility Testing Values of Aggregate Source II Mixtures with Various Modified Binders and Anti-Stripping Additives (ASAs)

Mix Type	ASA Type	Dry ITS (kPa)		Wet ITS (kPa)		TSR (%)
		Mean	Std. Dev.	Mean	Std. Dev.	
II0	a0	1321.5	182.7	1527.2	122.3	115.6
	a1	1147.6	91.3	1063.2	98.4	92.6
	a2	1142.7	56.2	1217.2	85.7	106.5
II1	a0	1256.9	35.1	1212.2	70.3	96.4
	a1	1197.3	91.3	1152.6	84.3	96.3
	a2	1299.7	16.9	1241.0	12.6	95.5
II2	a0	751.8	40.8	706.0	99.3	93.9
	a1	1096.9	86.7	994.9	101.3	90.7
	a2	1202.0	27.1	1184.8	279.1	98.6
II3	a0	964.0	103.6	956.7	82.3	99.2
	a1	980.3	146.0	949.8	52.1	96.9
	a2	1063.3	335.4	951.3	127.9	89.5
II4	a0	1384.9	90.2	1478.1	39.3	106.7
	a1	1310.3	3.2	1186.0	5.6	90.5
	a2	1600.3	10.4	1317.0	73.5	82.3
II5	a0	1192.4	18.0	985.8	0.0	82.7
	a1	1096.5	144.6	1128.3	37.5	102.9
	a2	1106.6	48.5	872.6	155.4	78.9

Notes: 0~SBS; 1~Plastomer 2; 2~ Terminally-blended GTR from Binder Source C; 3~Lab-blended 10% GTR;4~Elastomer; 5~PPA+SBS; a0~hydrated lime; a1~liquid ASA 1; a2~liquid ASA 2; ITS~Indirect Tensile Strength; TSR~tensile strength ratio

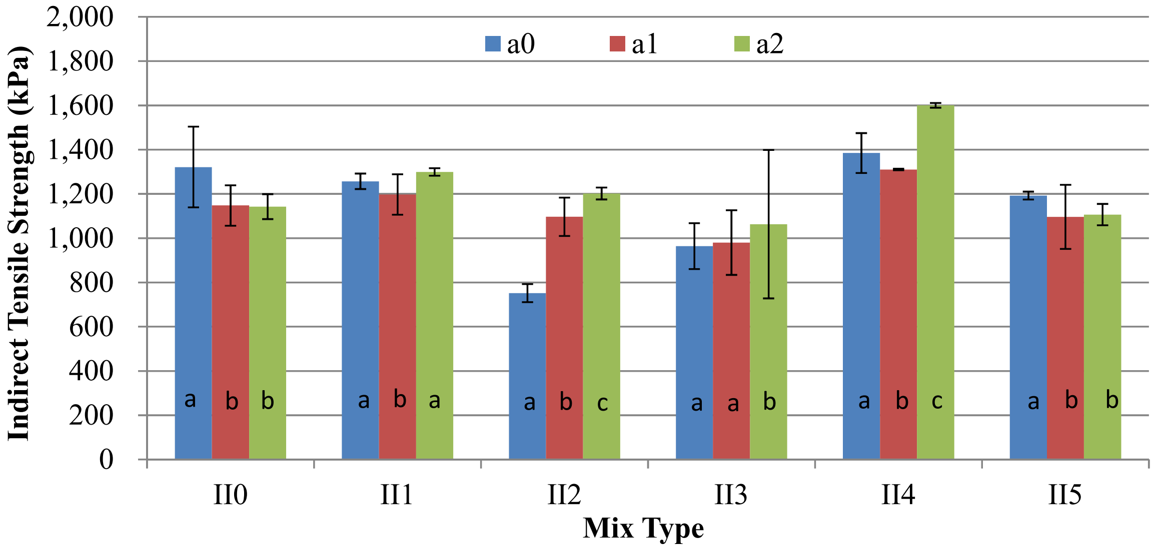


Figure 5-26 Dry Indirect Tensile Strength (ITS) Values of Aggregate Source II Mixtures with Various Modified Binders and ASAs

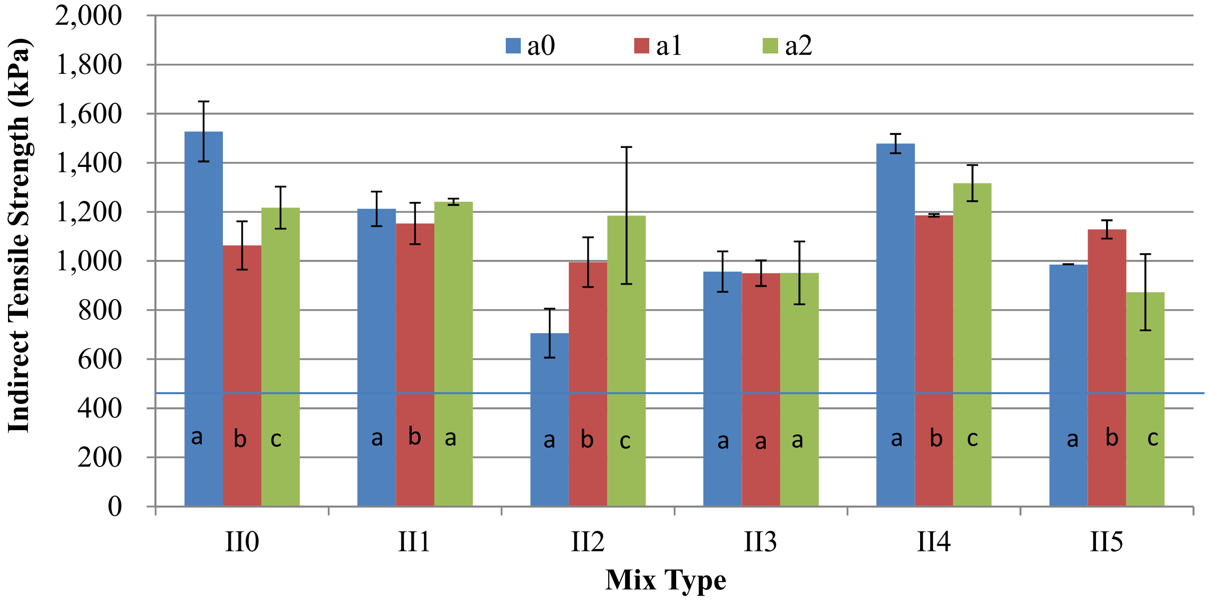


Figure 5-27 Wet Indirect Tensile Strength (ITS) Values of Aggregate Source II Mixtures with Various Modified Binders and ASAs

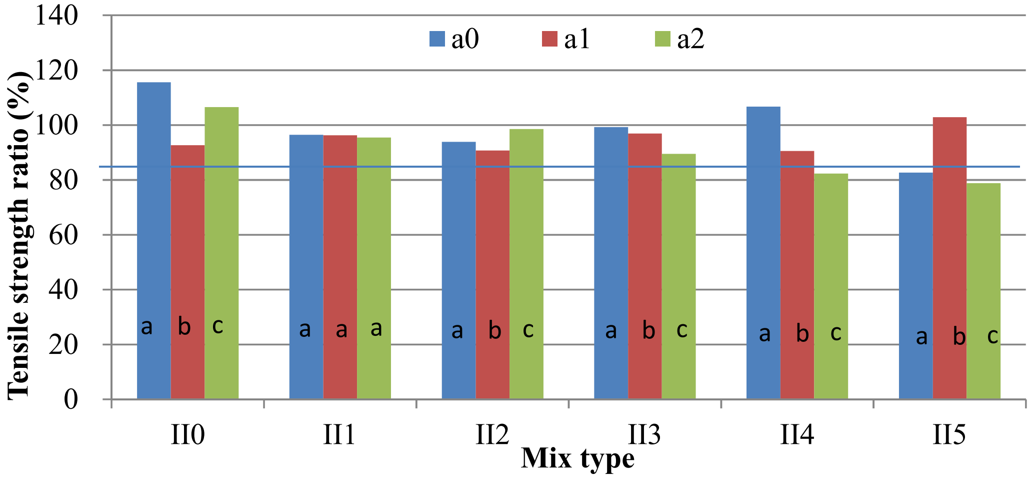


Figure 5-28 Tensile Strength Ratio (TSR) Values of Aggregate Source II Mixtures with Various Modified Binders and ASAs

The dry and wet flow values of various mixtures made with aggregate source I and different modified binders and anti-strip additives are shown in Table 5.10 and Figures 5.29 and 5.30. The results indicate that the SBS and plastomer-modified mixtures produced the lowest dry and wet flow values. The dry and wet flow values of mixtures made with the GTR-modified binders and the elastomer produced relatively the same dry and wet flow values, regardless of the ASA type.

Table 5-10 Flow Values of Aggregate Source I Mixtures with Various Modified Binders and Anti-Stripping Additives (ASA)

Mix type	ASA type	Dry flow (mm)		Wet flow (mm)	
		Mean	Std	Mean	Std
I0	a0	3.94	0.36	4.00	0.09
	a1	4.06	1.26	3.75	0.09
	a2	4.32	0.18	4.25	0.09
I1	a0	3.75	0.09	4.00	0.09
	a1	4.19	0.18	3.81	0.72
	a2	3.87	0.27	3.68	0.36
I2	a0	5.14	0.00	4.90	0.14
	a1	5.95	0.71	5.30	0.28
	a2	5.39	0.35	5.30	0.14
I3	a0	5.19	0.35	4.90	0.00
	a1	6.40	0.64	5.65	0.21
	a2	5.64	0.71	5.25	0.78
I4	a0	5.39	0.07	5.10	0.28
	a1	5.44	0.14	5.95	0.07
	a2	5.29	0.07	5.25	0.07

Notes: 0~SBS; 1~Plastomer 2; 2~ Terminally-blended GTR from Binder Source C; 3~Lab-blended 10% GTR; 4~Elastomer; a0~hydrated lime; a1~liquid ASA 1; a2~liquid ASA 2

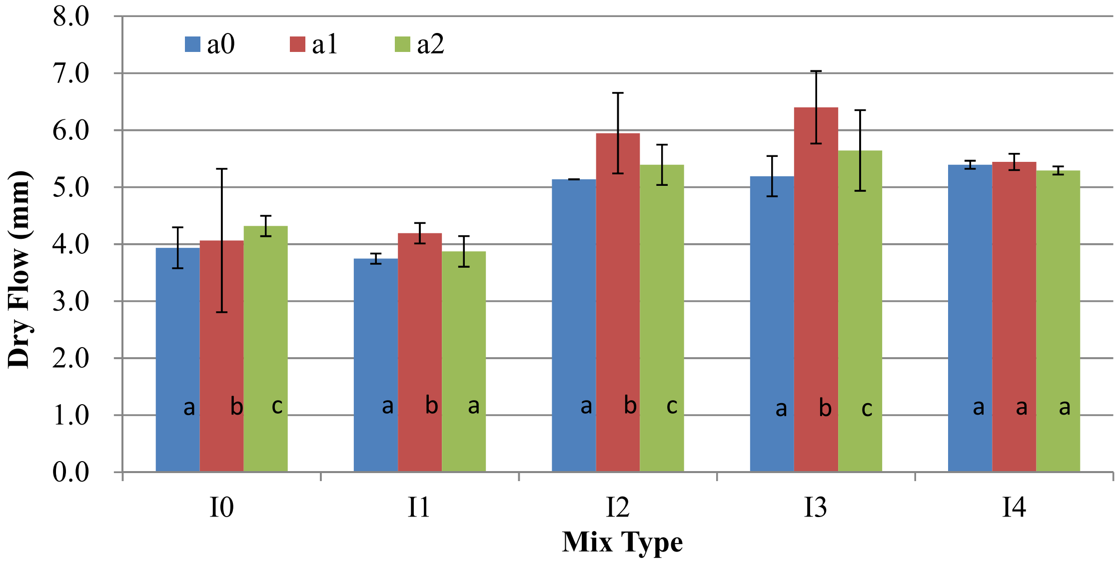


Figure 5-29 Flow Values of Aggregate Source I Mixtures with Various Modified Binders and Anti-Stripping Additives (ASA)

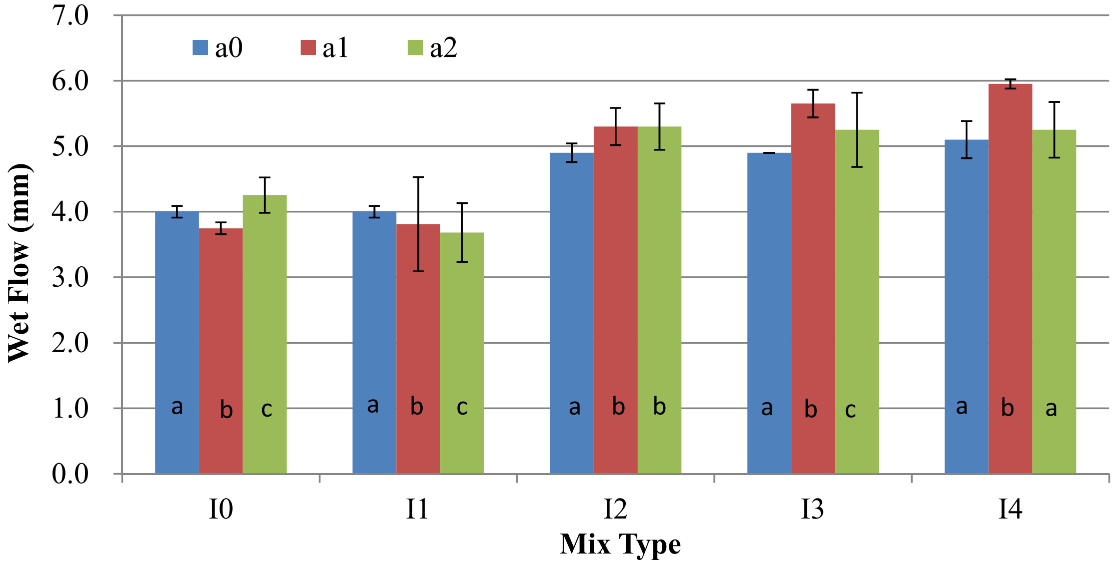


Figure 5-30 Wet Flow Values of Aggregate Source I Mixtures with Various Modified Binders and ASAs

The dry and wet flow values of various mixtures made with aggregate source II and different modified binders and anti-strip additives are shown in Table 5.11 and Figures 5.31 and 5.32. The results indicate that the SBS and plastomer-modified mixtures produced the lowest dry and wet flow values. The dry and wet flow values of mixtures made with the GTR-modified binders, the elastomer, and the PPA+SBS produced relatively the same dry and wet flow values, regardless of the ASA type.

Table 5-11 Flow Values of Aggregate Source II Mixtures with Various Modified Binders and Anti-Stripping Additives (ASA)

Mix type	ASA type	Dry flow (mm)		Wet flow (mm)	
		Mean	Std	Mean	Std
II0	a0	3.56	0.36	3.81	0.00
	a1	3.87	0.09	3.75	0.09
	a2	4.25	0.09	3.75	0.27
II1	a0	3.94	0.18	3.95	0.02
	a1	3.62	0.09	3.87	0.27
	a2	3.56	0.18	3.87	0.45
II2	a0	5.95	0.21	5.90	0.42
	a1	4.65	0.21	5.55	0.35
	a2	5.10	0.28	5.15	0.35
II3	a0	5.25	0.49	4.90	0.28
	a1	6.35	0.07	6.60	0.42
	a2	5.20	0.42	6.10	0.57
II4	a0	5.15	0.35	4.95	0.07
	a1	5.70	0.85	5.40	0.00
	a2	5.20	0.14	5.00	0.42
II5	a0	5.25	0.24	5.35	0.35
	a1	5.45	0.64	4.65	0.21
	a2	5.15	0.21	6.10	1.27

Notes: 0~SBS; 1~Plastomer 2; 2~ Terminally-blended GTR from Binder Source C; 3~Lab-blended 10% GTR;4~Elastomer; 5~PPA+SBS; a0~hydrated lime; a1~liquid ASA 1; a2~liquid ASA 2;

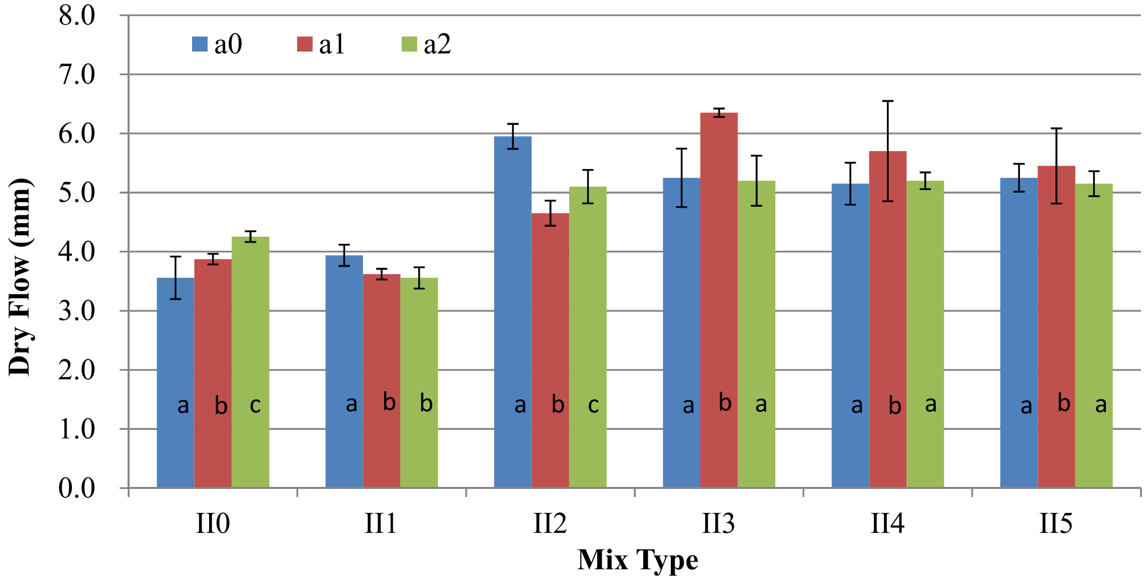


Figure 5-31 Dry Flow Values of Aggregate Source II Mixtures with Various Modified Binders and ASAs

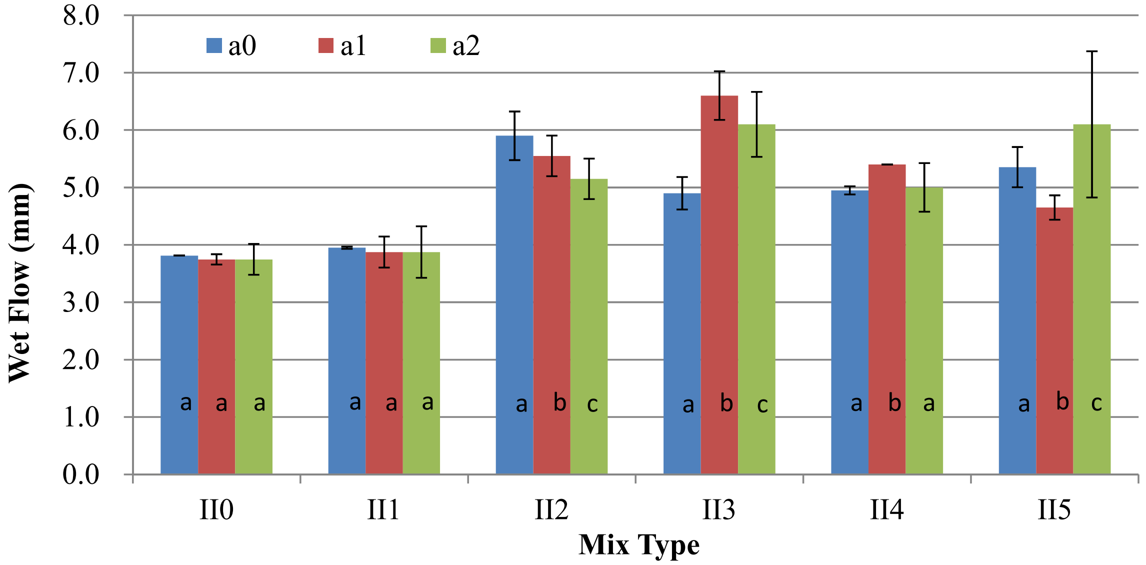


Figure 5-32 Wet Flow Values of Aggregate Source II Mixtures with Various Modified Binders and ASAs

Asphalt Pavement Analyzer (APA) Rut Resistance

The rut resistance of all mixtures (2 aggregate sources, various modified binders and 3 ASAs) were measured using the Asphalt Pavement Analyzer (APA) machine, and the results are shown in Table 5.12 and Figures 5.33 and 5.34. For all samples tested, AASHTO T 340 was followed to conduct the test (6000 cycles). None of the samples produced a rut depth greater than 3 mm, regardless of the aggregate source, modified binder and ASA type used for this phase of the research. A clear trend could not be established to identify the effects of different variables used to test the samples. The mixtures containing an elastomer produced the lowest rut depths compared to all other mixtures. The results indicate (Figure 5.33) that the samples made with aggregate source I and liquid ASAs produced rut depths that were higher than those made with hydrated lime. However, Figure 5. 34 shows that this was not the case for aggregate source II.

Table 5-12 Asphalt Pavement Analyzer (APA) Rut Values of Mixtures with Various Modified Binders and Anti-Stripping Additives (ASAs)

Mix type	ASA type	APA (mm)		Mix type	ASA type	APA (mm)	
		Mean	Std			Mean	Std
I0	a0	1.19	0.24	II0	a0	1.73	0.50
	a1	1.72	0.77		a1	1.45	0.39
	a2	1.55	0.66		a2	1.54	0.53
I1	a0	1.66	0.32	II1	a0	1.78	0.77
	a1	1.95	0.56		a1	1.37	0.48
	a2	1.72	0.37		a2	1.04	0.32
I2	a0	2.72	1.07	II2	a0	1.27	0.97
	a1	1.31	0.30		a1	0.68	0.27
	a2	1.26	0.33		a2	1.23	0.28
I3	a0	1.80	1.07	II3	a0	1.24	0.71
	a1	2.46	0.35		a1	0.91	0.28
	a2	2.27	0.69		a2	0.96	0.10
I4	a0	0.79	0.25	II4	a0	0.90	0.71
	a1	1.63	0.57		a1	0.39	0.22
	a2	0.84	0.38		a2	0.55	0.15
				II5	a0	1.33	0.51
					a1	1.12	0.31
					a2	1.41	0.44

Notes: I and II ~ aggregate sources; 0~SBS; 1~Plastomer 2; 2~ Terminally-blended GTR from Binder Source C; 3~Lab-blended 10% GTR; 4~Elastomer; 5~PPA+SBS; a0~hydrated lime; a1~liquid ASA 1; a2~liquid ASA 2

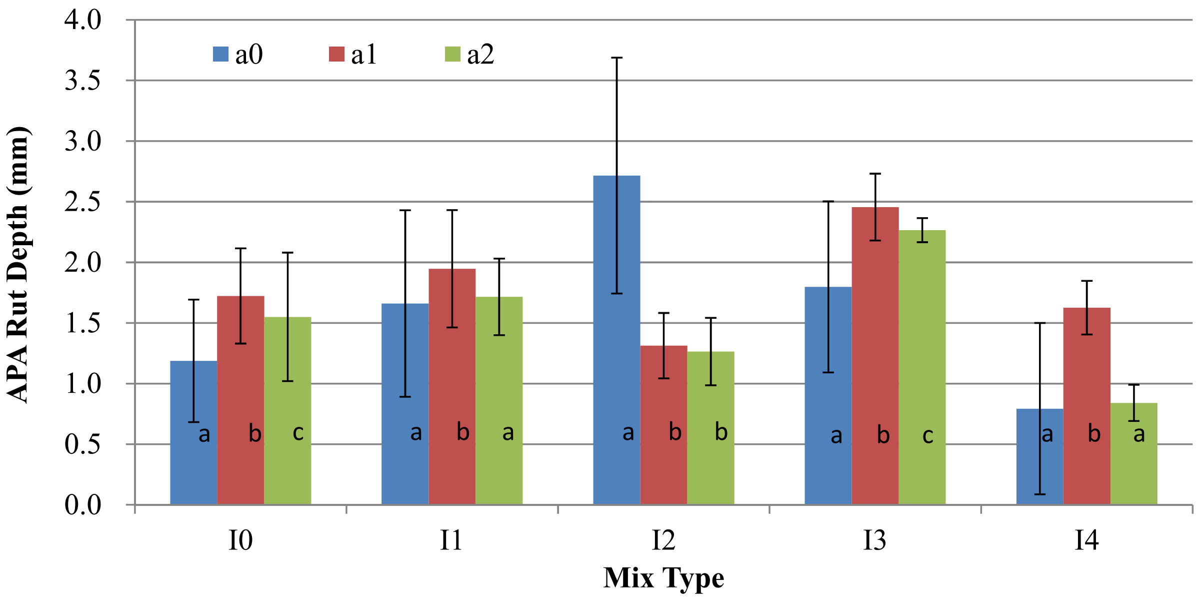


Figure 5-33 APA Rut Values of Aggregate Source I Mixtures with Various Modified Binders and ASAs

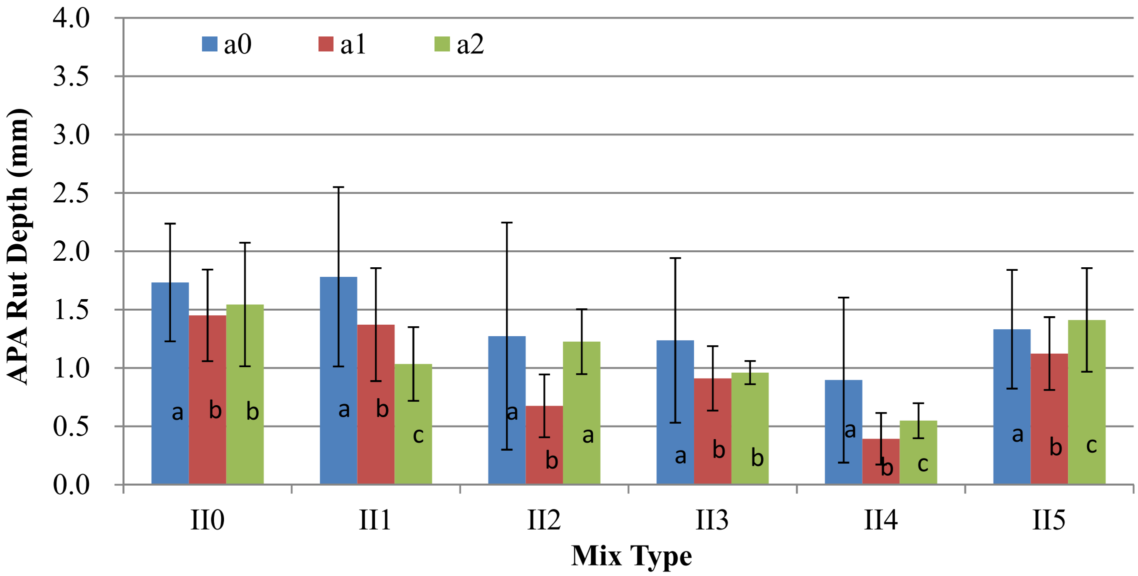


Figure 5-34 APA Rut Values of Aggregate Source II Mixtures with Various Modified Binders and ASAs

Dynamic Modulus and Flow Number

The Asphalt Mixture Performance Tester (AMPT) complements the existing binder and mixture testing procedures. The AMPT is a servo-hydraulic testing machine that determines, among many other properties, the rutting resistance of the mixtures using the flow number test. The flow number has been correlated to rutting resistance of mixtures tested in full scale field testing. The AMPT also can provide the data needed for developing the dynamic modulus master curves needed for the newly-developed pavement design process. AASHTO TP 79 testing procedures were used to conduct this test. AASHTO PP 60 was used for preparation of cylindrical performance test specimens. AASHTO PP 61 was used to develop dynamic modulus master curves for hot mix asphalt using AMPT. Several properties could be obtained from testing the mixtures using AMPT including: E* – Dynamic Modulus; F_n – Flow Number (Repeated Load); and F_t – Flow Time (Static Load).

The size of the specimens used to conduct this test is 100 mm (4 in) diameter by 150 mm (6 in) high test specimens. These samples are cored and sawed from larger 150 mm (6 in) diameter by 170 mm (6.75 in) high gyratory specimens prepared in a gyratory compactor. The reason for taking a core from the middle of a larger gyratory specimen is to improve specimen uniformity by eliminating high air voids that occur at the ends of the samples and around the circumference. During flow number testing, a specimen at a specific temperature is subjected to a repeated compressive load pulse, and the resulting permanent axial strains are measured for each load pulse. This is used to calculate the flow number, or the point where the specimen exhibits uncontrolled tertiary flow.

After obtaining the flow number, it is compared to criteria developed in NCHRP Project 9-33 for hot mix asphalt (HMA) or NCHRP 9-43 for warm mix asphalt (WMA). The criteria for the flow numbers of HMA mixtures include the following: 3 to 10 million ESAL=50; 10 to 30 million ESAL=190; and over 30 million ESALs, the flow number =740. These samples are short-term conditioned for 4 hours at 135 °C.

For this phase of the project, the dynamic modulus and flow number of many mixtures utilizing various modified binders and different ASAs were obtained. The testing for each sample was conducted at several temperatures and frequencies. The results of the AMPT testing for mixtures made with aggregate source I and various ASAs is shown in Figures 5.35 to 5.37. The respective results for aggregate source II are shown in Figures 5.38 to 5.40. The results indicate, in general, that the aggregate source makes a difference when analyzing the |E*| values. The samples made with aggregate source II at 4 °C produced dynamic modulus values that were lower than source I, regardless of type of ASA or modified binder used to prepare the samples. In addition, the trend of using different modified binders shows that they perform differently according the source of the aggregate.

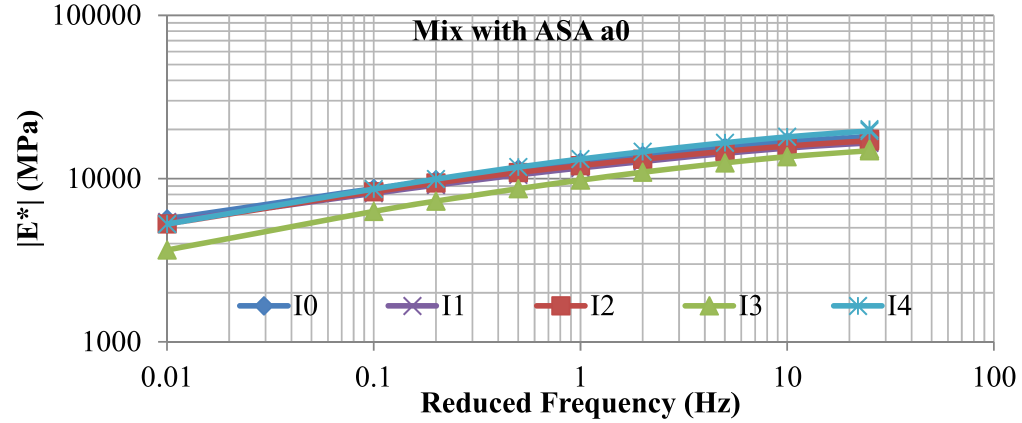


Figure 5-35 |E*| Values of Aggregate Source I Mixtures with ASA a0 and Various Modified Binders at 4°C

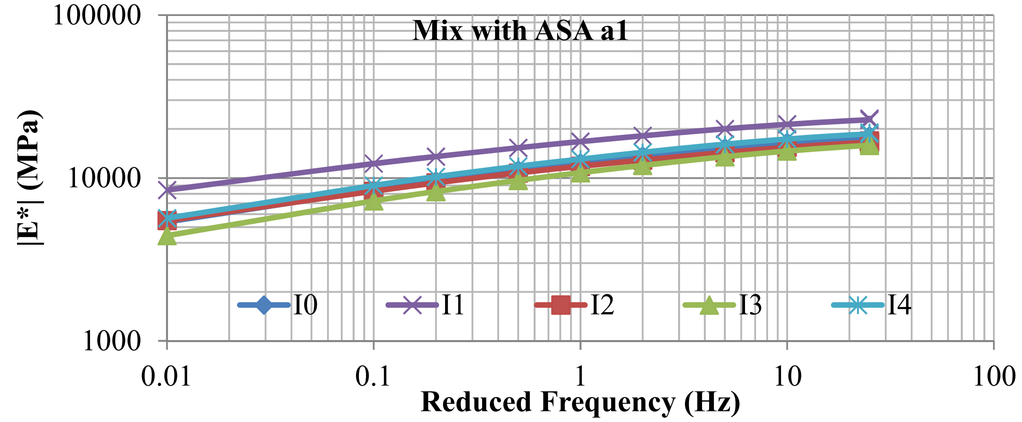


Figure 5-36 |E*| Values of Aggregate Source I Mixtures with ASA a1 and Various Modified Binders at 4°C

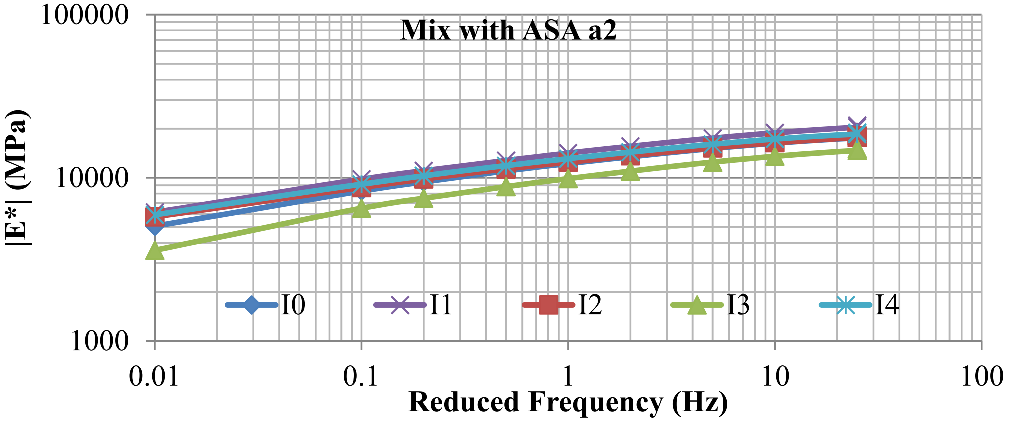


Figure 5-37 |E*| Values of Aggregate Source I Mixtures with ASA a2 and Various Modified Binders at 4°C

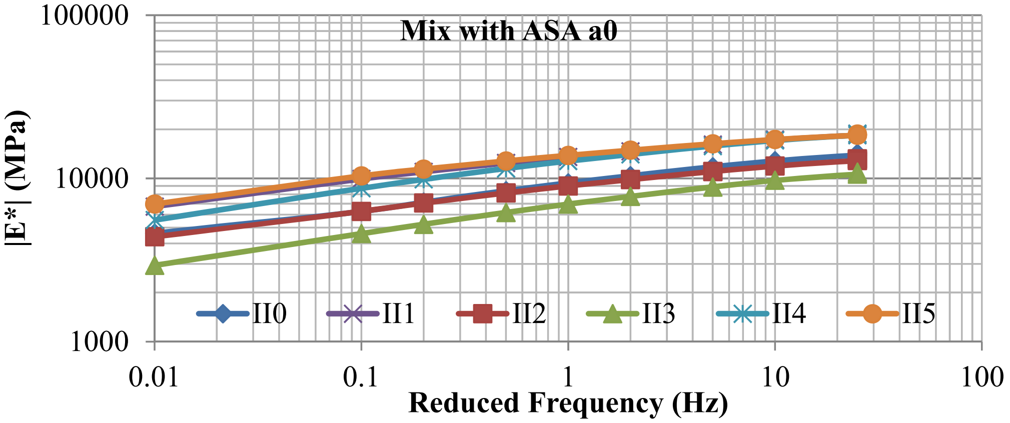


Figure 5-38 |E*| Values of Aggregate Source II Mixtures with ASA a0 and Various Modified Binders at 4°C

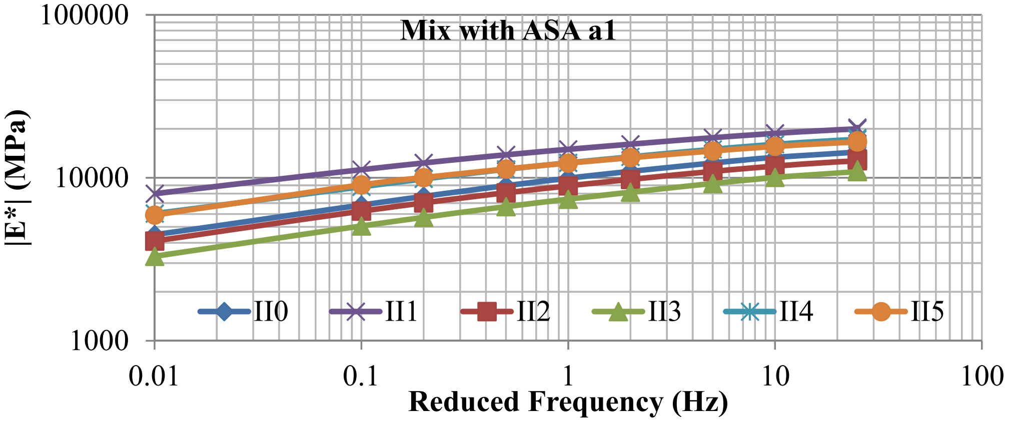


Figure 5-39 |E*| Values of Aggregate Source II Mixtures with ASA a0 and Various Modified Binders at 4°C

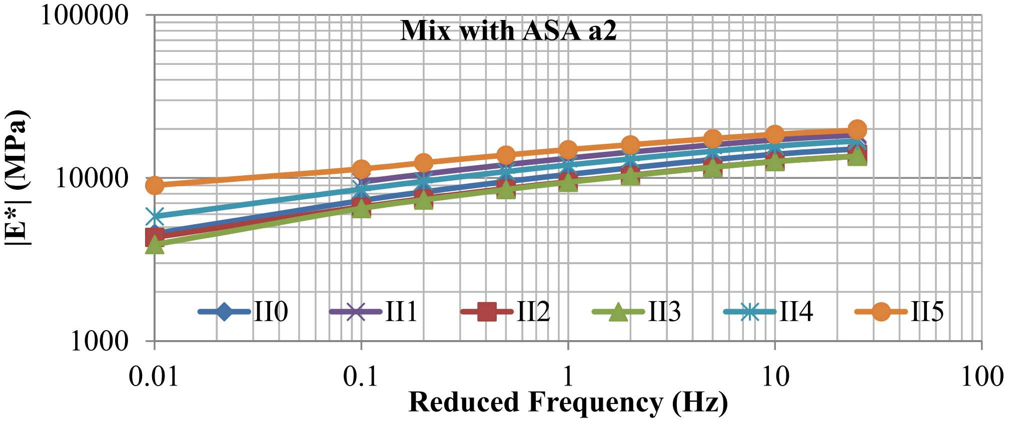
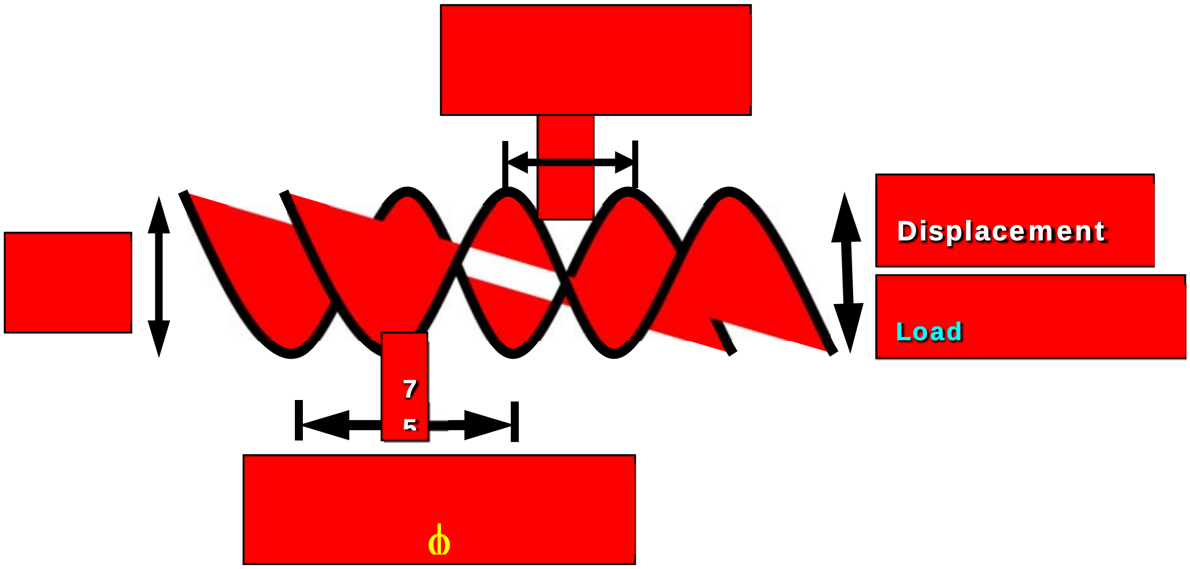


Figure 5-40 |E*| Values of Aggregate Source II Mixtures with ASA a2 and Various Modified Binders at 4°C

A schematic of the dynamic modulus test is shown below. The phase angle results of all mixtures measured at 4^{o}C for aggregate source I are shown in Figures 5.41 to 5.43. As shown in these figures, the modified asphalt binder has a major effect on the performance of the mixture when considering the phase angle. The phase angle results of all mixtures measured at 4^{o}C for aggregate source II are shown in Figures 5.44 to 5.46. The results indicate that, in general, the aggregate source has a major impact on the performance of the mixture.



The |E*| values of all mixtures made with aggregate sources I and II at 20^{o}C are shown in Figures 5.47 to 5.52. The corresponding phase angles for these mixtures are shown in Figures 5.53 to 5.58. The |E*| values of all mixtures made with aggregate sources I and II at 45^{o}C are shown in Figures 5.59 to 5.64. The corresponding phase angles for these mixtures are shown in Figures 5.64 to 5.70.

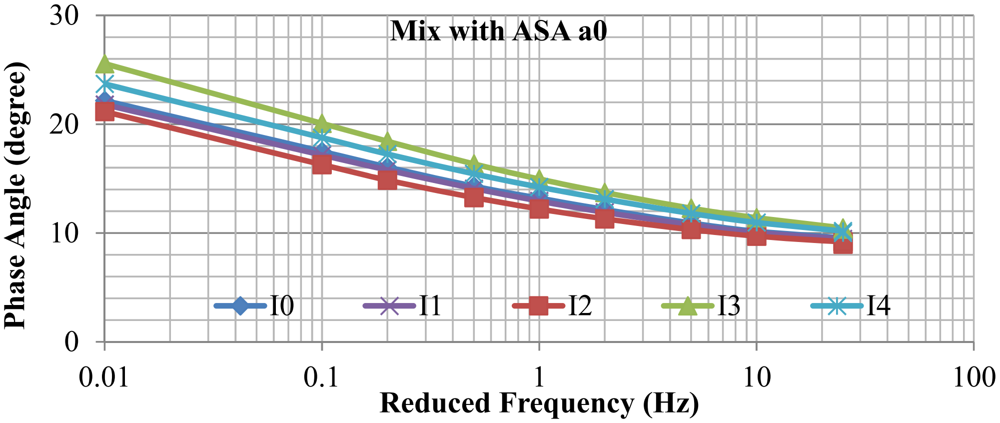


Figure 5-41 Phase Angles of Aggregate Source I Mixtures with ASA a0 and Various Modified Binders at 4°C

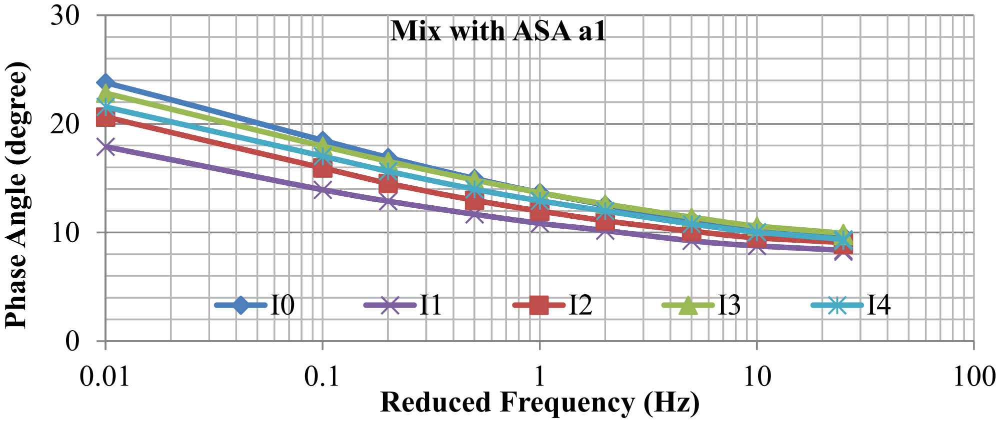


Figure 5-42 Phase Angles of Aggregate Source I Mixtures with ASA a1 and Various Modified Binders at 4°C

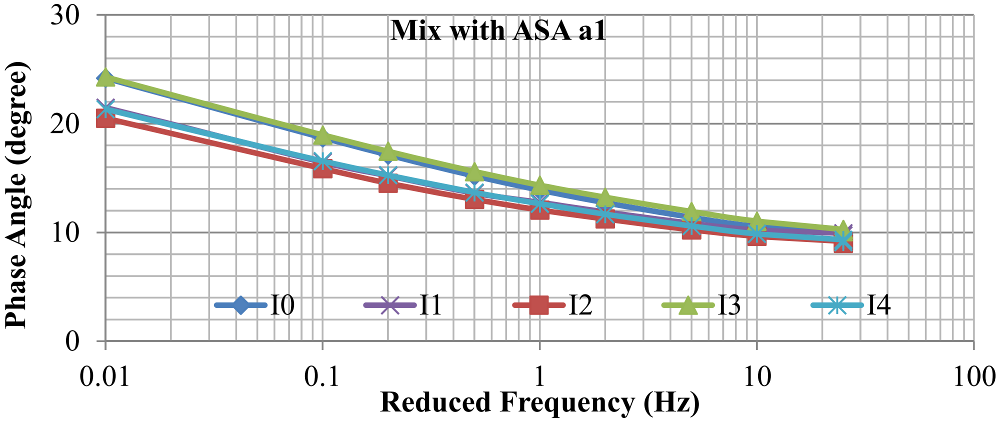


Figure 5-43 Phase Angles of Aggregate Source I Mixtures with ASA a2 and Various Modified Binders at 4°C

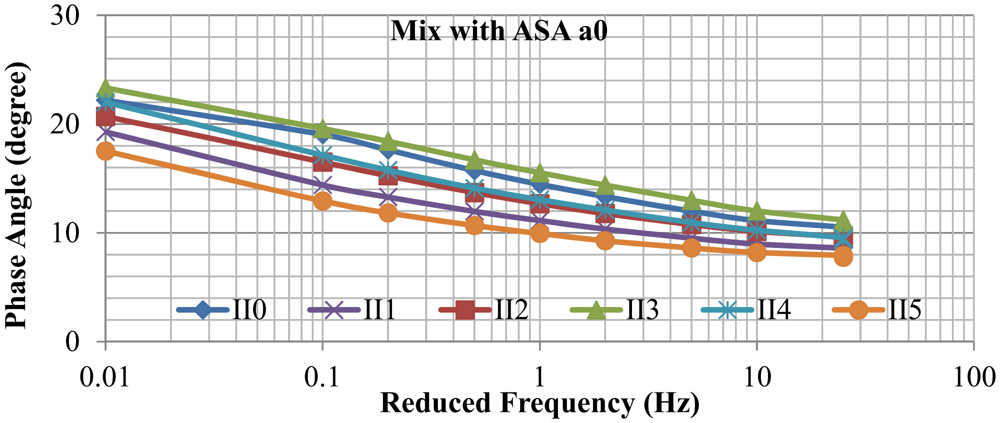


Figure 5-44 Phase Angles of Aggregate Source II Mixtures with ASA a0 and Various Modified Binders at 4°C

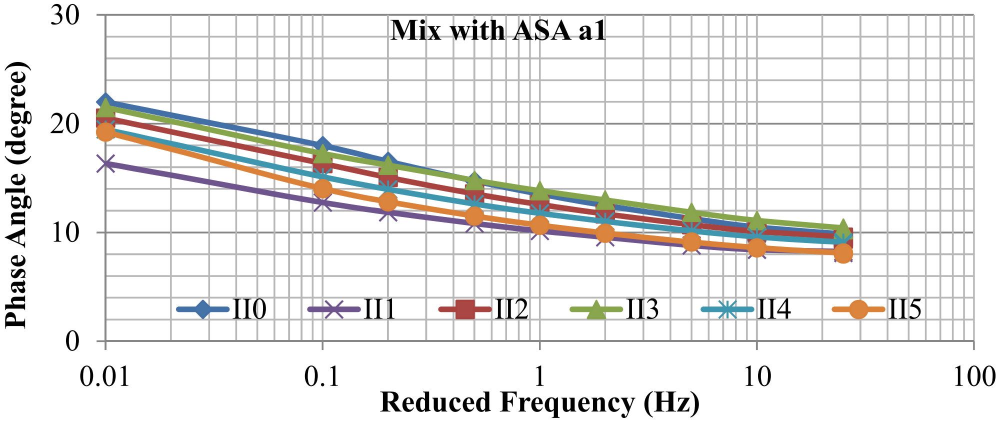


Figure 5-45 Phase Angles of Aggregate Source II Mixtures with ASA a1 and Various Modified Binders at 4°C

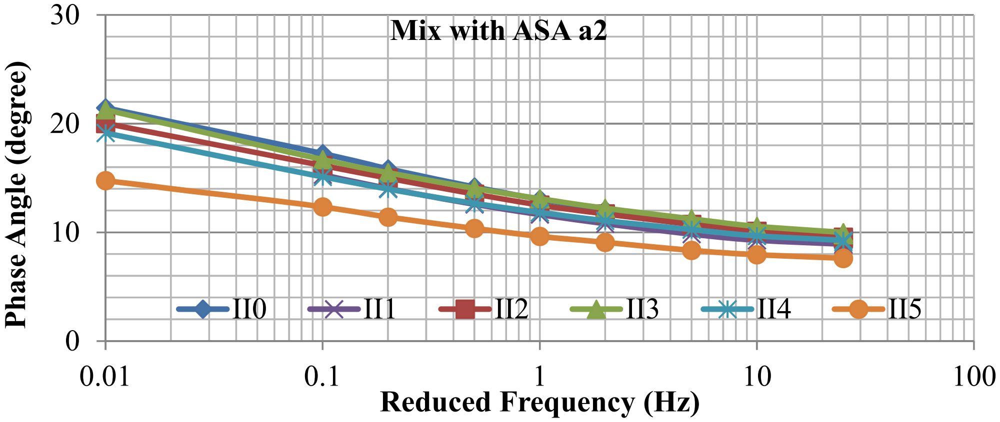


Figure 5-46 Phase Angles of Aggregate Source II Mixtures with ASA a2 and Various Modified Binders at 4°C

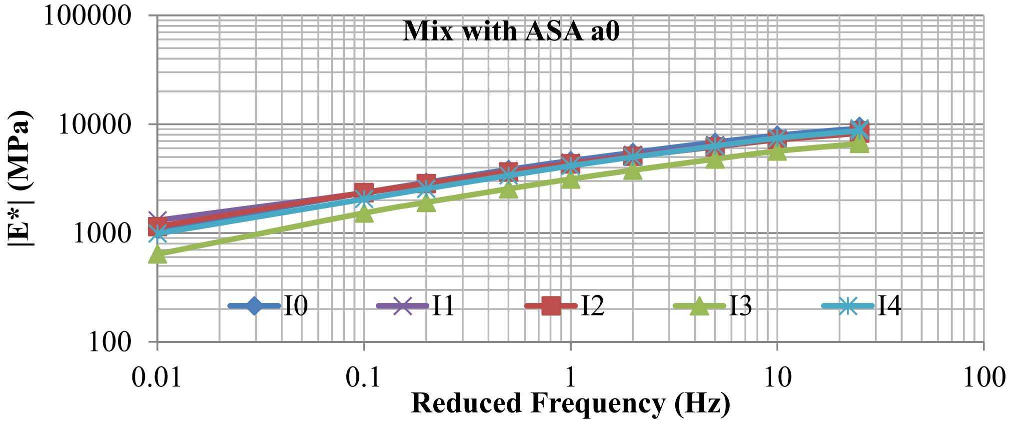


Figure 5-47 |E*| Values of Aggregate Source I Mixtures with ASA a0 and Various Modified Binders at 20°C

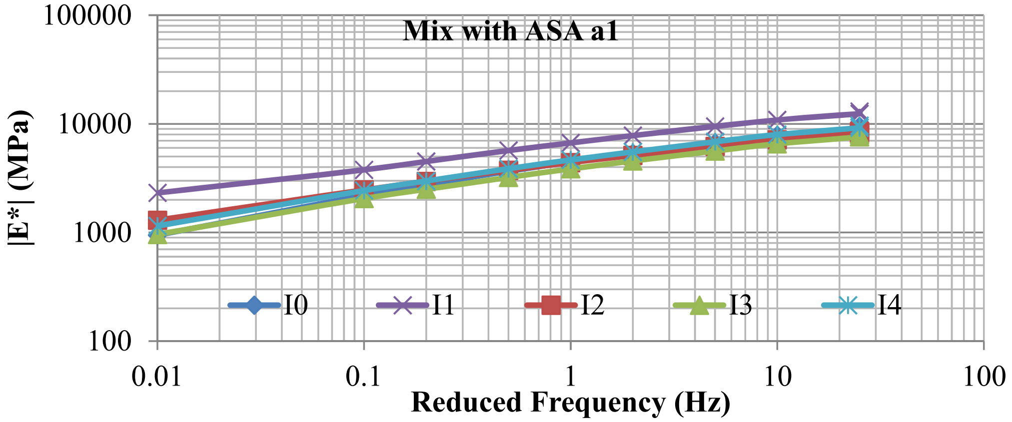


Figure 5-48 |E*| Values of Aggregate Source I Mixtures with ASA a1 and Various Modified Binders at 20°C

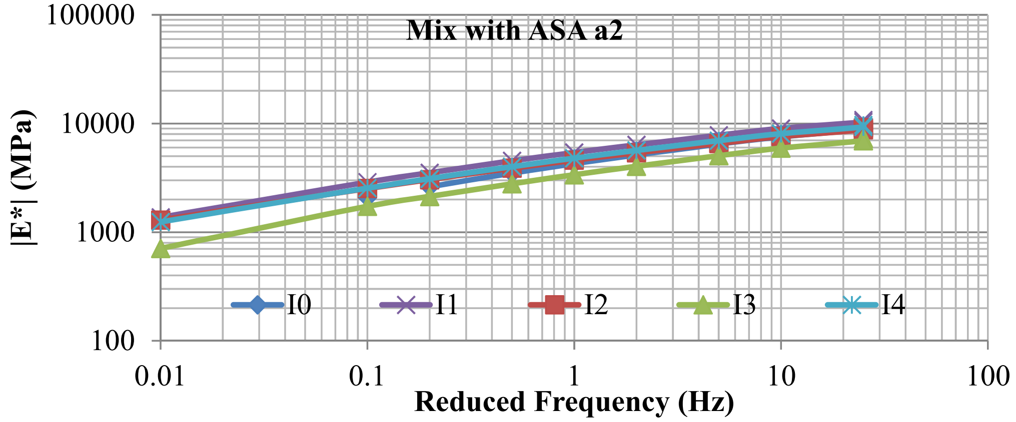


Figure 5-49 |E*| Values of Aggregate Source I Mixtures with ASA a2 and Various Modified Binders at 20°C

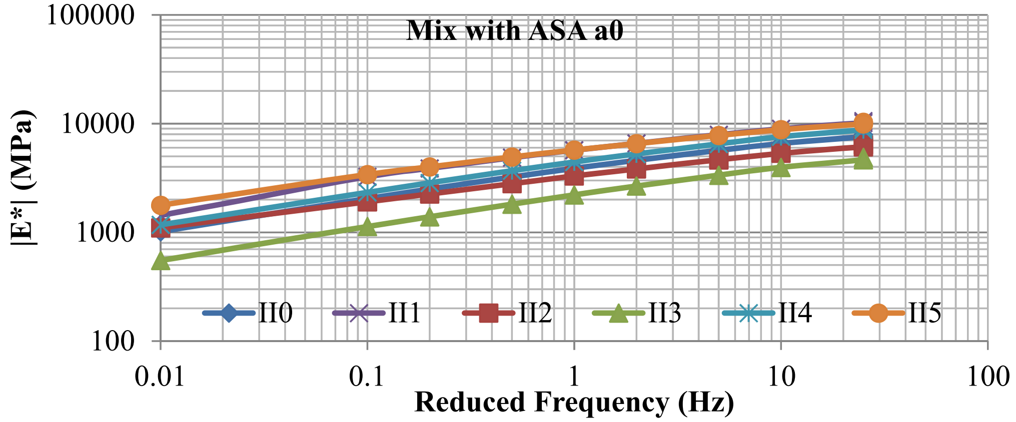


Figure 5-50 |E*| Values of Aggregate Source II Mixtures with ASA a0 and Various Modified Binders at 20°C

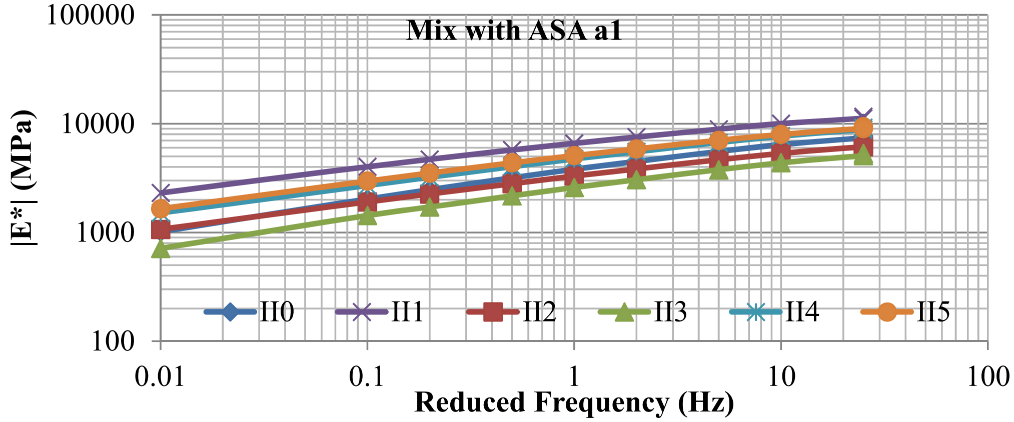


Figure 5-51 |E*| Values of Aggregate Source II Mixtures with ASA a1 and Various Modified Binders at 20°C

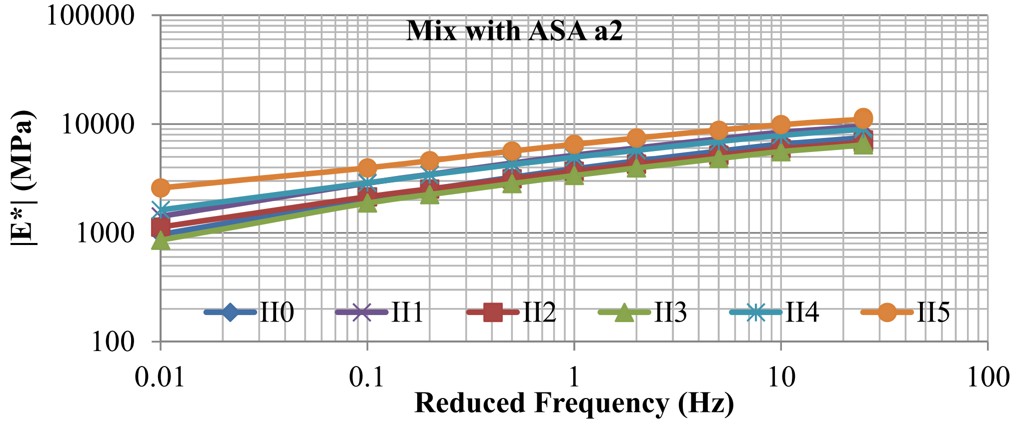


Figure 5-52 |E*| Values of Aggregate Source II Mixtures with ASA a2 and Various Modified Binders at 20°C

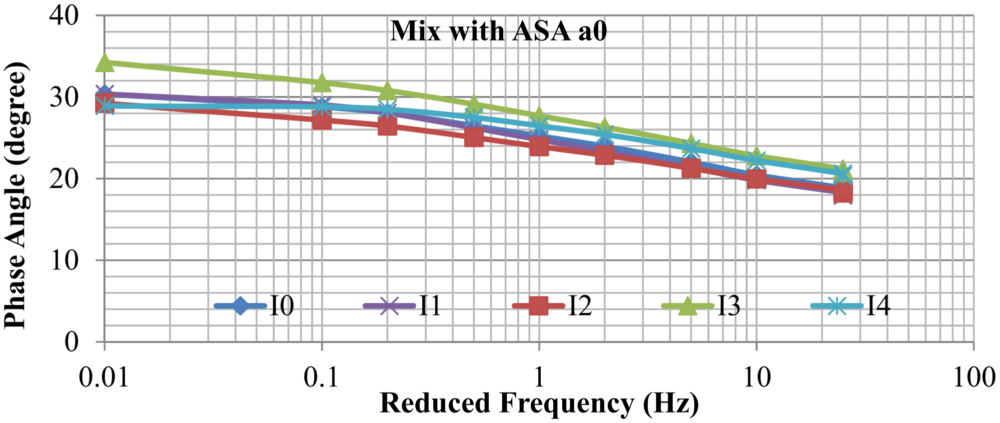


Figure 5-53 Phase Angle Values of Aggregate Source I Mixtures with ASA a0 and Various Modified Binders at 20°C

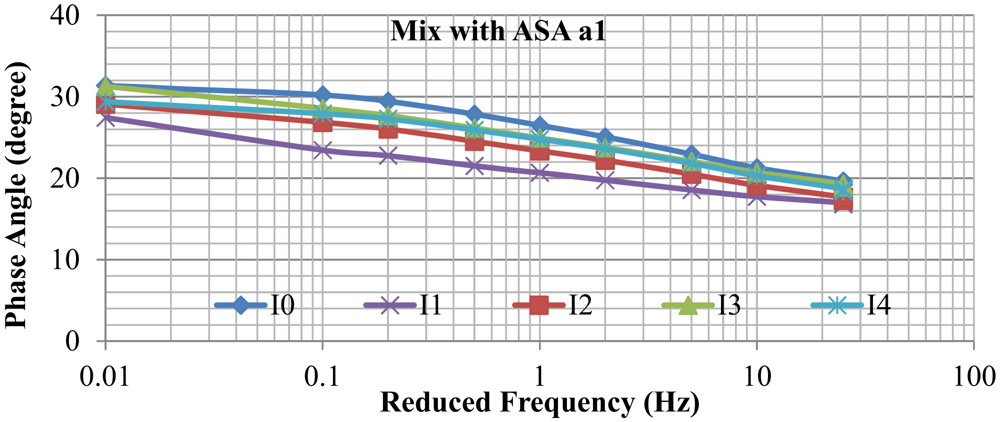


Figure 5-54 Phase Angle Values of Aggregate Source I Mixtures with ASA a1 and Various Modified Binders at 20°C

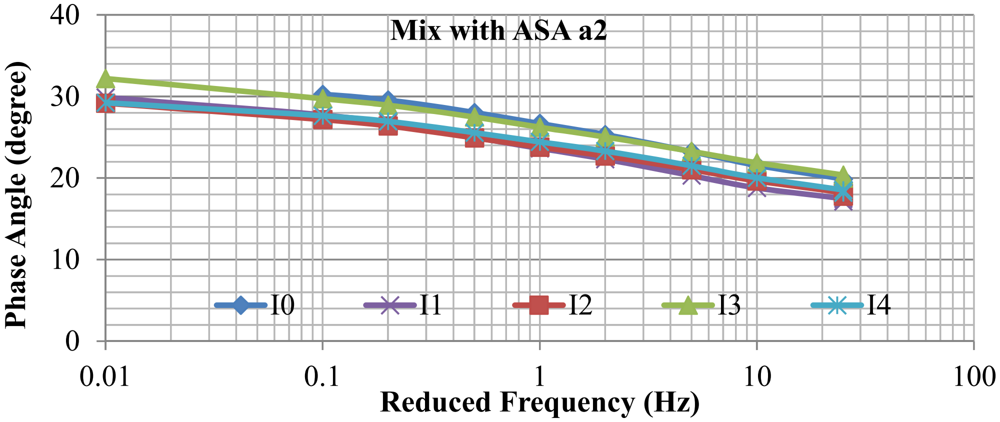


Figure 5-55 Phase Angle Values of Aggregate Source I Mixtures with ASA a2 and Various Modified Binders at 20°C

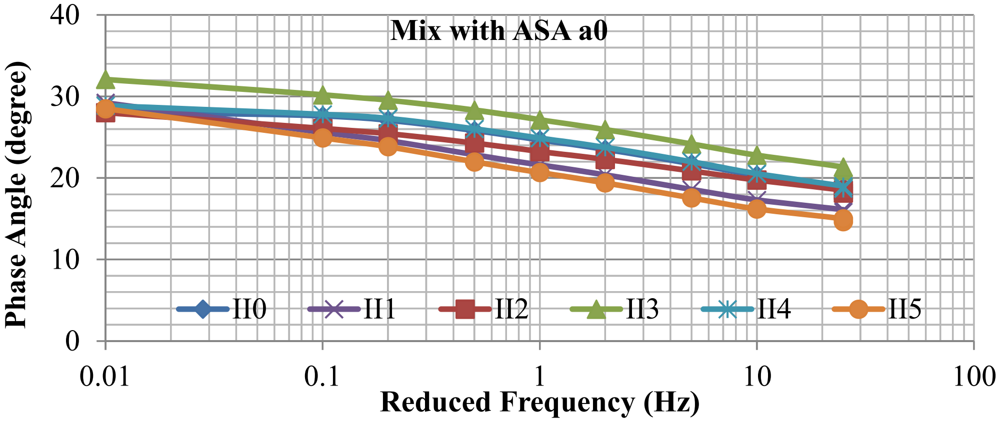


Figure 5-56 Phase Angle Values of Aggregate Source II Mixtures with ASA a0 and Various Modified Binders at 20°C

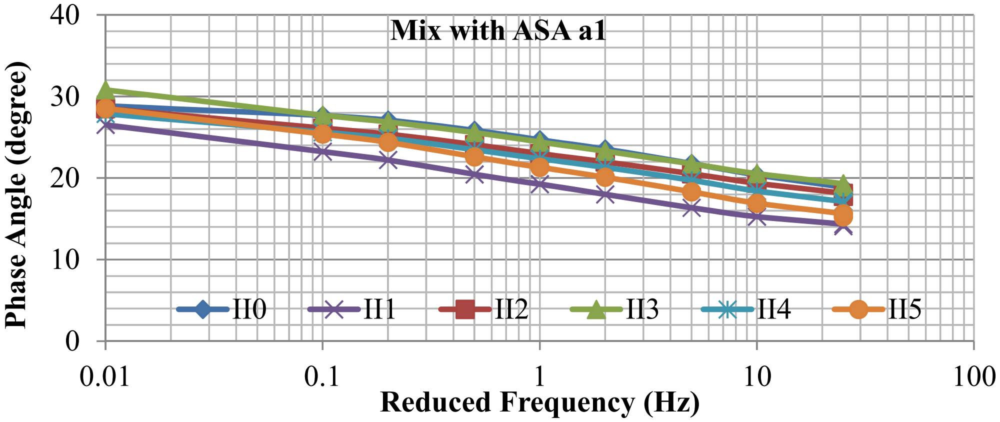


Figure 5-57 Phase Angle Values of Aggregate Source II Mixtures with ASA a1 and Various Modified Binders at 20°C

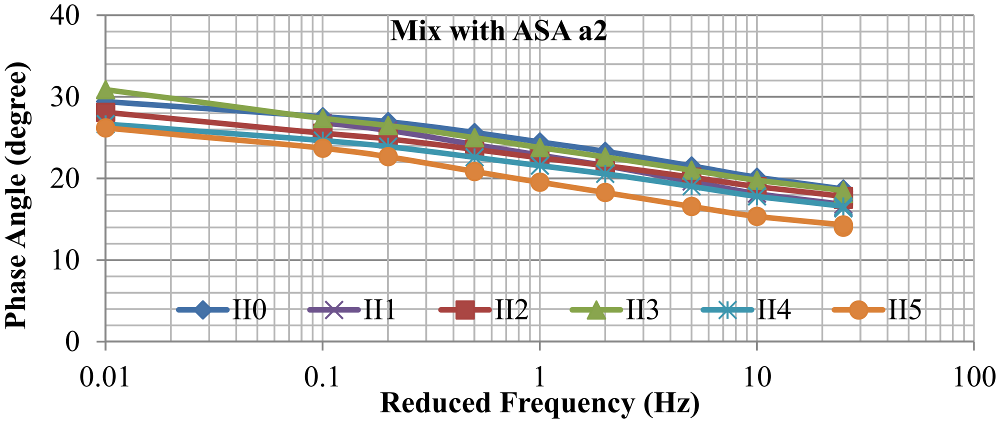


Figure 5-58 Phase Angle Values of Aggregate Source II Mixtures with ASA a2 and Various Modified Binders at 20°C

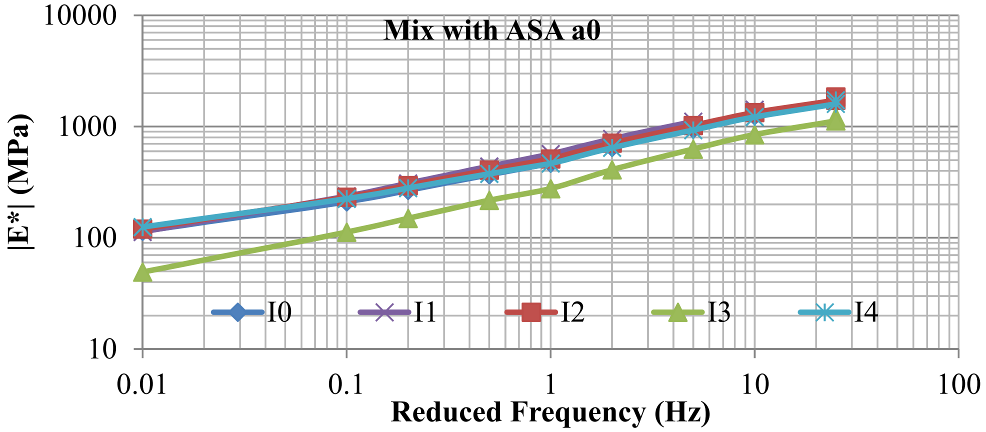


Figure 5-59 |E*| Values of Aggregate Source I Mixtures with ASA a0 and Various Modified Binders at 45°C

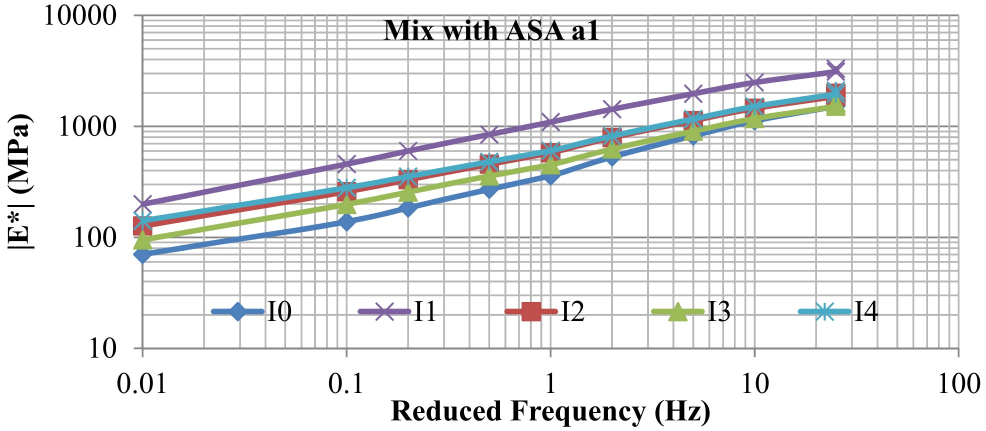


Figure 5-60 |E*| Values of Aggregate Source I Mixtures with ASA a1 and Various Modified Binders at 45°C

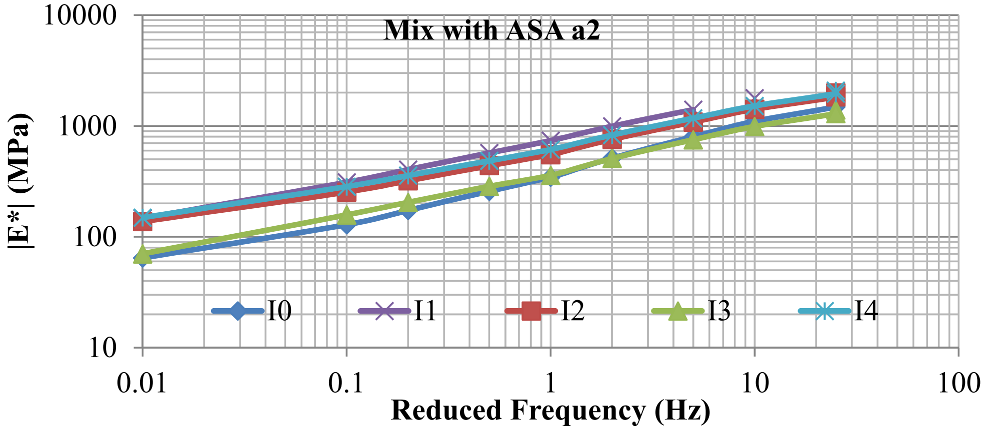


Figure 5-61 |E*| Values of Aggregate Source I Mixtures with ASA a2 and Various Modified Binders at 45°C

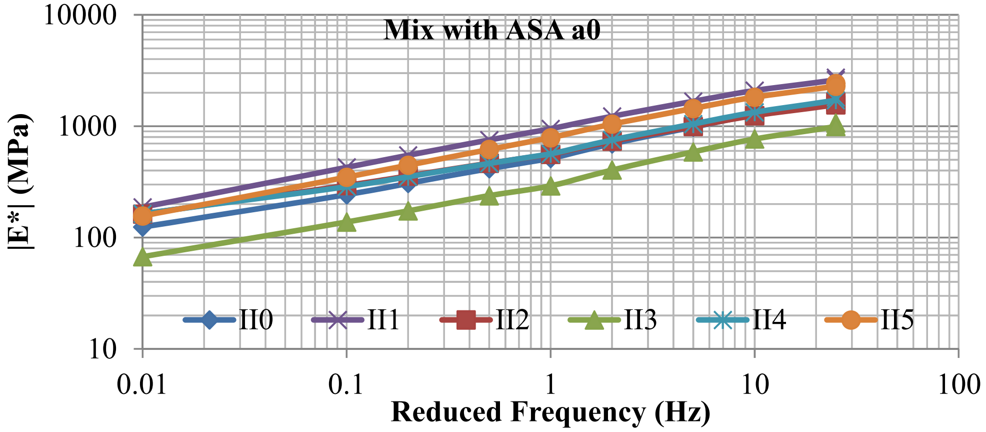


Figure 5-62 |E*| Values of Aggregate Source II Mixtures with ASA a0 and Various Modified Binders at 45°C

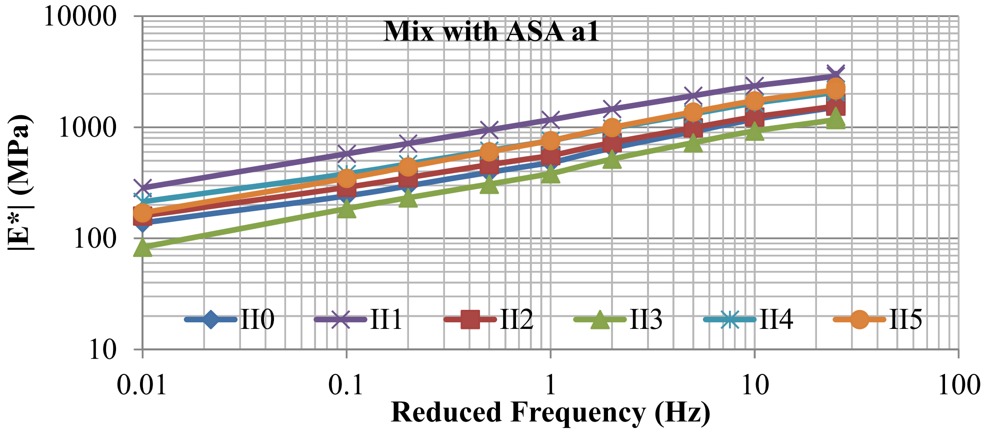


Figure 5-63 |E*| Values of Aggregate Source II Mixtures with ASA a1 and Various Modified Binders at 45°C

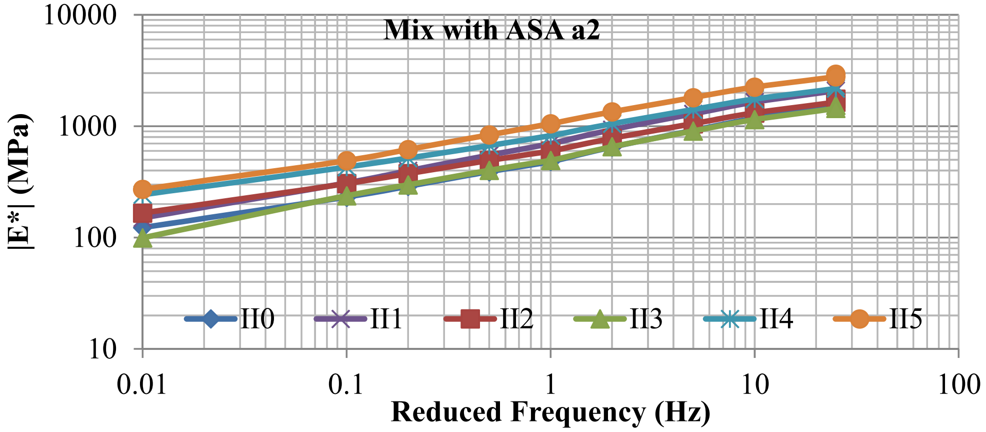


Figure 5-64 |E*| Values of Aggregate Source II Mixtures with ASA a2 and Various Modified Binders at 45°C

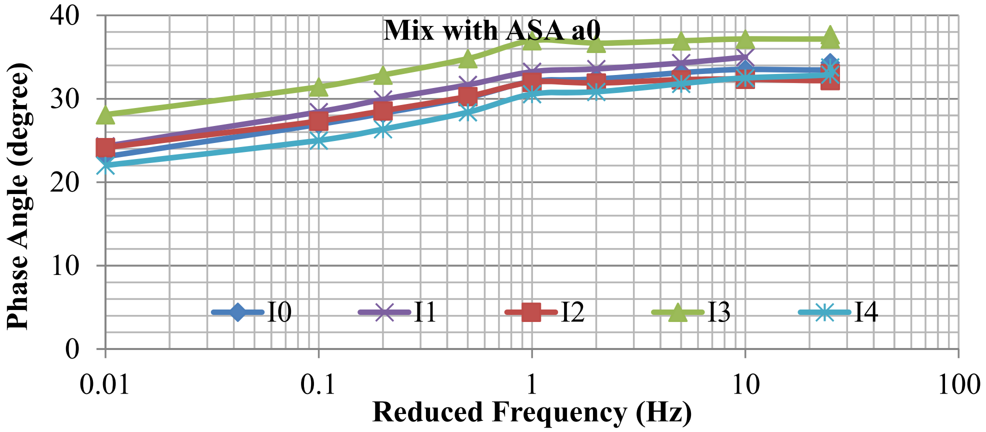


Figure 5-65 Phase Angle Values of Aggregate Source I Mixtures with ASA a0 and Various Modified Binders at 45°C

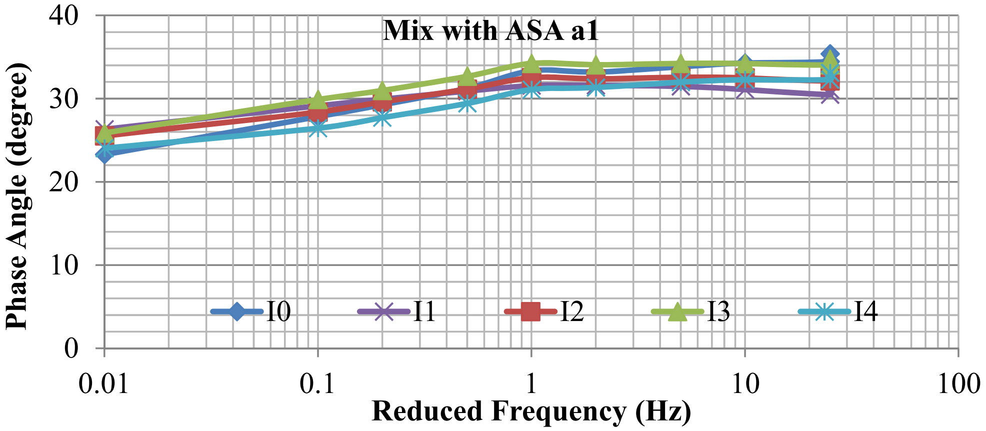


Figure 5-66 Phase Angle Values of Aggregate Source I Mixtures with ASA a1 and Various Modified Binders at 45°C

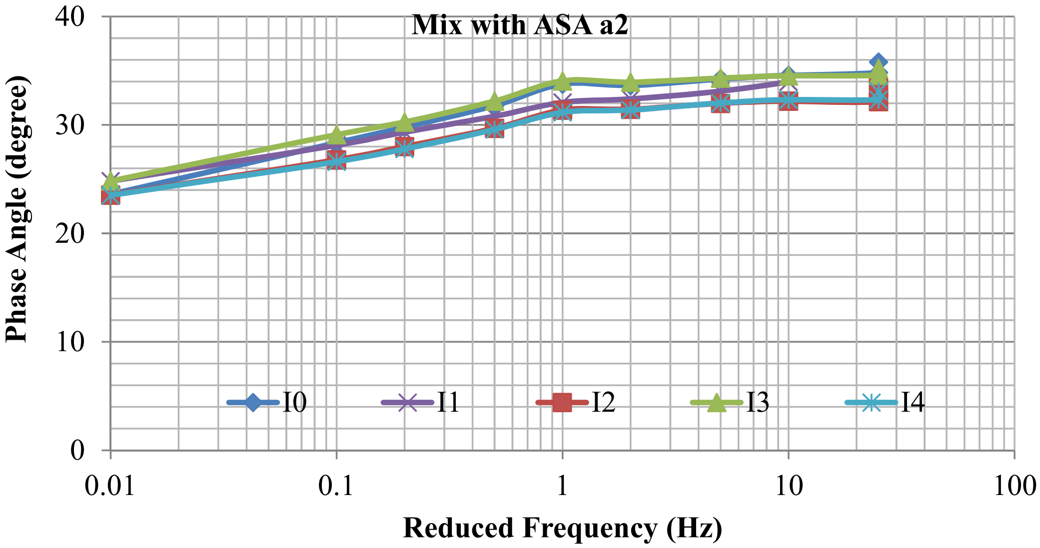


Figure 5-67 Phase Angle Values of Aggregate Source I Mixtures with ASA a2 and Various Modified Binders at 45°C

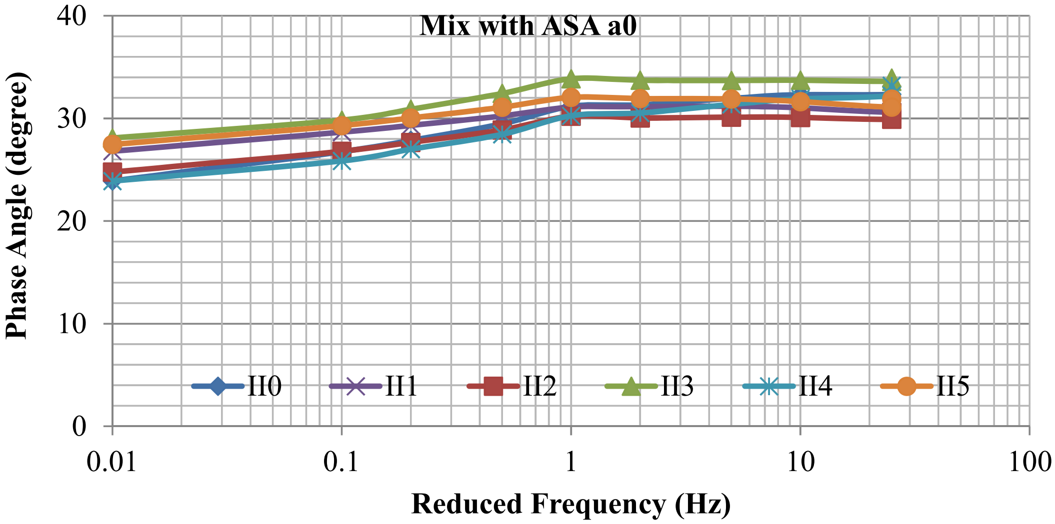


Figure 5-68 Phase Angle Values of Aggregate Source II Mixtures with ASA a0 and Various Modified Binders at 45°C

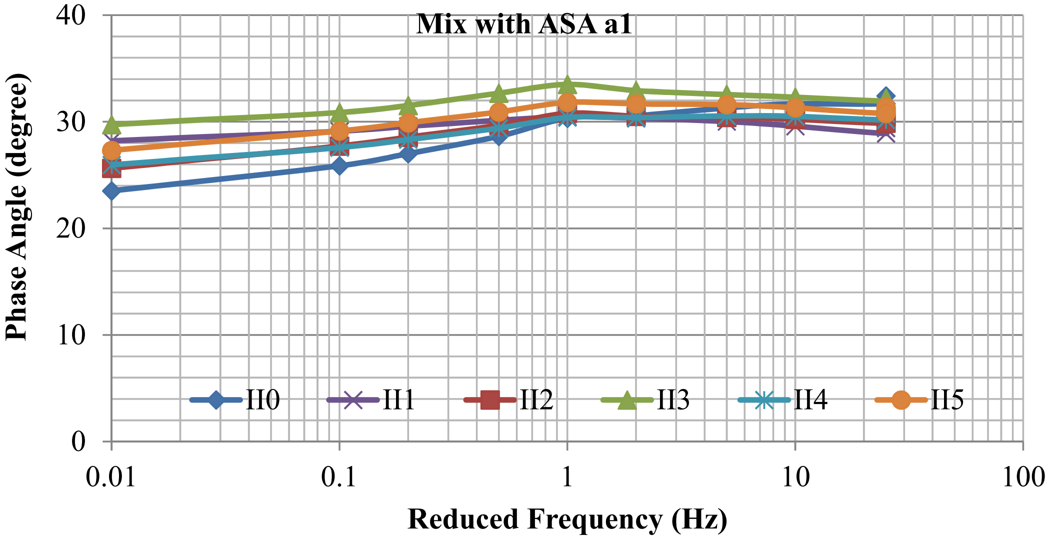


Figure 5-69 Phase Angle Values of Aggregate Source II Mixtures with ASA a1 and Various Modified Binders at 45°C

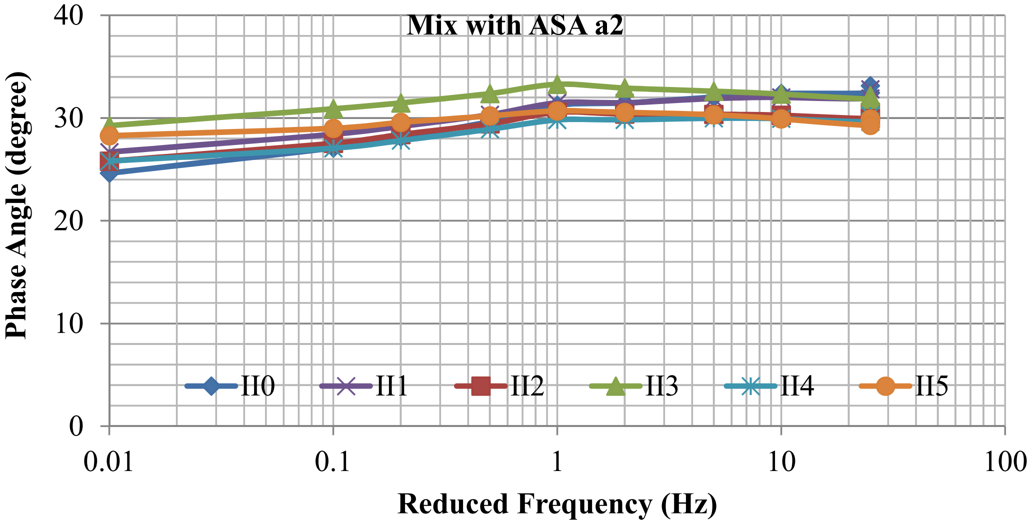


Figure 5-70 Phase Angle Values of Aggregate Source II Mixtures with ASA a2 and Various Modified Binders at 45°C

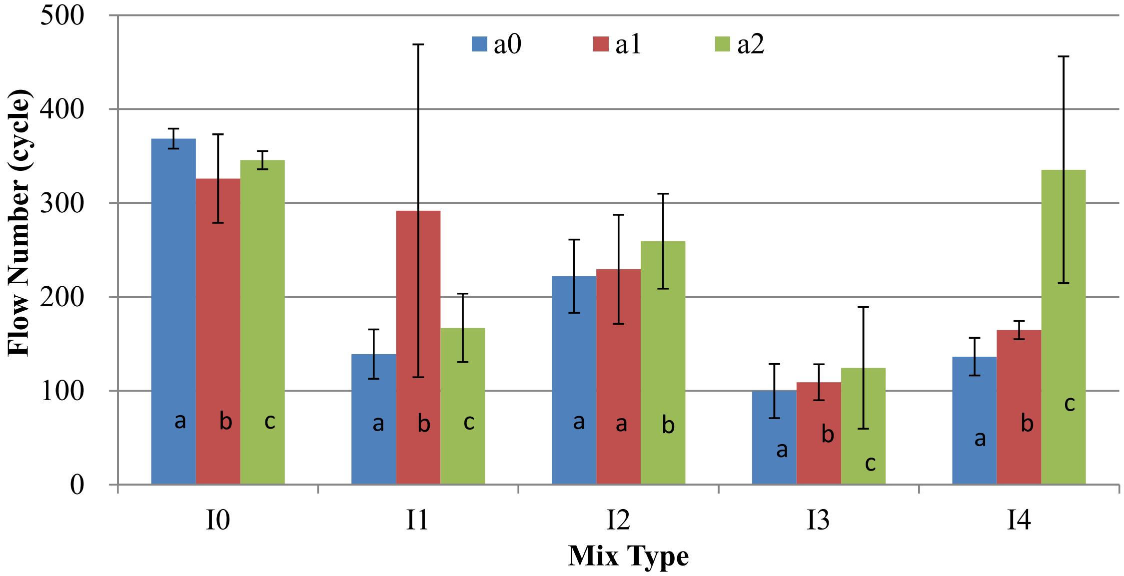
Table 5.13 and Figure 5.71 show the flow numbers of all mixtures made with several modified binders and containing various ASAs and two aggregate sources. The results indicate that with the exception of one case (aggregate II, lime and lab-blended GTR), all other flow numbers are greater than 50, which is the AASHTO criteria set for traffic loading of 3 million to less than 10 million ESAL.

In most cases, the flow numbers for mixtures made with aggregate source I were greater than those made from source II. For example, the flow numbers of samples made with aggregate source I, SBS, and all of the ASAs produced flow numbers that were greater than 190, which is the AASHTO requirement for traffic loading of 10 million to less than 30 million ESAL. However, the samples made with aggregate source II and those same materials produced only one case that satisfied this requirement (liquid ASA 1, a1). In addition, samples made with aggregate source I, terminally-blended GTR and all of the ASAs produced flow numbers that were all greater than 190; however, none of the flow numbers for aggregate source II for those same materials produced any values greater than 110.

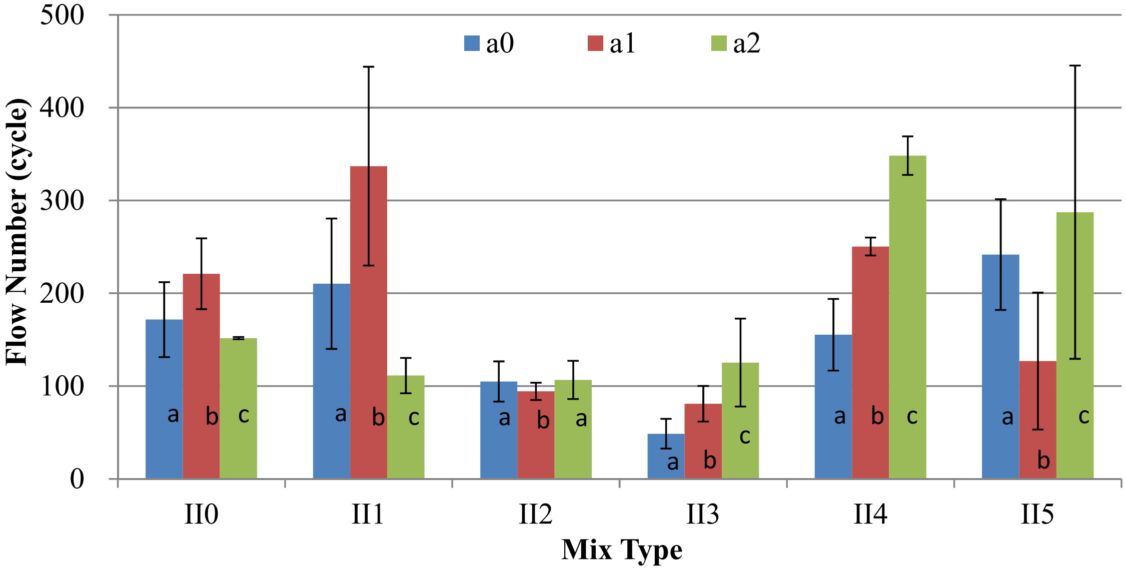
Table 5-13 Flow Numbers at 59°C of Mixtures with Various Modified Binders and Anti-Stripping Additives (ASAs)

Mix type	ASA type	Flow (cycle)		Mix type	ASA type	APA (mm)	
		Mean	Std			Mean	Std
I0	a0	369	11	II0	a0	172	40
	a1	326	47		a1	221	38
	a2	346	10		a2	152	1
I1	a0	139	26	II1	a0	210	70
	a1	292	177		a1	337	107
	a2	167	36		a2	111	19
I2	a0	222	39	II2	a0	105	22
	a1	229	58		a1	94	9
	a2	259	51		a2	107	21
I3	a0	100	29	II3	a0	49	16
	a1	109	19		a1	81	27
	a2	124	65		a2	125	47
I4	a0	136	20	II4	a0	155	39
	a1	165	10		a1	250	74
	a2	335	121		a2	348	21
				II5	a0	242	60
					a1	127	20
					a2	287	158

Notes: I and II ~ aggregate sources; 0~SBS; 1~Plastomer 2; 2~ Terminally-blended GTR from Binder Source C; 3~Lab-blended 10% GTR; 4~Elastomer; 5~PPA+SBS; a0~hydrated lime; a1~liquid ASA 1; a2~liquid ASA 2



(a)



(b)

Figure 5-71 FlowNumbers at 59°C of Mixtures with Various Modified Binders and Anti-Stripping Additives (ASAs), (a) Aggregate I, (b) Aggregate II

Hamburg Wheel-Tracking Rut Resistance

The Hamburg test method is used to characterize the rutting and moisture-susceptibility of hot mix asphalt pavement samples in the Hamburg Wheel-Tracking (HWT) Device, which is applied to determine the premature failure susceptibility of HMA due to weakness in the aggregate structure, inadequate binder stiffness, or moisture damage. This test method measures the rut depth and number of passes to failure. In this study, we used 20,000 passes to test the rut depth values of each mixture with 4 samples.

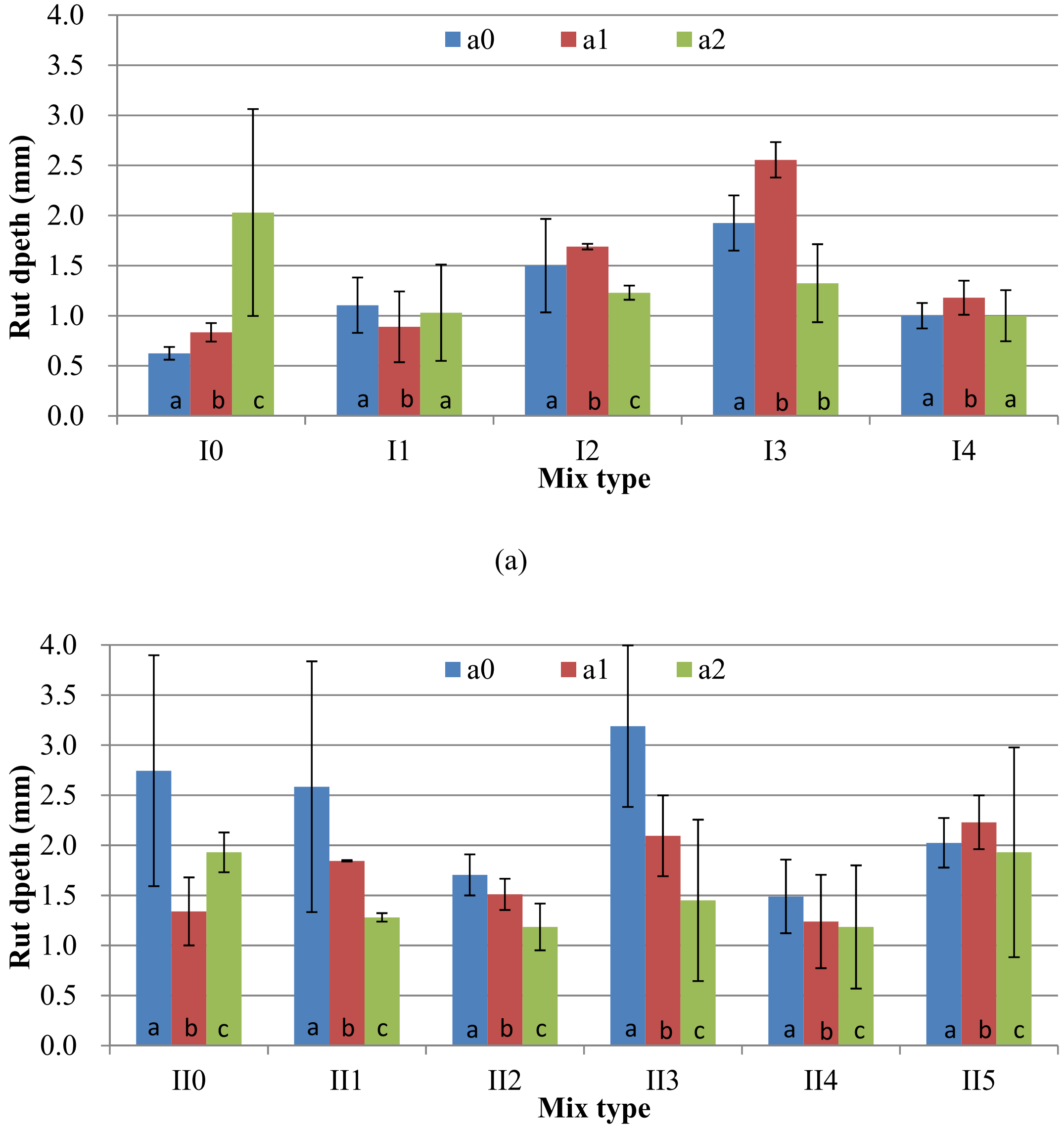
The samples were compacted in the laboratory with a Superpave gyratory compactor (SGC) according to AASHTO T 312, with a diameter of 150mm and a height of 60mm. In accordance with AASHTO T 324 (Hamburg Wheel-Track Testing of Compacted Hot Mix Asphalt), each laboratory-compacted specimen should have an air void value of 7.0 ± 1.0 percent. The test temperature was 50°C in this research.

The obtained HWT rut depth values are shown in Table 5.14 and Figure 5.72. It can be noted that all rut depth values from these modified mixtures were less than 4 mm after 20,000 passes with a load of 70.3kg (155 lb). Even though there were some slight differences between any two modified mixtures, all rut depths satisfied the requirements of permanent deformation for Type A mixtures. In addition, the effect of ASA type on the rut depth and moisture susceptibility of these mixtures was not remarkable.

Table 5-14 HWT rut depths of various polymerized mixtures at 50°C

Mix type	ASA type	HWT Rut depth (mm)		Mix type	ASA type	HWT Rut depth (mm)	
		Mean	Std			Mean	Std
I0	a0	0.63	0.06	II0	a0	2.75	1.15
	a1	0.84	0.09		a1	1.34	0.34
	a2	2.03	1.03		a2	1.93	0.20
I1	a0	1.11	0.28	II1	a0	2.59	1.25
	a1	0.89	0.35		a1	1.85	0.01
	a2	1.03	0.48		a2	1.28	0.04
I2	a0	1.50	0.47	II2	a0	1.71	0.21
	a1	1.69	0.03		a1	1.51	0.16
	a2	1.23	0.07		a2	1.19	0.23
I3	a0	1.93	0.28	II3	a0	3.19	0.81
	a1	2.56	0.18		a1	2.10	0.40
	a2	1.33	0.39		a2	1.45	0.81
I4	a0	1.00	0.13	II4	a0	1.49	0.37
	a1	1.18	0.17		a1	1.24	0.47
	a2	1.00	0.25		a2	1.19	0.62
				II5	a0	2.03	0.25
					a1	2.23	0.27
					a2	1.93	1.05

Notes: 0~SBS; 1~Plastomer 2; 2~ Terminally-blended GTR from Binder Source C; 3~Lab-blended 10% GTR;4~Elastomer; 5~PPA+SBS; a0~hydrated lime; a1~liquid ASA 1; a2~liquid ASA 2;I~ aggregate one; II~ aggregate two



(a)

(b)

Figure 5-72 HWT rut depths of various polymerized mixtures at 50°C, (a) Aggregate I, (b) Aggregate II

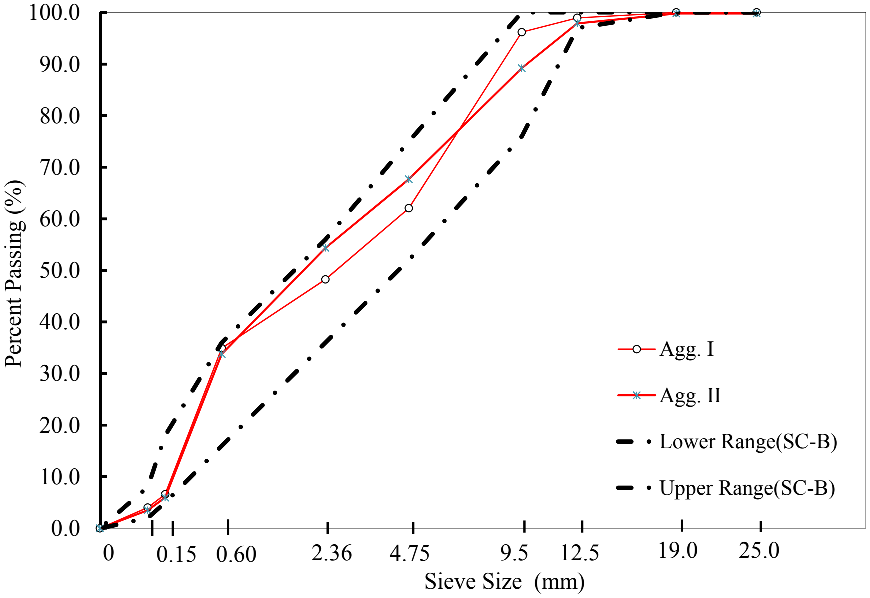
Chapter 6 – Results: Natural Sand

Materials

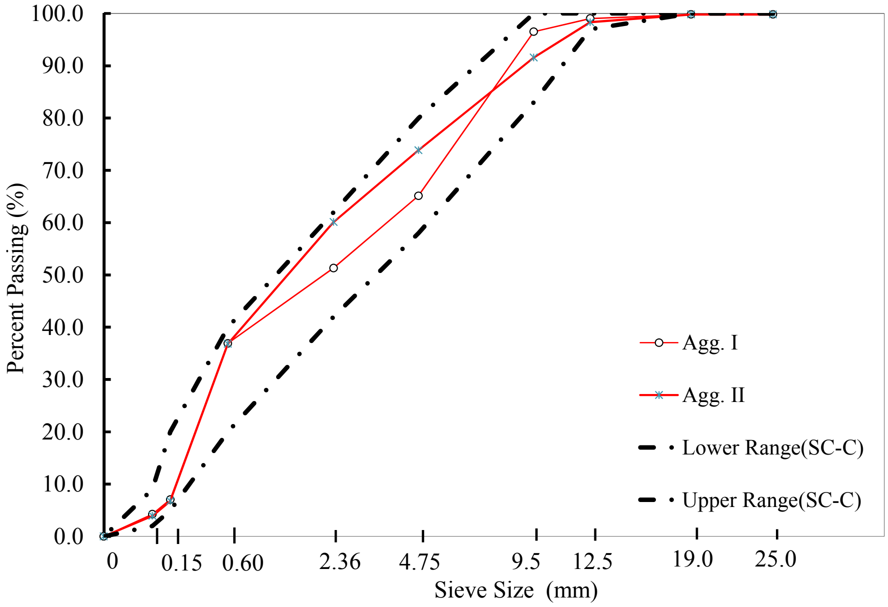
The experimental design detailed in this section included the utilization of one PG 64-22 binder, two aggregate sources (designated as I and II) and one natural sand source. Three anti-stripping additives (ASAs) including hydrated lime (designated as a0) and two liquid ASAs (referred to as a1 and a2) were used for preparing samples. In addition, two percentages of reclaimed asphalt pavement (RAP) (25% and 30% aged binders) were selected. For Surface Type B and Surface Type C mixtures, 25% and 30% aged binders were selected, respectively. The 20% natural sand was used for all mixtures in this research.

Mix Design, Sample Fabrication and Testing

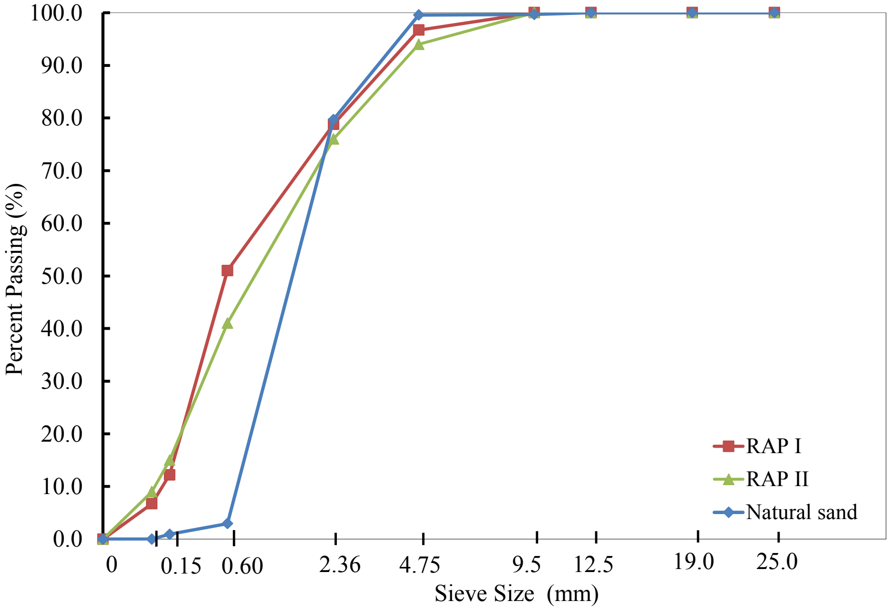
The mix designs included aggregates that satisfied the specifications set forth by the South Carolina Department of Transportation (SCDOT) for a Surface B mixture ($N_{design} = 75$) and a Surface C mixture ($N_{design} = 50$). The gradations for each aggregate source (I and II) and natural sand are shown in Figures 6.1 a-c. The engineering properties of the aggregate sources are shown in a later chapter of this report in Table 7.1. In addition, the RAPs materials used in this study were the -#4 (passing No. 4 sieve) materials. The design aggregate gradations for each aggregate source were the same when using various ASAs in this study. Based on the recommendations from the binder supplier and the use of RAP materials in the mixture, the mixing and compaction temperatures used in this study were 153°C and 145°C, respectively.



(a)



(b)



(c)

Figure 6-1 Gradations of Surface Types B and C with Natural Sand

In this study, the optimum binder content was defined as the amount of binder required to achieve 3.5-4.5% air voids in accordance with SCDOT volumetric specifications. In addition, the mix design master binder limits are 4.8 – 6.0% for Surface Type B and 5.0 – 6.8% for Surface Type C. After the mix designs were completed and the optimum asphalt binder contents were determined for each aggregate/ASA/RAP combination, four Superpave gyratory-compacted (SGC) specimens (150 mm in diameter and 95 mm in height) were prepared with 7.0 ± 1.0% air voids. These samples were then tested at 25°C (77°F) to determine the indirect tensile strengths. Two of the samples were tested in dry condition and the other two in wet condition as per the SCDOT procedure for determining the moisture susceptibility (SC-T-70). A total of 48 ITS samples were made and tested in this study.

In addition, six SGC specimens for each mixture (150 mm in diameter and 75 mm in height) were prepared with 4.0 ± 0.5% air voids. These samples 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 (8050 cycles). A total of 72 APA sample were fabricated and tested in this study.

Four SGC specimens for each mixture (150 mm in diameter and 60 mm in height) were prepared with 7.0 ± 1.0% air voids for Hamburg Wheel Testing (HWT). The samples were then cut to the suitable size according to the requirements of the equipment. These samples were tested with a loading of 71.7kg (158 lb) for 20,000 cycles at 50°C. A total of 48 HWT samples were fabricated and tested in this study.

Additionally, three SGC specimens for each mixture (150 mm in diameter and 170 mm in height) were prepared with 7.0 ± 1.0% air voids. These samples were cored and cut to a size of 100mm in diameter and 150mm in height and were then conditioned and tested to obtain the dynamic modulus at the temperatures of 5°C, 20°C and 45°C. After that, these samples were tested for flow number at a temperature of 59°C according to the LTPP software recommendation. A total of 36 dynamic modulus samples were fabricated and tested for the natural sand mixtures.

Test Results

Superpave Mix Design Analysis

As shown in Table 6.1, two Superpave mix designs (Surface Type B and Surface Type C) were completed for the asphalt mixtures containing aggregate sources I and II, respectively. For the Surface Type B mixtures, 20% natural sand and 25% aged binder (23% RAP) were used while Surface Type C mixtures were designed with 20% natural sand and 30% aged binder (27% RAP).

Table 6.1 shows that the optimum binder content (OBC) of the Surface Type B mixtures from the two aggregate sources was 5.7%, a value between 4.8 to 6.0% that satisfies the SCDOT's specifications. The obtained voids in mineral aggregate (VMA), voids filled with asphalt (VFA), and dust/asphalt (D/A) ratios of the Surface

Type B mixtures were in the range of the defined specifications for SCDOT mix design per SC-M-402. Similarly, the results show the OBC value of the Surface Type C mixtures made with the two aggregate sources was 6.3%. In addition, the VMA and VFA values were generally close.

Table 6-1 Mix Designs of Surfaces B and C Mixtures

20% Natural sand		Aged binder (%)	OBC (%)	MSG	BSG	VMA (%)	VFA (%)	Dust/Asphalt ratio
				Specifications (Surface B)				
Mix type	Aggregate	≤ 25	4.8-6.0	-	-	>14.5	70-80	0.6-1.2
Surface B (N^{design} =75)	Agg. I	25	5.7	2.454	2.355	17.0	76.2	0.70
	Agg. II	25	5.7	2.443	2.337	17.2	74.9	0.61
				Specifications (Surface C)				
		≤ 30	5.0-6.8	-	-	>14.5	70-77	0.6-1.2
Surface C (N^{design} = 50)	Agg. I	30	6.3	2.439	2.330	18.6	76.1	0.68
	Agg. II	30	6.3	2.403	2.298	18.4	76.2	0.63

Indirect Tensile Strength (ITS) Analysis

The results shown in Figure 6.2 indicate that the dry ITS values of specimens from aggregate source I were generally higher than those values from aggregate source II in terms of same type of mixture. In addition, in most cases, the samples from Surface Type B had higher dry ITS values than the samples from Surface Type C. The results also show that the samples with hydrated lime had slightly different ITS values compared to other samples containing liquid ASAs. Generally, no obvious trends could be found for these dry ITS values when using three ASAs in this study. The statistical analysis shown in Table 6.2 indicates that there were no significantly-different dry ITS values between any two samples with different ASAs regardless of mixture type (Surface B or C).

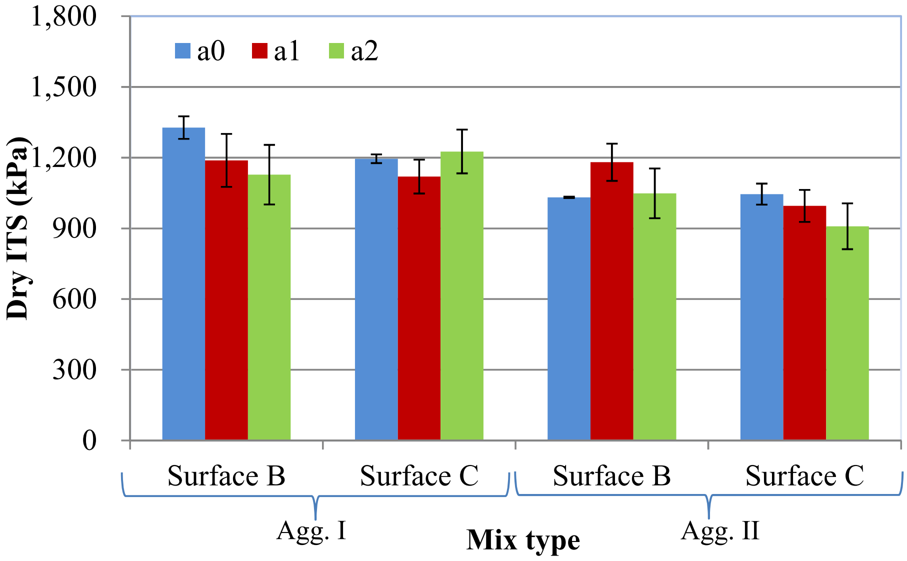


Figure 6-2 Dry ITS Values of Surfaces B and C Mixtures

As shown in Figure 6.3, the wet ITS values for all samples made with aggregate I were generally similar when using the same ASA. However, Surface Type B mixtures exhibited higher wet ITS values when using aggregate II regardless of ASA type even though all wet ITS values for aggregates I and II were greater than 448 kPa, which is the minimum wet ITS value set forth by SCDOT's specification. Statistical analysis results are shown in Table 6.2. In terms of the ASA effect, it can be noted that no significant differences in wet ITS values could be found except for the Surface Type B mixtures containing hydrated lime and liquid a2. These wet ITS values were caused by a combined effect of natural sand, RAP, and ASAs. In addition, Table 6.2 shows that the dry ITS values from all of these mixtures had no statistical differences at a level of 95% significance.

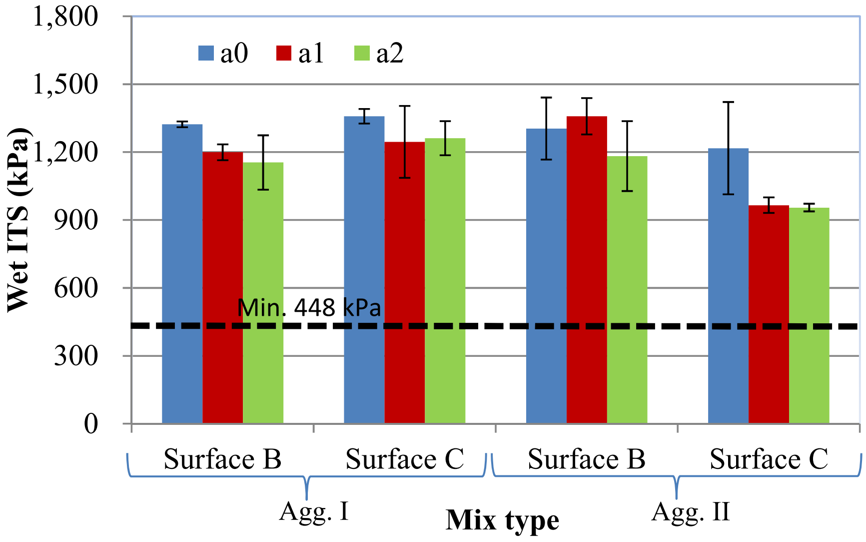


Figure 6-3 Wet ITS Values of Surfaces B and C Mixtures

Table 6-2 Statistical Analysis of Surfaces B and C Mixtures

α = 0.05 Condition		ITS			Flow			Dissipated energy		
		a0-a1	a0-a2	a1-a2	a0-a1	a0-a2	a1-a2	a0-a1	a0-a2	a1-a2
Surface B	Dry	N	N	N	N	N	N	N	N	N
	Wet	N	Y	N	N	N	N	N	Y	N
Surface C	Dry	N	N	N	N	N	N	N	N	N
	Wet	N	N	N	N	N	N	N	Y	N

Note: a0: hydrated lime, a1 and a2: liquid anti-strip additives, Y: P-value < α = 0.05 (significant difference), N: P-value > α = 0.05 (No significant difference)

Tensile Strength Ratio (TSR) Analysis

The TSR results from the Surface Type B and C mixtures are presented in Figure 6.4. It can be noted that all specimens had TSR values higher than 85%, which is the minimum specification value set by SCDOT. Additionally, most of the TSR values were greater than 100%. In addition, the mixtures with hydrated lime generally exhibited slightly higher TSR values than the mixtures containing liquid ASAs, but no obvious trends can be noted for the two liquid ASAs. In Figure 6.4, the impacts of aggregate source, ASA, and mixture type on TSR values of mixtures containing natural sand were not generally obvious for the materials used in this study.

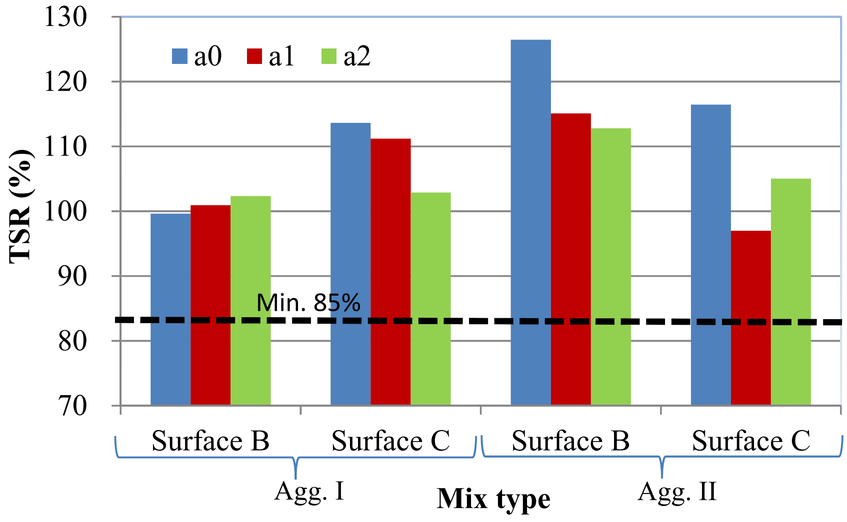
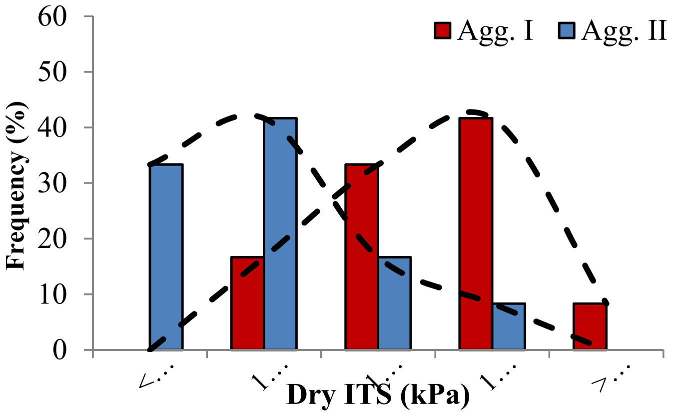


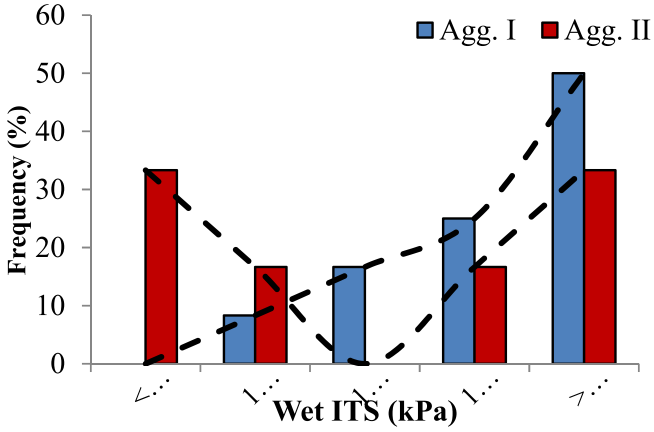
Figure 6-4 TSR Values of Surfaces B and C Mixtures

Distribution Analysis of ITS Values

Three categories were used to explore the distribution ranges of ITS values of mixtures with natural sand and RAP. In terms of the effect of aggregate source, Figure 6.5 indicates that the peak value of frequency from aggregate II was approximately 40%, with dry ITS values in a range of 1,000 to 1,100 kPa. The frequency values of the ITS values less than 1,000 kPa and in other ranges were generally low. However, the peak values of the frequency were over 40% when the mixtures were made with aggregate I with ITS values between 1,200 to 1,300 kPa. Therefore, the frequency distribution analysis indicates that the mixtures from aggregate I generally had greater dry ITS values than those from aggregate II. Figure 6.5b shows that, the frequency distribution value of wet ITS values of mixtures from aggregate I increases from the range of 1,000-1,100 kPa to greater than 1,300 kPa, but the mixtures from aggregate II have higher frequency values when the wet ITS values are less than 1,000 kPa or greater than 1,300 kPa. Consequently, the mixtures from aggregate I generally have higher dry and wet ITS values than those from aggregate II regardless of mixture type and ASA.



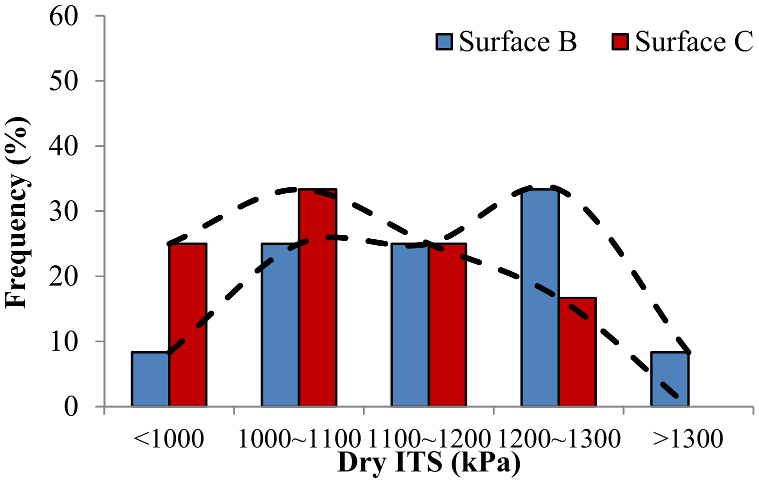
(a)



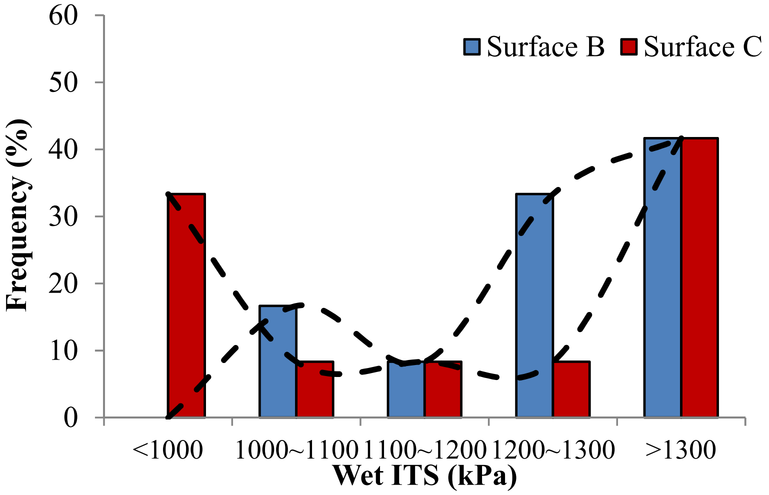
(b)

Figure 6-5 Distribution of ITS in Terms of Aggregate Source Effect

In terms of the effect of mixture type, Figure 6.6 shows that, for Surface Type C, the peak value of frequency for dry ITS was 1,000 to 1,100 kPa, while this peak value for dry ITS was 1,200 to 1,300 kPa for Surface Type B. In addition, Figure 6.6 indicates that the frequency values of Surface Type B and C mixtures were same when the wet ITS values were greater than 1,300 kPa, but Surface Type C mixtures had higher frequency values when wet ITS values were less than 1,000 kPa. Therefore, it could be concluded that the dry and wet ITS values from Surface Type B mixtures are generally higher than those from Surface Type C mixtures regardless of aggregate source and ASA.



(a)



(b)

Figure 6-6 Distribution of ITS in Terms of Surface Type Effect

Regarding the effects of ASA on ITS values, Figure 6.7(a) indicates that the frequency value was the highest when the mixtures contained hydrated lime and the dry ITS values were in the range of 1,000 to 1,100 kPa. In addition, Figure 6.7 shows that higher dry ITS values were found from mixtures containing liquid a1 compared to mixtures made with liquid a2. In Figure 6.7(b), it can be observed that the mixtures with hydrated lime had the highest frequency values in wet ITS value greater than 1,300 kPa. In addition, the results indicate that the frequency values of wet ITS values from the mixtures containing liquid ASAs a1 and a2 are the same. The mixtures with hydrated lime generally showed higher dry and wet ITS values regardless of aggregate source and mixture type for the materials used in this study.

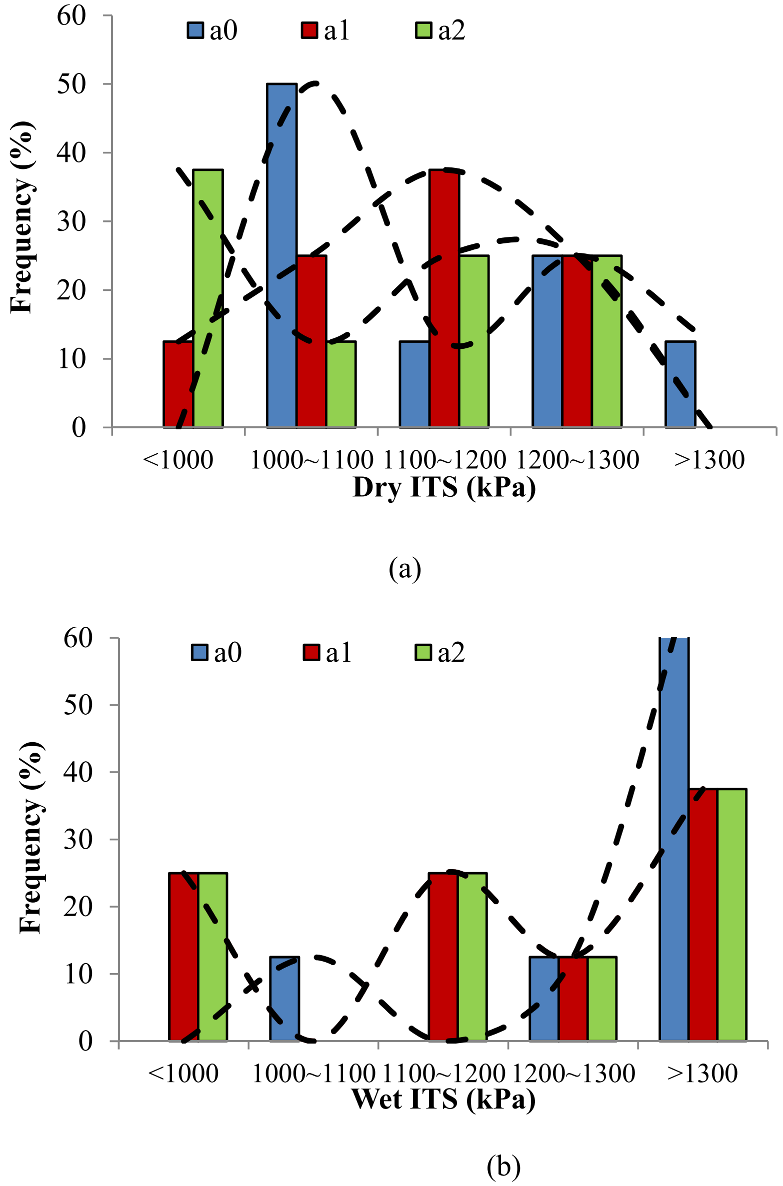


Figure 6-7 Distribution of ITS in Terms Of ASA Type Effect

Deformation (Flow) Analysis

The deformation (flow) resistance of ITS specimens, which is a measure of the material's resistance to permanent deformation in service, was also used for moisture susceptibility analysis of the mixture. As shown in Figure 6.8, the deformation results indicate that, in general, similar dry flow values were found when using various ASAs. In addition, Surface Type B mixtures generally had slightly higher dry flow values regardless of aggregate source and ASA. However, the wet flow values (Figure

6.9) of mixtures from aggregates I and II were generally close to 4 mm irrespective of mixture type and ASA. Therefore, mix type, aggregate source, and ASA type did not play a key role in determining the flow values of mixtures containing natural sand and RAP used in this study. As shown in Table 6.3, there were not significantly different deformation values between any two mixtures containing various ASAs. As a result, the effect of ASA on the deformations of the mixture can be ignored for the materials used in this research.

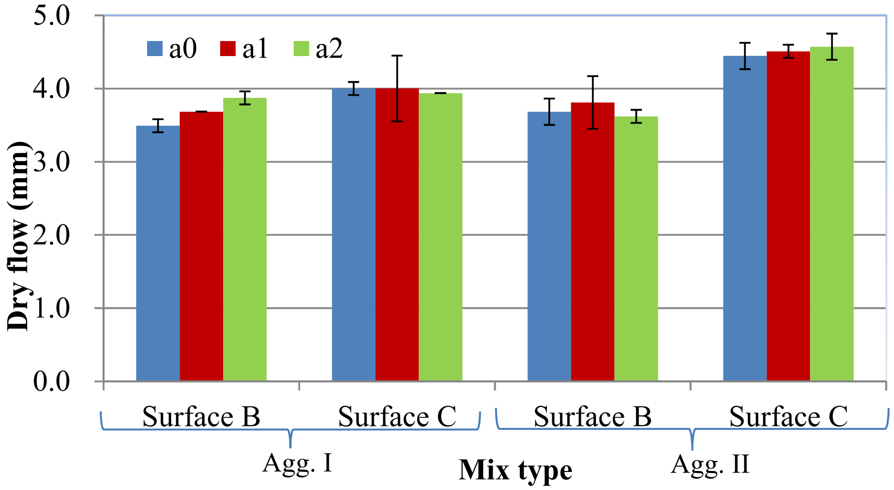


Figure 6-8 Dry Flow Values of Surface B and C Mixtures

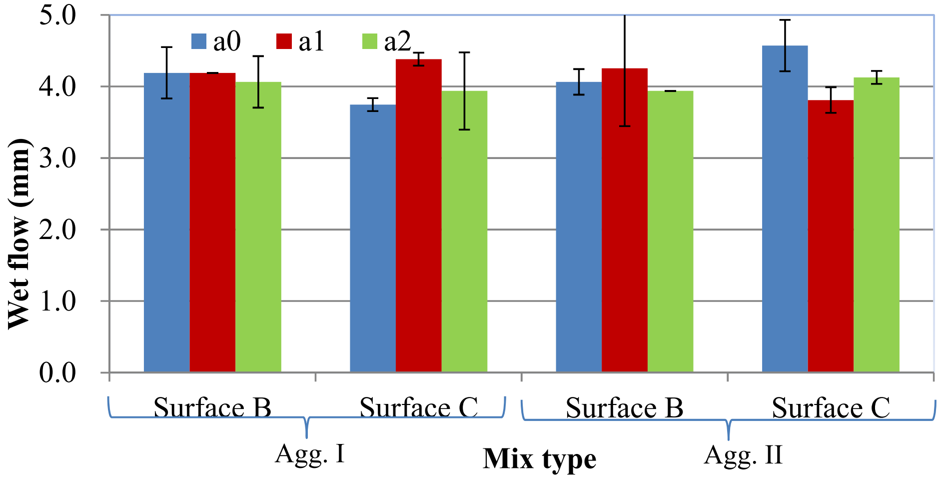


Figure 6-9 Wet Flow Values of Surface B and C Mixtures

APA Rut Depth Analysis

According to the specifications set forth by SCDOT, the maximum rutting susceptibility of Surface Type B is 5 mm, but no rut requirements are specified for Surface Type C mixtures. The rut depth results shown in Figure 5.10 indicate that the rut depths of the mixtures from aggregate I were generally lower than 5 mm regardless of ASA and mixture type. However, the APA rut depths of mixtures from aggregate II were slightly higher than 5 mm when using a0 and a2. In addition, in Figure 6.10, it can be noted that the Surface Type C mixtures made with aggregate II had rut depths higher than 8.0 mm. The reason for these higher rut values might be that these mixes made with aggregate II had a relatively higher percentage of fine aggregate compared to the mixtures made with aggregate I.

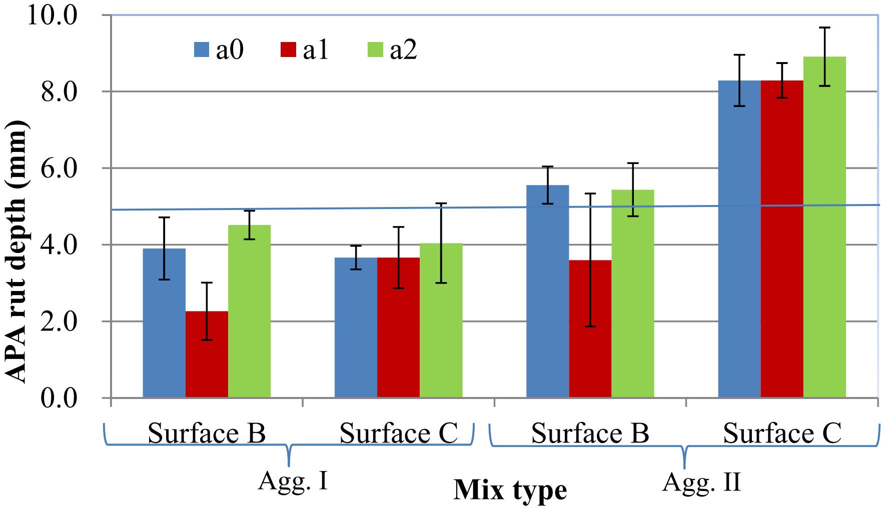


Figure 6-10 Rut Depth Values of Surfaces B and C Mixtures

The effects of air voids on rutting resistance are shown in Figure 6.11. The results indicate that, as expected, increased air voids led to an increase of rut depth regardless of surface type. However, this increase in rut depth was more noticeable in Surface Type C. In the range of air voids between 3.5 to 4.5% (SCDOT mix design requirements for these mixtures), some rut depths greater than 5 mm were observed. Therefore, it may be necessary to reduce the percentage of fine aggregate (crushed sand) when using aggregate source II to satisfy the APA requirement for Surface Type B mixtures.

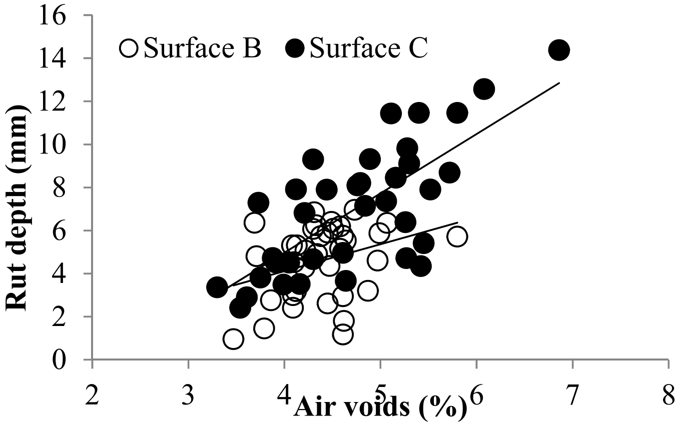


Figure 6-11 Rut Depth Values of Surfaces B and C Mixtures in Terms of Air Voids

In terms of the effects of aggregate source and mixture type, frequency analysis of rut depth is shown in Figure 6.12. It can be noted that the peak frequency values of Surface Type B mixtures from aggregates I and II are over 40% when their rut depths are in the range of 4.0-6.0 mm. As shown in Figure 5.12, most rut depths of these two mixtures are less than 4 mm. In addition, the frequency values of the Surface Type C mixtures from aggregate I are similar to Surface Type B mixtures, but the rut depths of Surface Type C mixtures from aggregate II have peak loads of frequency value over 40% when the rut depths are 8 to 10 mm. Additionally, their distributions of rut depths are more than 6 mm, and some are even greater than 10 mm.

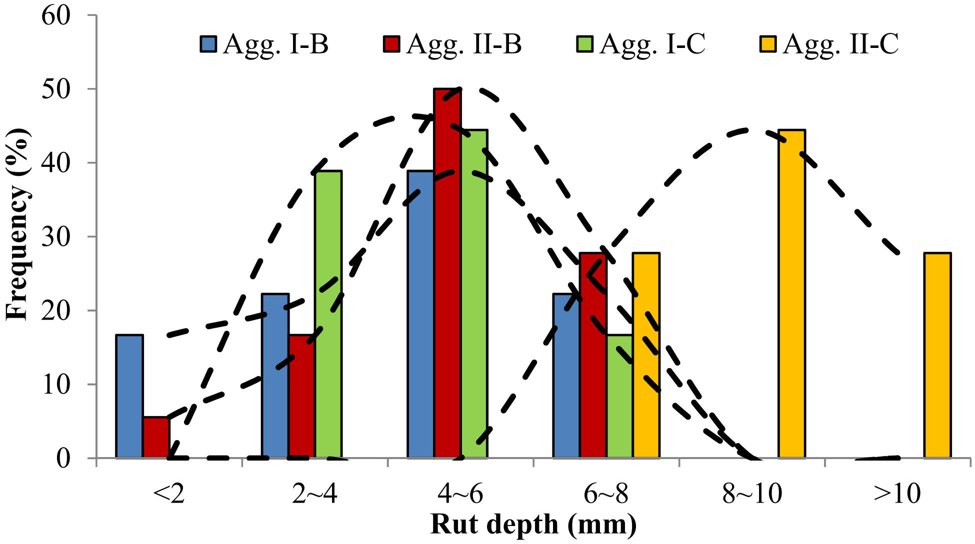


Figure 6-12 Distribution of Rut Depth in Terms of Aggregate and Surface Type Effects

Fracture Energy (Dissipated Energy) Analysis

A typical asphalt sample continuously yields viscoelastic permanent deformation until the maximum tensile strength is reached as the slow load is applied to the body. Fracture energy is defined as the area under the load-deformation curve as the load increases from 0 to the maximum tensile stress. Fracture energy could be effective in determining the total dissipated energy of an asphalt mixture before it is destroyed under traffic loading.

The fracture energy values of Surface Types B and C are shown in Figure 6.13. It can be noted that the dry samples from aggregate I showed similar fracture energy regardless of ASA. In addition, Surface Type C mixtures made with aggregate II showed slightly higher fracture energy values than the Surface Type B mixtures. Statistical analysis results shown in Table 6.2 indicate that there were no significant differences in fracture energy of dry samples when using various ASAs.

The fracture energy values of wet samples are shown in Figure 6.14. Compared to the dry samples, these wet samples generally had higher fracture energy values regardless of mixture type, aggregate source, and ASA. Some slight differences can be noted in wet fracture energy in terms of mixture type. Similarly, aggregate source and ASA had slight effects on wet fracture energy. The statistical analysis shown in Table 6.2 indicates that the only significant differences in wet fracture energy were in the mixtures with hydrated lime and liquid a2 . Therefore, it could be concluded that the mixture type, aggregate source, and ASA type generally do not influence the dissipated energy of various mixtures when using natural sand and RAP.

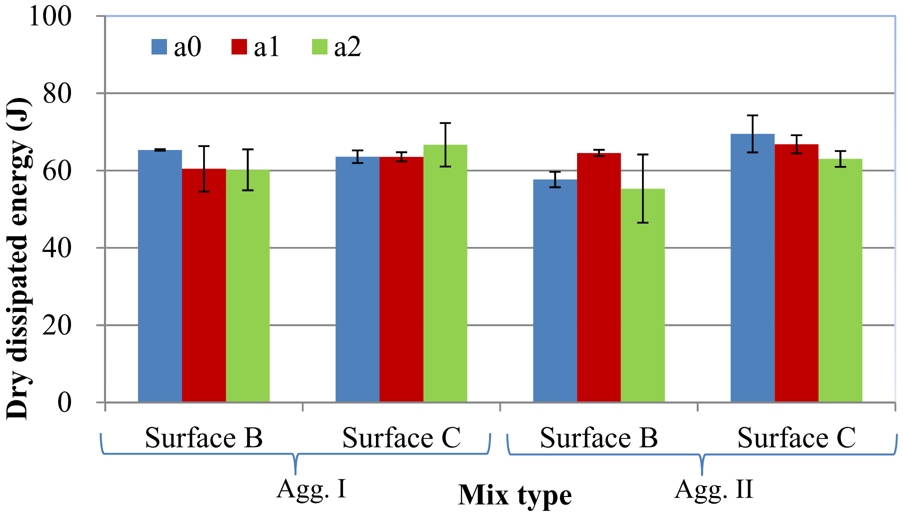


Figure 6-13 Dry Dissipated Energy Values of Surfaces B And C Mixtures

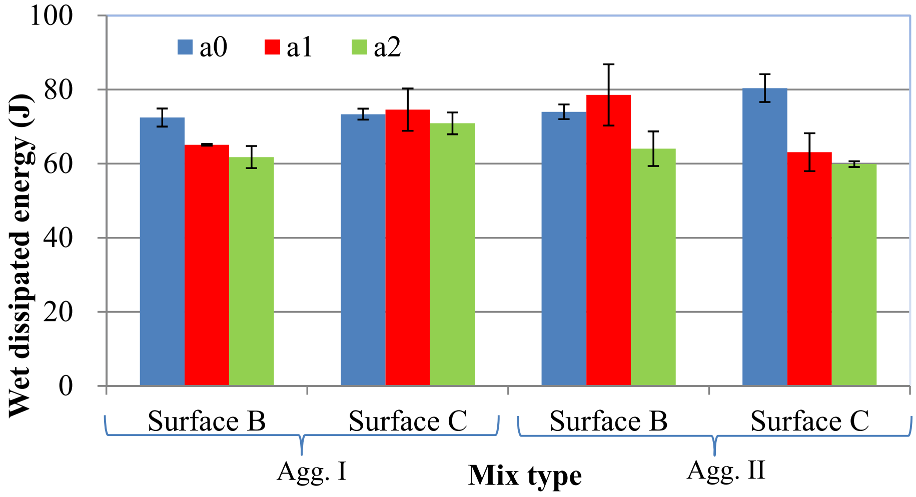
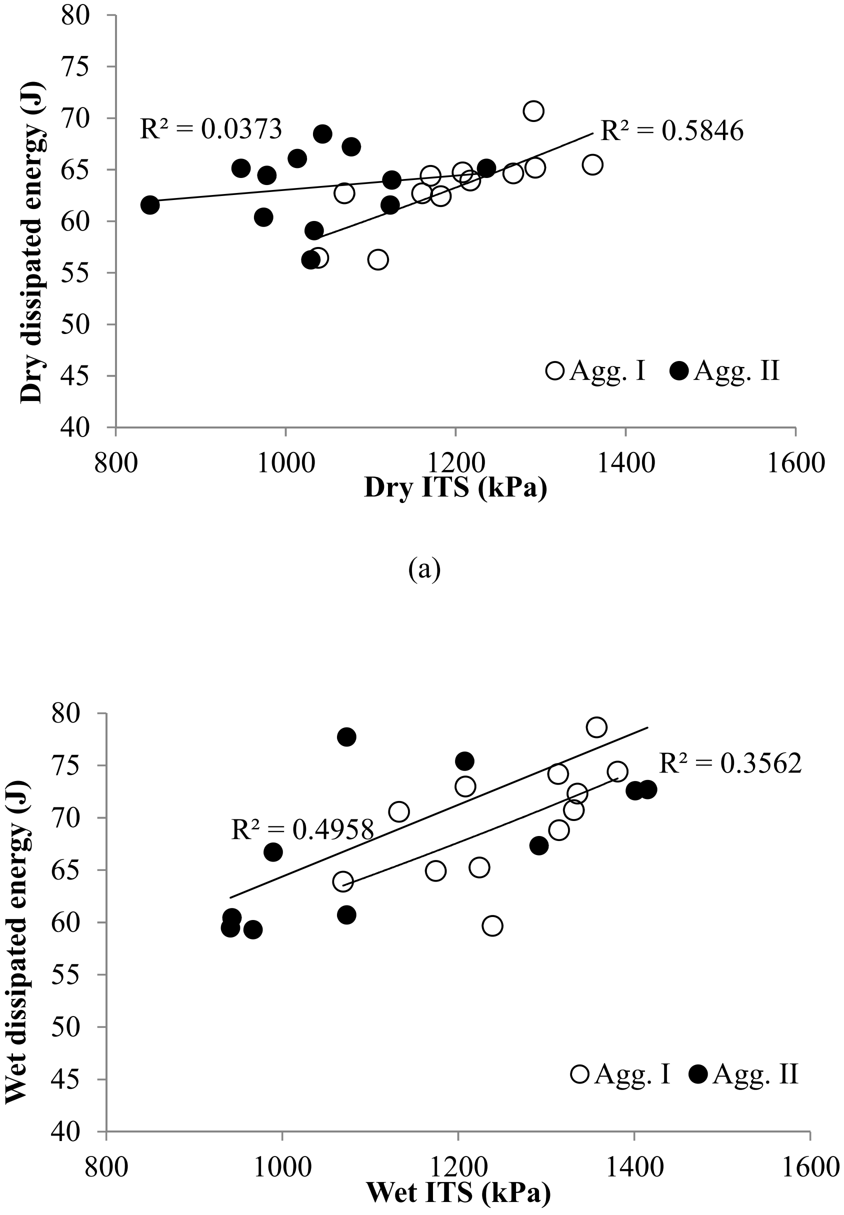


Figure 6-14 Wet Dissipated Energy Values of Surfaces B and C Mixtures

Correlation Analysis

The stored dissipated energy (fracture energy) is an important indicator of asphalt mixture performance before observing any damage due to long term traffic loading. This fracture energy is associated with indirect tensile strength and the corresponding flow value. In this study, some correlations have been developed to explore the relationship of dissipated energy and ITS values. As shown in Figure 6.15, in terms of the effect of aggregate source, it can be observed that increasing dry ITS values generally resulted in an increase of fracture energy. The linear trends can be observed for both aggregates I and II. The coefficients of determination (R^2) are poor for the mixtures from aggregate II and good for the mixtures from aggregate I. In addition, correlations between wet ITS values and their dissipated energy are shown in Figure 6.16. For the mixtures from both aggregates I and II, some R^2 values are low due to the limited data used for this study. Therefore, more research studies are recommended to achieve ideal R^2 values regarding various mixture types, aggregate gradation, and other properties. In general, correlations between fracture energy and ITS values indicate that an increased ITS value improves the fracture resistance of the mixture in terms of aggregate source.

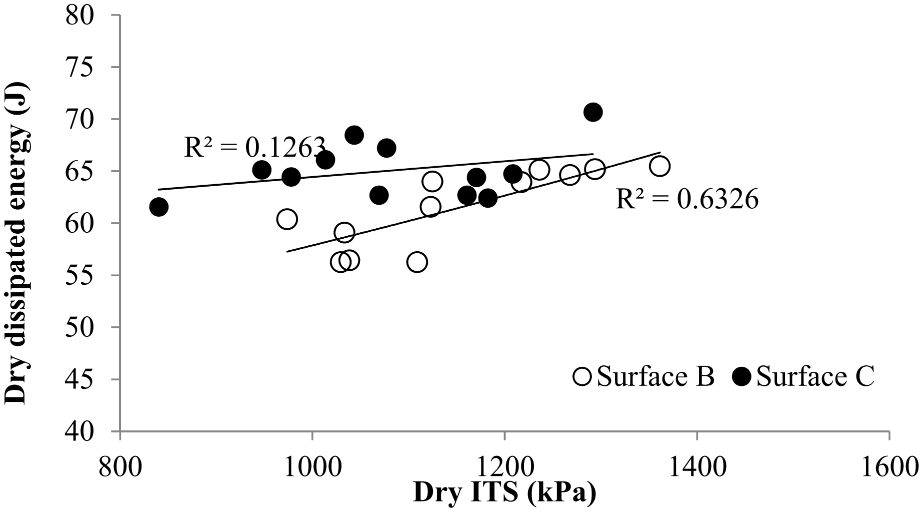
Similarly, in terms of mixture type, the results indicate that an increased ITS value results in an increase of fracture energy. There are linear trends between dissipated energy and dry ITS values for both Surface Types B and C, which have relatively good R^2 values. In addition, in Figure 6.15, similar trends can be noted for wet ITS and fracture energy regardless of mixture type. As a result, correlations can be conducted based on the ITS values and their corresponding fracture energy.



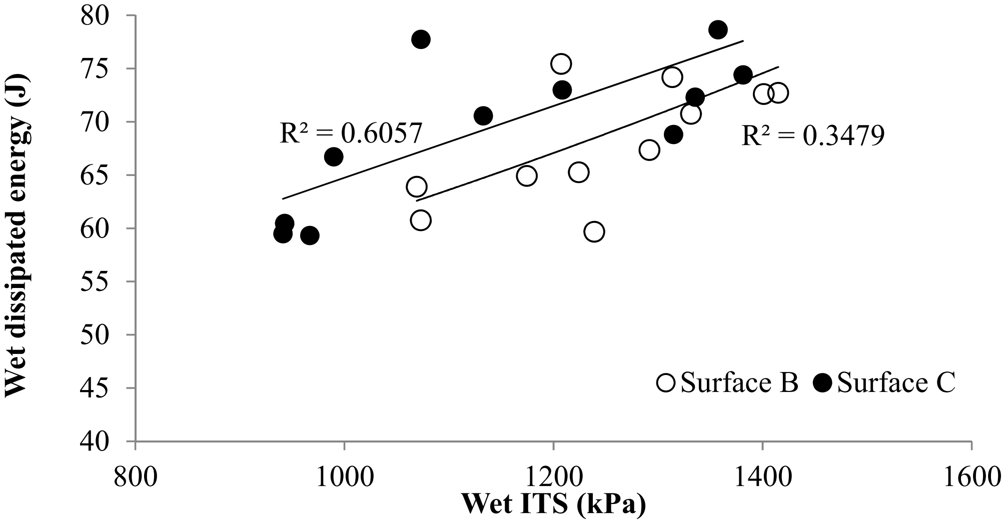
(a)

(b)

Figure 6-15 Correlations Between Dissipated Energy and ITS in Terms of Aggregate Source



(a)



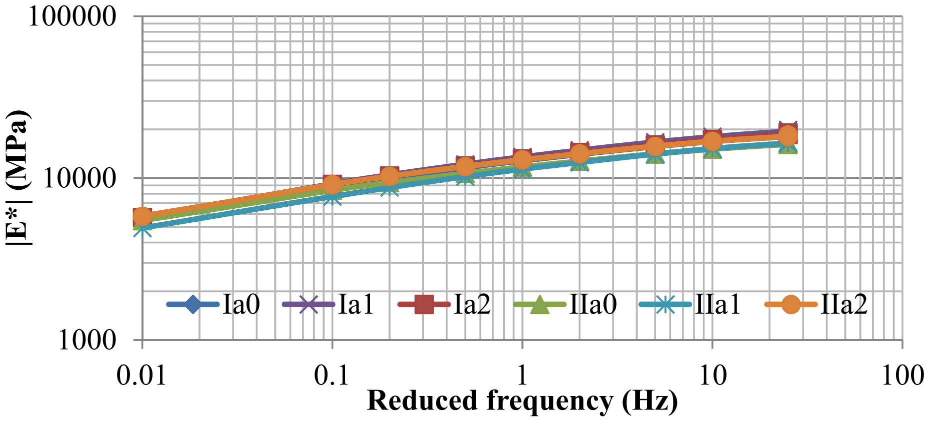
(b)

Figure 6-16 Correlations Between Dissipated Energy and ITS in Terms of Surface Type

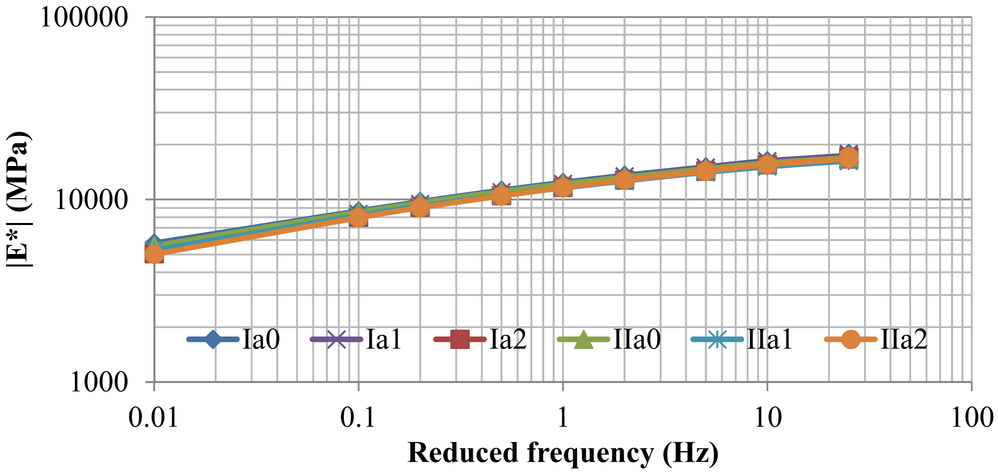
Dynamic Modulus Analysis

Complex dynamic modulus |E*| test results can be used as performance criteria for fatigue cracking resistance of the asphalt concrete mixture to be used in conjunction with the Superpave volumetric mix design method. In this test, a cored cylindrical specimen (100 mm in diameter x 150 mm in height) is subjected to a continuous haversine axial compressive load. The specimens in this project were conditioned to the test temperatures of 4°C, 20°C, and 45°C in a calibrated environmental chamber before testing. Test specimens were placed in the device with no confining pressure and subjected to a sinusoidal axial compressive stress with varying frequencies. A detailed description of the test procedure can be found in AASHTO TP 79. Three replicate dynamic modulus specimens were fabricated and tested for each mix type in this study. The test results for the Surface Types B and C at 4°C are shown in Figure 6.17. It can be noted that all dynamic modulus values were comparable regardless of the loading frequency, ASA and aggregate type.

The phase angle values of these mixtures are shown in Figure 6.18. It can be observed that a higher frequecy resulted in a reduction of phase angle regardless of mixture type. In addition, it can also be observed that when the test temperature was 4°C, the phase angle values for all mixtures were closer when performing a higher loading frequency compared to a lower loading frequcy. Therefore, traffic loading could affect the viscoelastic characteristic of the flexible pavement. However, this trend could not be found when the test temperatures were 20°C and 45°C. In addition, the phase angle value increased when the frequency increased at 45°C, which was not observed in the tests at 4°C and 20°C.

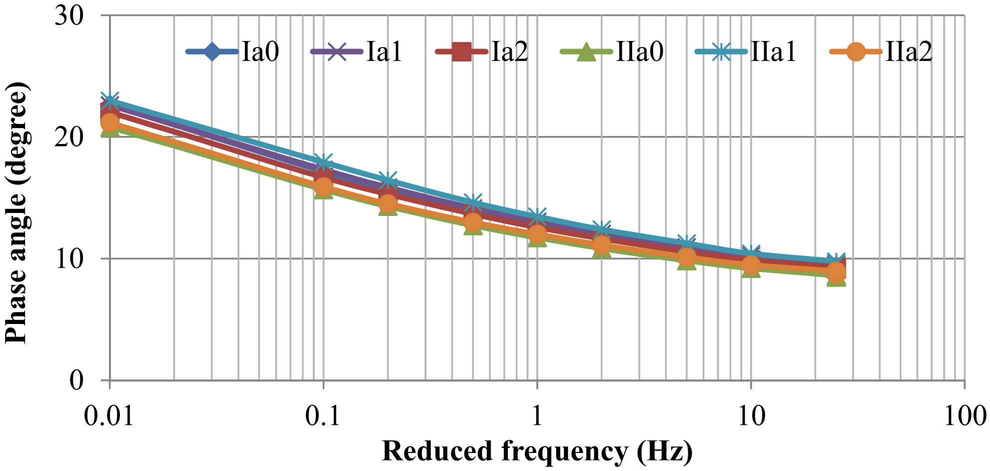


(a)

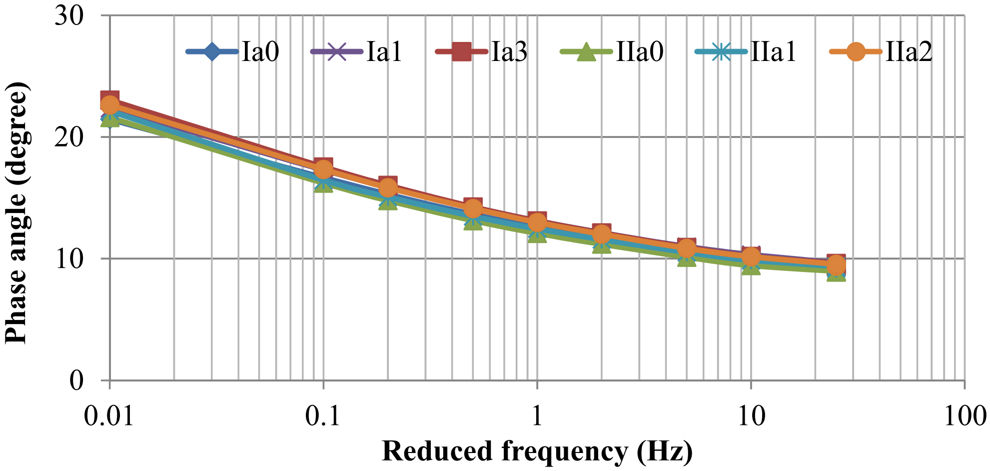


(b)

Figure 6-17 Dynamic Modulus Values of Surfaces B and C Mixtures At 4°C, (A) Surface B, (B) Surface C

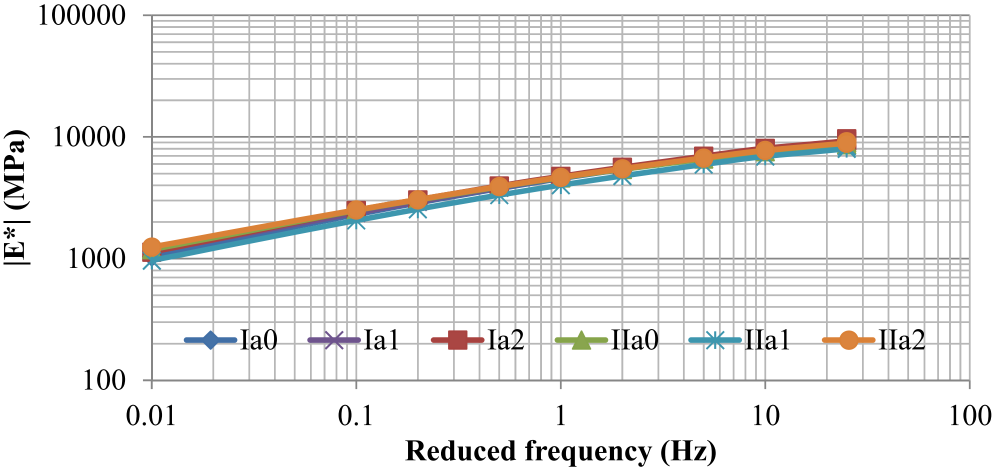


(a)

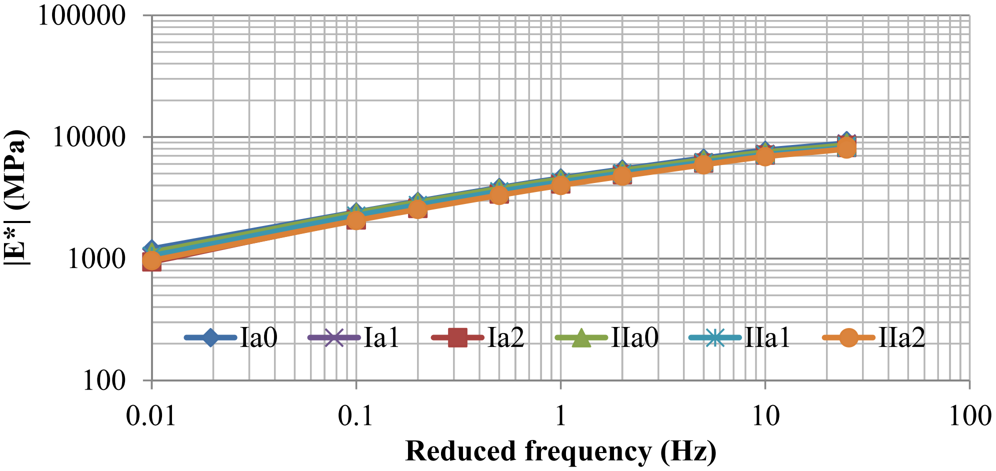


(b)

Figure 6-18 Phase Angle Values of Surfaces B and C Mixtures at 4°C, (a) Surface B, (b) Surface C

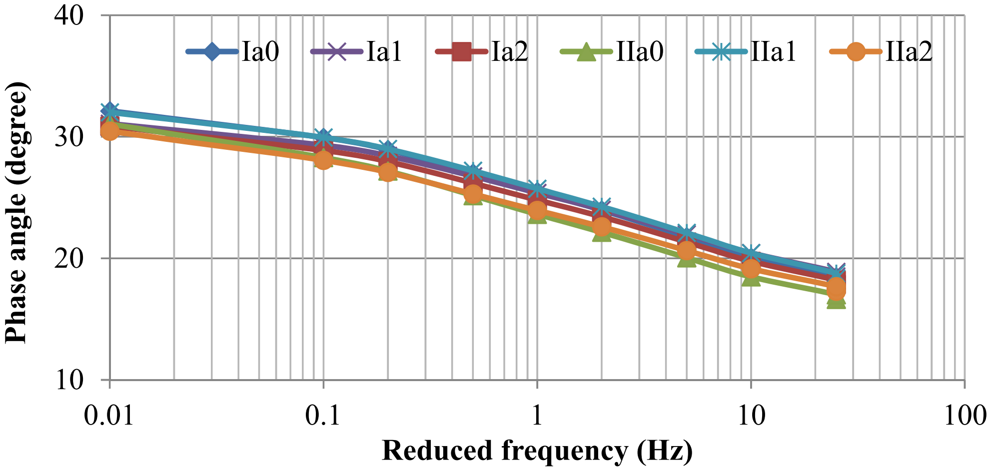


(a)

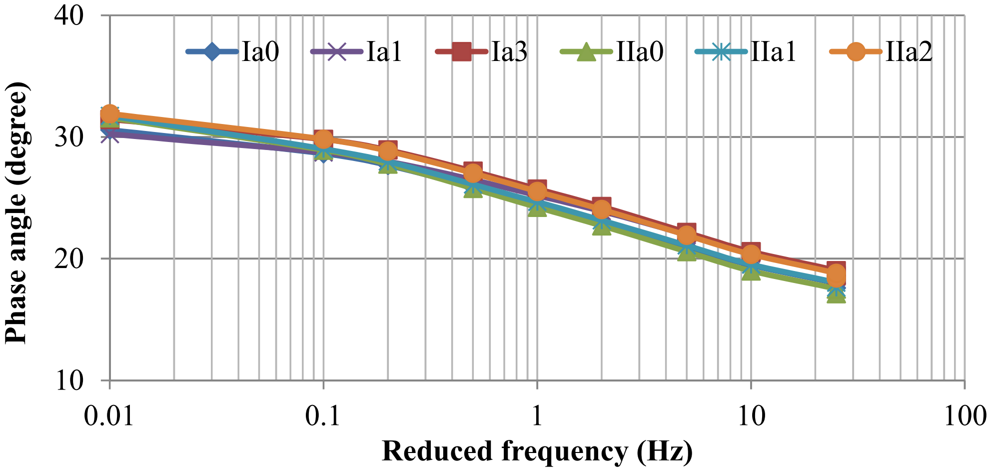


(b)

Figure 6-19 Dynamic Modulus Values of Surfaces B and C Mixtures At 20°C, (a) Surface B, (b) Surface C

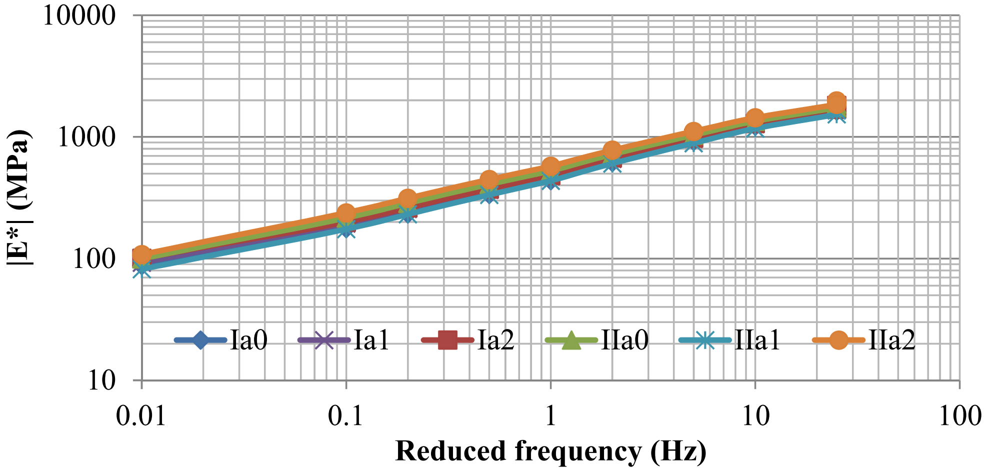


(a)



(b)

Figure 6-20 Phase Angle Values of Surfaces B and C Mixtures at 20°C, (a) Surface B, (b) Surface C



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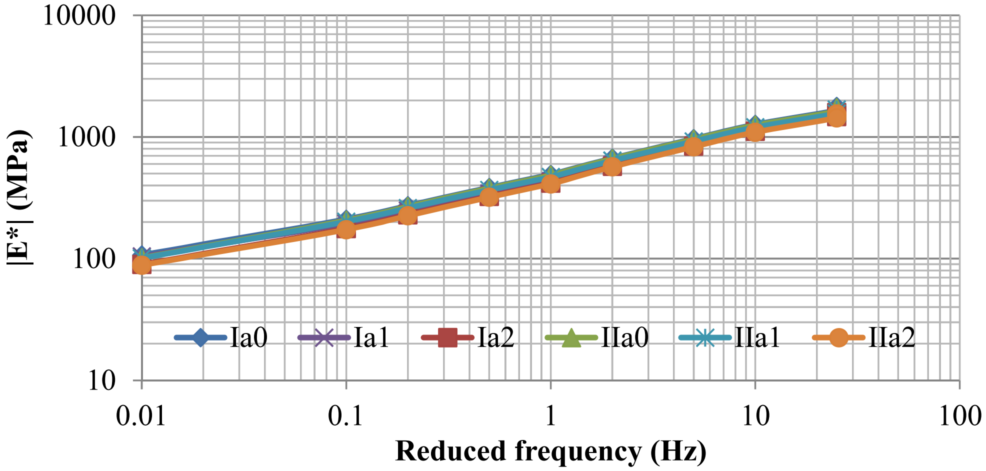
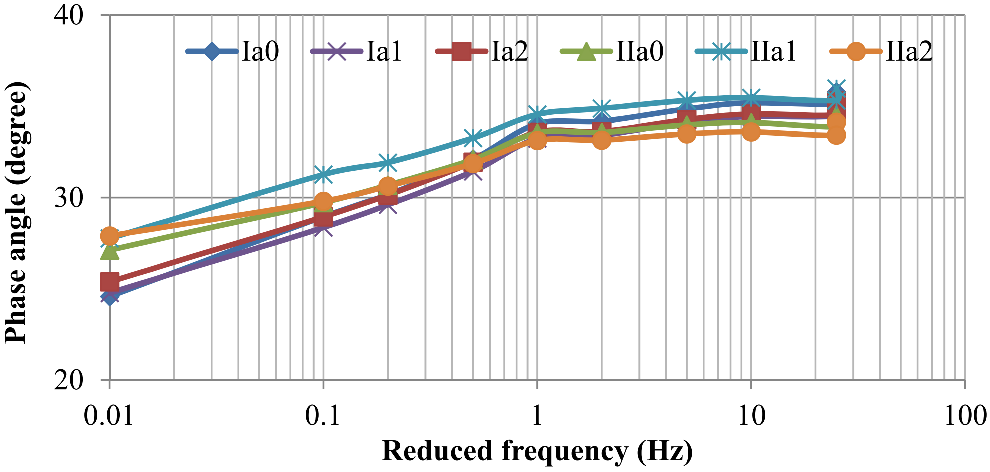
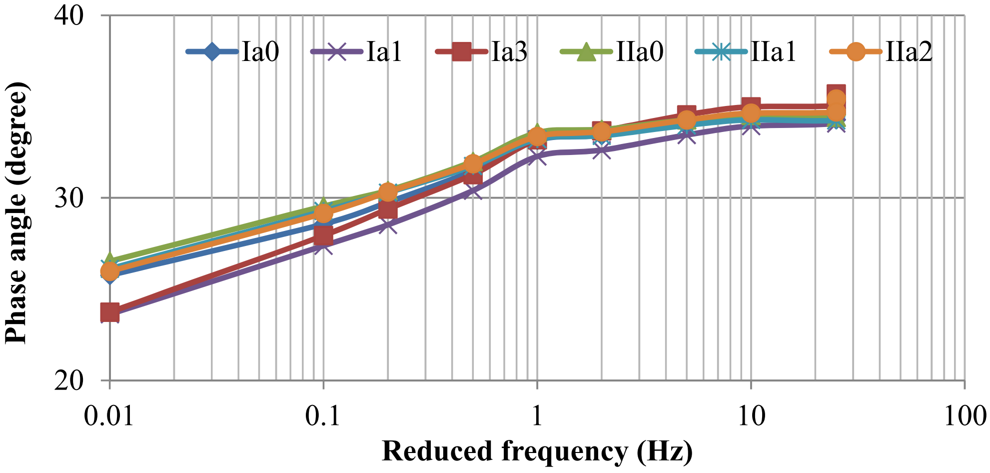


(b)

Figure 6-21 Dynamic Modulus Values of Surfaces B and C Mixtures at 45°C, (a) Surface B, (b) Surface C



(a)



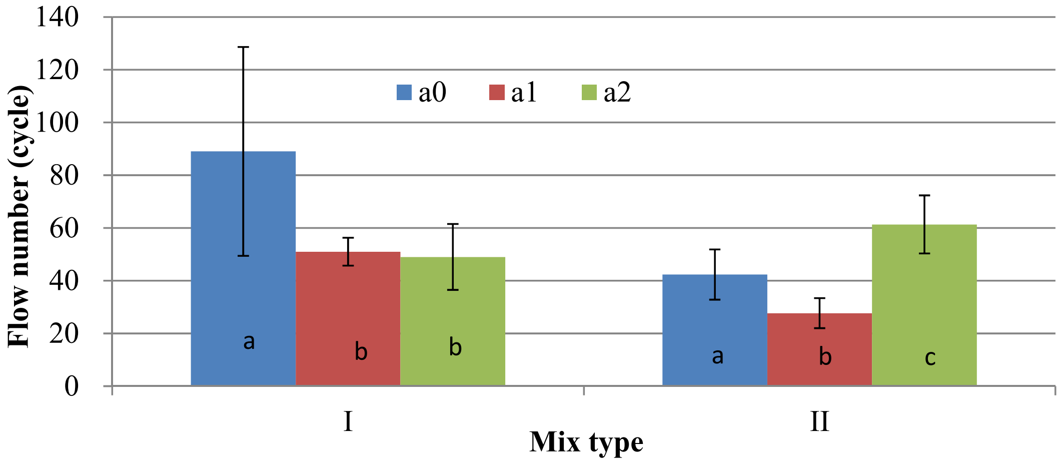
(b)

Figure 6-22 Dynamic Modulus Values of Surfaces B and C Mixtures at 45°C, (a) Surface B, (b) Surface C

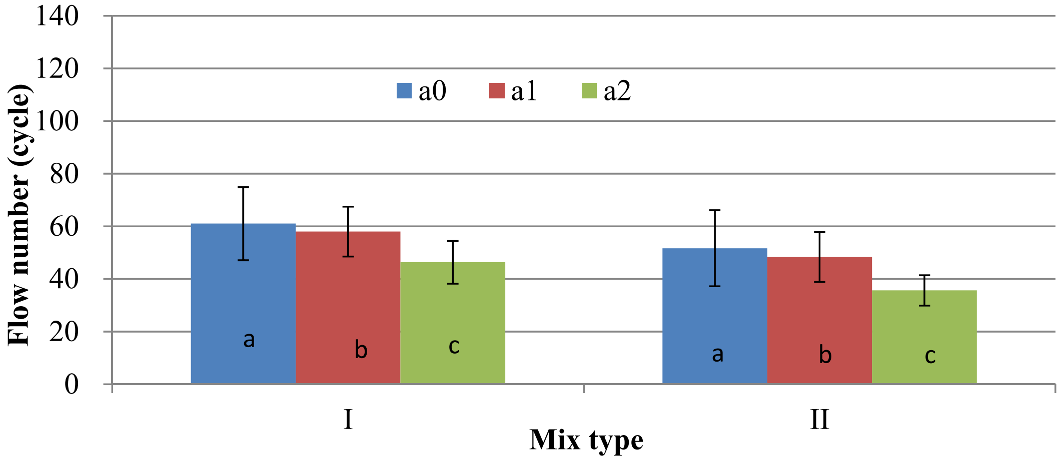
The flow number test is used to measure the rutting potential of asphalt concrete mixtures. The flow number is defined as the number of load pulses when the minimum rate of change in permanent strain occurs during the repeated load test. It is determined by differentiation of the permanent strain versus number of load cycle curve. The unconfined repeated load tests were conducted with a deviatoric stress of 600 kPa and a test temperature of 59°C according to the LTPPBind 3.1 software. The flow numbers of the Surface Types B and C mixtures are shown in Table 6.3 and Figure 6.23. It can be noted that the mixtures with hydrated lime generally exhibited slightly higher flow numbers than mixtures with liquid ASAs when using the same aggregate and mix type.

Table 6-3 Flow numbers of Surface Type B and C mixtures at 59°C

Surface type	Agg type	ASA type	Flow (cycle)	
			Mean	Std
B	I	a0	89.00	39.60
		a1	51.00	5.29
		a2	49.00	12.49
	II	a0	42.33	9.50
		a1	27.67	5.69
		a2	61.33	11.02
C	I	a0	61.00	13.89
		a1	58.00	18.19
		a2	46.33	8.14
	II	a0	51.67	14.47
		a1	48.33	9.50
		a2	35.67	5.77



(a)



(b)

Figure 6-23 Flow Numbers of Surfaces B and C Mixtures at 59°C, (A) Surface B, (B) Surface C

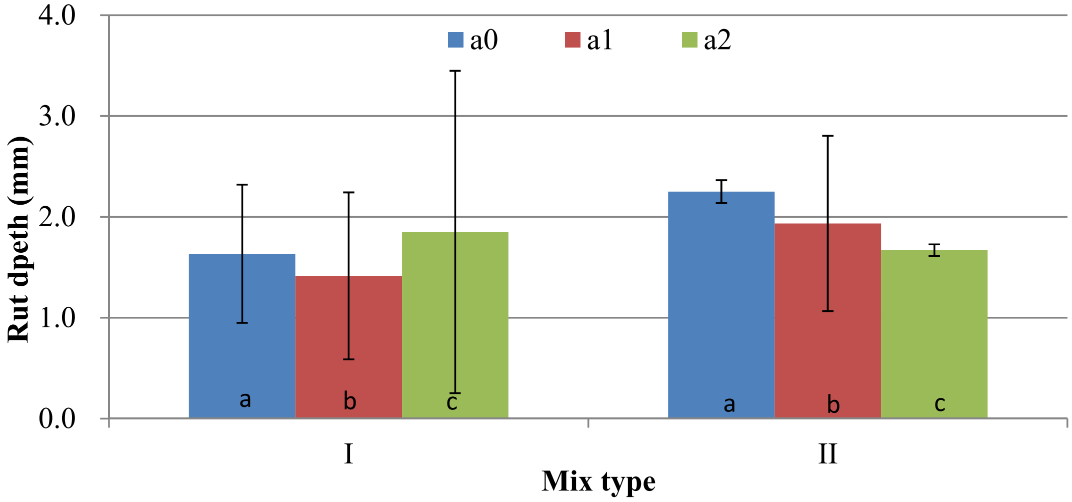
Hamburg Wheel-Tracking Rut Depth Analysis

The Hamburg test results for the Surface Type B and C mixtures are presented in Table 6.4 and Figure 6.24. It can be observed that the HWT rut depths of the Surface Type B mixtures were generally less than 4 mm regardless of aggregate source and ASA type. However, the HWT rut depths of the Surface Type C mixtures were greater than 15 mm when the liquid ASA a2 was used in the mixture, regardless of aggregate type. In addition, the mixtures from aggregate II had higher HWT rut depths compared to the mixtures from aggregate I.

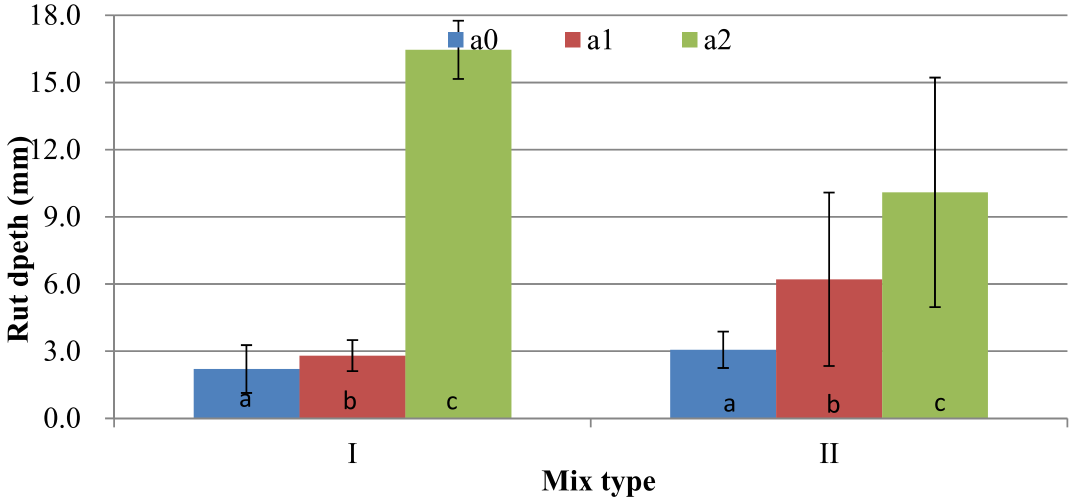
Table 6-4 HWT rut depths of Surface Type B and C mixtures at 50°C

Surface type	Agg. type	ASA type	HWT Rut depth (mm)	
			Mean	Std
B	I	a0	1.64	0.69
		a1	1.42	0.83
		a2	1.85	1.60
	II	a0	2.25	0.11
		a1	1.94	0.87
		a2	1.67	0.06
C	I	a0	2.21	1.07
		a1	2.80	0.69
		a2	16.46	1.30
	II	a0	3.07	0.81
		a1	6.21	3.87
		a2	10.10	5.13

Notes: a0~hydrated lime; a1~liquid ASA 1; a2~liquid ASA 2; ITS ~Indirect Tensile Strength; TSR ~tensile strength ratio



(a)



(b)

Figure 6-24 HWT rut depths of Surface Type B and C mixtures at 50°C, (a) Surface B, (b) Surface C

Summary

(1) The optimum binder contents of Surface Type B or C mixtures made with aggregates I and II were the same when using similar gradations, the same natural sand, and the same RAP content. The binder content, VMA, VFA, and dust/asphalt ratio values of these various mixtures met the requirements of specifications. Therefore, it can be concluded that for the materials used, the effects of natural sand and aggregate source on the volumetric characteristics of Superpave mix design can be ignored.

(2) Even though 20% natural sand had been used to produce Surface Type B and C mixtures, these mixtures had wet ITS values much higher than minimum 448 kPa required by SCDOT. Consequently, it is concluded that hydrated lime and liquid ASAs can be used to resist moisture damage of asphalt pavement with 20% natural sand regardless of aggregate source and mixture type for the materials tested in this study.

(3) TSR values of all mixtures were greater than 80% regardless of surface type, aggregate source, and ASA type. In most cases, the mixtures with hydrated lime had relatively-higher TSR values. However, based on the test results, other liquid ASAs also are recommended for use in Surface Types B and C mixtures.

(4) The rut depths of Surface Type B mixtures were generally less than 5 mm, irrespective of aggregate source and ASA type. In addition, the Surface Type C mixtures made with aggregate II generally exhibited relatively weaker resistance to permanent deformation.

(5) There were no significant differences found in the fracture energy of dry samples when using various ASAs, aggregate sources, and mixture types. However, these variables did slightly affect the dissipated energy of wet samples.

(6) There are some correlations between dissipated energy values and ITS values in this study. However, more research is recommended in order to obtain the ideal relationships in terms of aggregate source and mixture type.

(7) The increase of frequency resulted in an increase of dynamic modulus and a reduction of phase angle at the testing temperatures of 4°C and 20°C. However, at 45°C, the increase of frequency resulted in an increase of phase angle regardless of mixture type, aggregate source, and ASA type. The dynamic modulus values were comparable for various mixtures. There were some differences in phase angles when tested at a higher temperature.

(8) Flow numbers were slightly different in general when using different aggregate sources or ASAs or mixture types. In most cases, flow numbers were greater than 30, satisfying the AASHTO flow number requirement for mixtures with lower traffic levels.

Chapter 7 – Field Project

Introduction

This section of the report describes the field portion of the research activities. In order to evaluate some alternate modified binders, newly-developed polymers were utilized in this portion of the project. After several meetings and discussions with SCDOT and the contractor, a location was selected for this project (U.S. Highway 76, Marion County). The project was 2.47 miles long; 4 lanes; 2” thick surface mixture; over 21,500 ADT; and included some RAP materials. The field project was divided into 6 sections (approximately 0.8 miles long each), which allowed for the testing of five new combinations of materials compared to the SBS (control) section.

The binders were tested in the laboratory to determine their properties. The mix designs for all 6 test sections were conducted following SCDOT’s specifications for Surface Type B mixtures. Cores from the pavement were obtained and tested for engineering properties (e.g., air voids, ITS, TSR, etc.). SCDOT officials and the PI visually inspected the test sections several times, and as of this date, there are no signs of distress.

For this phase of the project, several polymers (referred to as 1, 2 and 3 in this section of the report) were utilized. Polymer 1 was SBS-modified binder and was used as a control binder. Polymers 2 and 3 were Ethylene-based, 5,000-15,000 MW polyolefin polymers, and required no butadiene to be compatible with the binder. Polymer 2 is also used as a warm mix and anti-strip additive in addition to being used to increase the high-temperature grade of the binder. In some cases, a hybrid binder was formed by adding polymer 1 (SBS) and polymer 3 together (referred to as polymer 1+3 in this report). The laboratory and field results indicated that in general, for most mixtures, the use of polymers 1 and 2 and the hybrid binders produced mixes that performed as well as the SBS mixtures. Additionally, in some cases, polymer 2 exhibited additional benefits, such as warm mix and anti-strip additive properties.

Field Test Sections

After many conference calls with the polymer producer, meetings with SCDOT, and meetings with the contractor’s representatives, it was mutually decided to select U.S. Highway 76 (Marion County, SC) as the test section site (Figure 7.1). The contractor for this project was CR Jackson, Inc. Contractors (CR Jackson or CRJ thereafter), which is based in Columbia, SC. CRJ and SCDOT officials were in complete agreement with the testing program and the experimental design. The project was approximately 2.47 miles long consisting of 4 lanes, several turn lanes, and asphalt shoulders on both sides. Each test section was approximately 0.8-mile long (Figure 7.2).

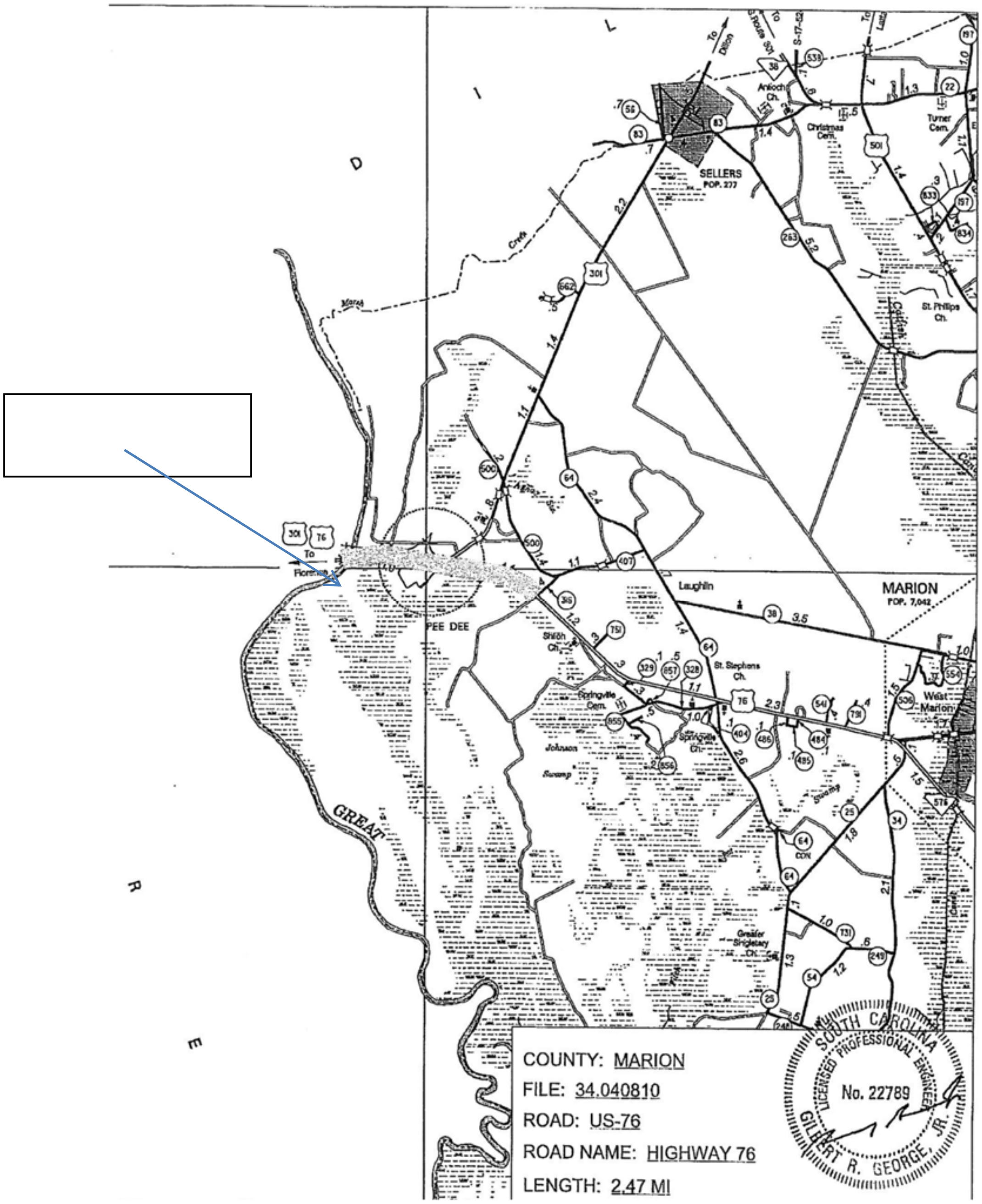


Figure 7-1 Field Test Section Location for the Field Test Section (2.47 miles)

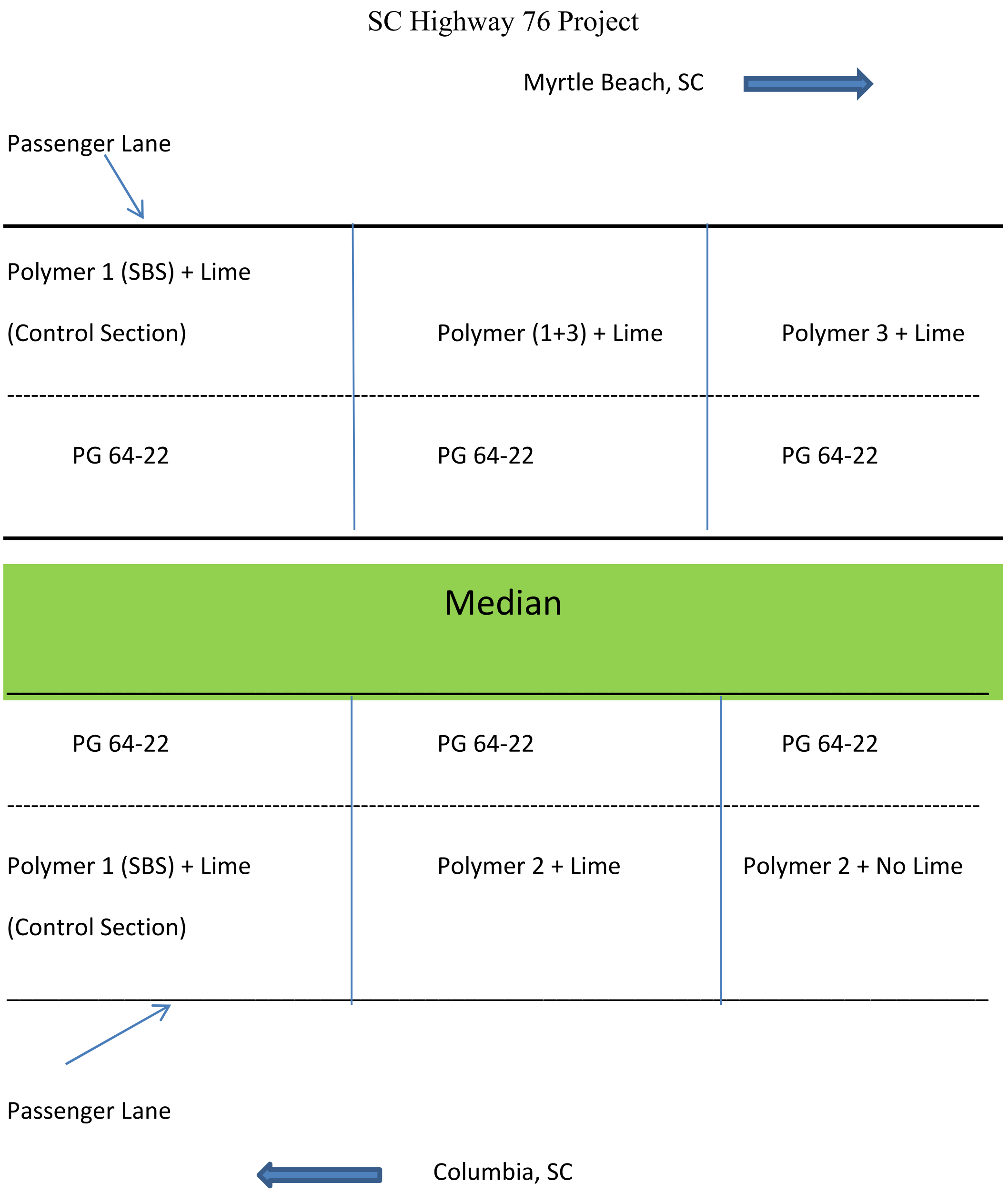


Figure 7-2 Experimental Design for the Field Test Sections

This section of the pavement had been scheduled to be paved during the summer of 2012 with PG 64-22 asphalt binder. However, DOT officials agreed to include PG 76-22 for the surface mixture. These six test strips were then monitored for the two years following construction. Several cores were taken and tested each year to determine the performance of the pavement sections. The cores were used to obtain the TSR, binder content and the aggregate gradation of each mix test section.

There were several polymers and binders used for Eastbound portion of this project. The first, which was used as the control, was a standard SBS PG 76-22 supplied by an asphalt binder supplier (referred to as polymer 1). The second was a combination of SBS and polymer 3 supplied by an asphalt binder supplier (referred to as polymer 1+3). The third was a PG 64-22 virgin binder modified with polymer 3 using the contractor's tank to mix the polymer with the binder (on-site blending).

All of the mixtures in the Eastbound portion of the project contained hydrated lime as an anti-strip additive, which is a requirement of SCDOT for all mixtures used on interstate or high-volume primary routes. Because polymer 2 can also be used as a warm mix additive and as an anti-strip additive, SCDOT officials agreed to use this polymer without hydrated lime in one test section on the Westbound portion of the project after receiving satisfactory results on preliminary testing.

For the Westbound portion of the project, three test sections were also constructed. The control section used a standard SBS-modified PG 76-22 supplied by an asphalt binder supplier. The second was a PG 64-22 virgin binder modified with polymer 2 using on-site blending with the contractor's tank. Both of the first two test sections in the Westbound portion contained hydrated lime as an anti-strip additive. The third test section was also a PG 64-22 virgin binder modified with polymer 2 using on-site blending, but there was no hydrated lime included in this test section. Thus, in the third test section on the Westbound portion of the project, polymer 2 was tested as a high-temperature binder grade modifier as well as an anti-strip additive. The mixtures for both the second and third test sections on the Westbound portion (the two sections containing polymer 2) were both produced as warm mix rather than hot mix.

A preliminary testing program was conducted to determine the moisture susceptibility of the mixture made with polymer 2 without hydrated lime. The results were shared with SCDOT officials to determine the effectiveness of this polymer as an anti-strip additive and warm mix additive. The following results were obtained: Dry ITS = 131.6 psi; Wet ITS = 115.3 psi. The TSR of these samples was found to be 87.6%. The SCDOT's specifications for mix design require a minimum of 65 psi for wet ITS and a minimum of 85% for TSR values. The mixture had 4.9% optimum binder content.

The proposed test section has an ADT of approximately 21,725 with 10% truck traffic. It is approximately 1.5 hours from Myrtle Beach and 1.5 hours from Columbia and is very close to Francis Marion University's main campus. The project had to be paved during night time from 7 p.m. to 6 a.m. only Monday through Thursday. It required a mix of 200 pounds per square yard (approximately 2" thickness) with a total project tonnage of approximately 11,390 tons of surface course. The existing pavement was milledm and some RAP was used in the mix. Some areas of the existing pavement, which was visually inspected by the PI before paving, showed severe fatigue cracking and some block cracking, as well as signs of reflective cracking in some other sections (Figure 7.3). There were concerns that the sub base of some of the test sections might not be structurally sound. There were no actions taken regarding this issue.

The scope of this portion of the project included the following:

1) Testing of all materials (four binders and aggregates);
2) Investigating the moisture susceptibility of the polymer 2 mixture before the start of the project;
3) Conducting mix designs for five mixtures (control mix design was already complete);
4) Constructing six field test sections (4 experimental and 2 SBS as control);
5) Obtaining samples from field mixtures and conducting laboratory testing (e.g., volumetrics, etc.); and
6) Monitoring the pavement for two years.

Figure 7-3 SCDOT Field Test Sections before Paving with Mixtures Containing Polymers 1 (SBS), 2, 3, and 1+3 (Hwy 76 – SC; April 2012)

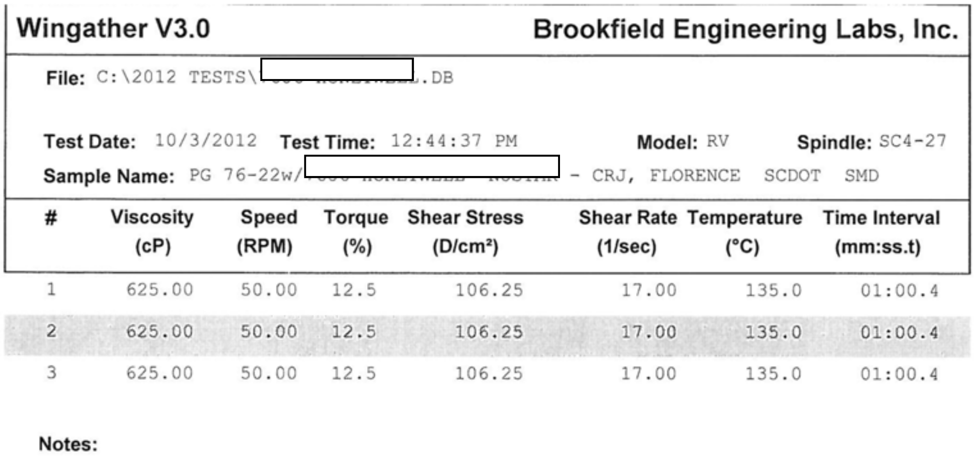
The field sections were divided into two production categories: one set used terminally-blended binders supplied by an asphalt supplier, and the other set used on-site blending. The supplied binder products delivered to the job site were either a hybrid product (SBS+polymer 3) or a typical PG 76-22 SBS product. The hybrid product was handled as a typical SBS product from the standpoint of plant delivery and operation. There were no modifications done to the plant or equipment.

The blending on site was accomplished by delivering the polymers to the contractor's plant in bags/sacks. Then, the polymer was added (approximately 2.5% by weight of the binder) to the contractor's agitated binder storage tank containing virgin PG 64-22 binder. The final product, after the agitation was completed, was tested by the SCDOT laboratory in Columbia to obtain the engineering properties of the binder.

All of the sections were paved during night time (Figure 7.4). Some details of the paving are reported below. Since the contractor was using different binders for each test section, the project was divided into several nights of paving, and each night a particular binder was utilized. The project started the first week of October 2012. Several sample bags of each asphalt mix were randomly selected from different trucks and brought back to the lab for making samples and conducting more testing, if needed. In addition, every night several gyratory samples were made and brought back to the laboratory for testing and analysis (for a total of 45 specimens). The mixture's maximum specific gravity (Rice) was also measured. The specific gravity of each gyratory sample was obtained, and the air voids of the mixture were calculated. Ignition oven was used in obtaining the binder content of each mixture in the field. The aggregate gradation for each mixture was then obtained from the residual aggregate after the completion of the ignition oven burn. The results of this testing are shown in other sections of this report.

Polymer 3 was blended on site, and after the binder was tested and approved by SCDOT representatives, the contractor initiated the production of the mix (Figure 7.5). One night, rain shut down the project at 2 a.m.; however, approximately 700 tons of the second polymer 2 segment was placed and compacted. For this section, seven trucks of materials were returned from the road due to the shutdown and were deposited on the rap pile. In most nights, approximately 860 tons of mix was produced and placed. Compaction was not a problem in any of the test sections, and the roller operator as well as many of the technicians indicated that the mix was easy to work with and compact. In most cases, the mixtures' densities were within the allowable specification.

Figure 7-4 Field Test Sections (Night Paving: Hwy 76, Marion County, SC)



Wingather V3.0 **Brookfield Engineering Labs, Inc.**

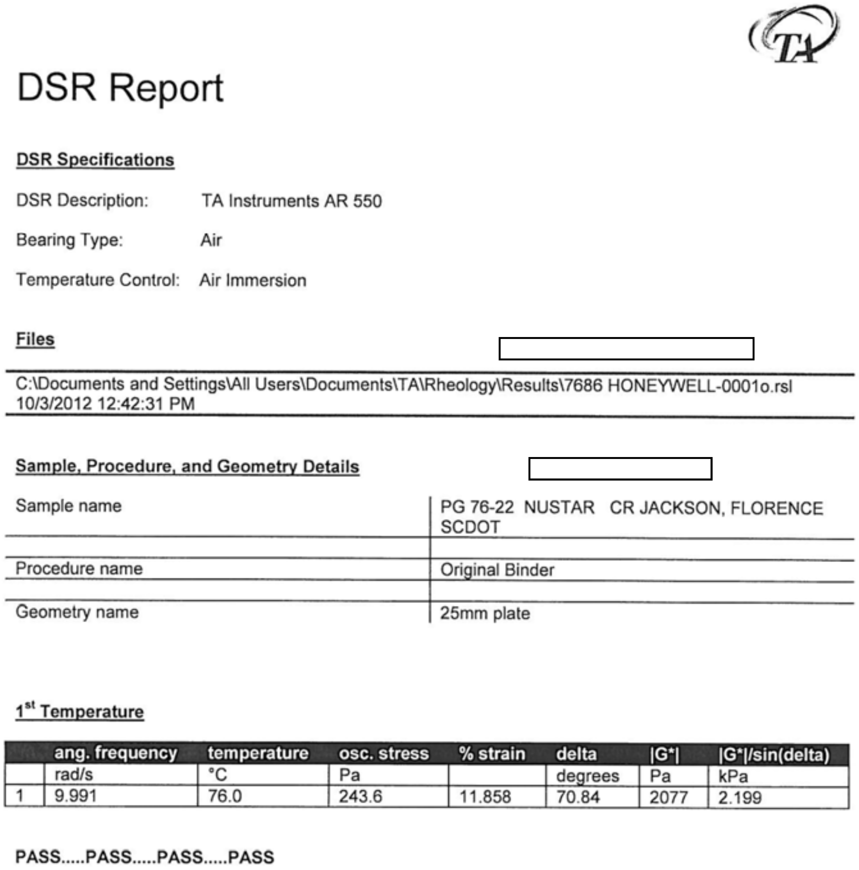
File: C:\2012 TESTS\[redacted].DB

Test Date: 10/3/2012 **Test Time:** 12:44:37 PM **Model:** RV **Spindle:** SC4-27

Sample Name: PG 76-22w/[redacted] - CRJ, FLORENCE SCDOT SMD

#	Viscosity (cP)	Speed (RPM)	Torque (%)	Shear Stress (D/cm²)	Shear Rate (1/sec)	Temperature (°C)	Time Interval (mm:ss.t)
1	625.00	50.00	12.5	106.25	17.00	135.0	01:00.4
2	625.00	50.00	12.5	106.25	17.00	135.0	01:00.4
3	625.00	50.00	12.5	106.25	17.00	135.0	01:00.4

Notes:



DSR Report

DSR Specifications

DSR Description:	TA Instruments AR 550
Bearing Type:	Air
Temperature Control:	Air Immersion

Files [redacted]

C:\Documents and Settings\All Users\Documents\TA\Rheology\Results\7686 HONEYWELL-0001o.rsl
10/3/2012 12:42:31 PM

Sample, Procedure, and Geometry Details [redacted]

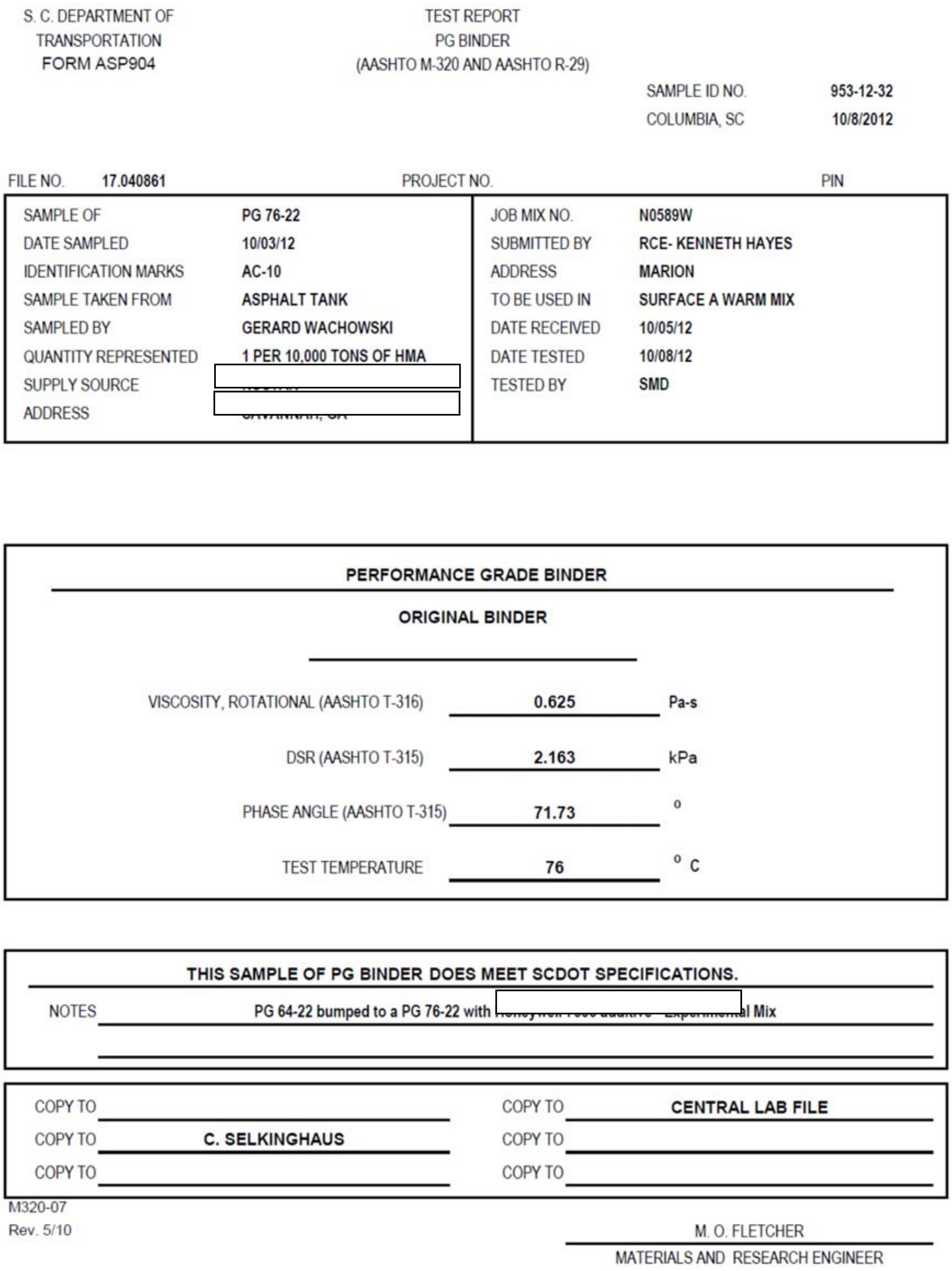
Sample name	PG 76-22 NUSTAR CR JACKSON, FLORENCE SCDOT
Procedure name	Original Binder
Geometry name	25mm plate

1st Temperature

	ang. frequency	temperature	osc. stress	% strain	delta	|G*|	|G*|/sin(delta)
	rad/s	°C	Pa		degrees	Pa	kPa
1	9.991	76.0	243.6	11.858	70.84	2077	2.199

PASS.....PASS.....PASS.....PASS

Figure 7-5 Binder Testing by SCDOT and Approval of the Binder for Use



S. C. DEPARTMENT OF
TRANSPORTATION
FORM ASP904

TEST REPORT
PG BINDER
(AASHTO M-320 AND AASHTO R-29)

SAMPLE ID NO.	**953-12-32**
COLUMBIA, SC	**10/8/2012**

FILE NO. **17.040861** PROJECT NO. PIN

SAMPLE OF	**PG 76-22**	JOB MIX NO.	**N0589W**
DATE SAMPLED	**10/03/12**	SUBMITTED BY	**RCE- KENNETH HAYES**
IDENTIFICATION MARKS	**AC-10**	ADDRESS	**MARION**
SAMPLE TAKEN FROM	**ASPHALT TANK**	TO BE USED IN	**SURFACE A WARM MIX**
SAMPLED BY	**GERARD WACHOWSKI**	DATE RECEIVED	**10/05/12**
QUANTITY REPRESENTED	**1 PER 10,000 TONS OF HMA**	DATE TESTED	**10/08/12**
SUPPLY SOURCE	[redacted]	TESTED BY	**SMD**
ADDRESS	[redacted]		

PERFORMANCE GRADE BINDER

ORIGINAL BINDER

VISCOSITY, ROTATIONAL (AASHTO T-316)	**0.625**	Pa-s
DSR (AASHTO T-315)	**2.163**	kPa
PHASE ANGLE (AASHTO T-315)	**71.73**	°
TEST TEMPERATURE	**76**	° C

THIS SAMPLE OF PG BINDER DOES MEET SCDOT SPECIFICATIONS.

NOTES **PG 64-22 bumped to a PG 76-22 with [redacted] l Mix**

COPY TO		COPY TO	**CENTRAL LAB FILE**
COPY TO	**C. SELKINGHAUS**	COPY TO	
COPY TO		COPY TO	

M320-07
Rev. 5/10

M. O. FLETCHER
MATERIALS AND RESEARCH ENGINEER

Figure 7.5 Continued

With the exception of the polymer 2 sections, mixtures were produced at 325°F.and placed at approximately 300°F. The materials were very workable and flowable in the field with no issues during the compacting process. Cores were obtained by SCDOT officials to check the mixtures for density and air voids. The polymer 2 sections were produced at 285°F. The placement temperature of the mixtures in those sections was in the range of 250 to 265°F.

Mix Designs

For this project, five mix designs were conducted and provided to SCDOT for approval. Aggregate, RAP materials and hydrated lime were obtained from the contractor, while the polymers and binders (including the hybrid binder) were obtained from the polymer producer and the binder supplier, respectively. The polymer 2 mix was designed both with lime and without lime. The aggregate properties for all field mixtures are shown in Table 7.1. In addition, a summary of all mix designs used in the field test sections is included in Table 7.2. The approved mix designs for the field test sections and more details of each mixture are shown in Appendix C.

Table 7-1 Properties of Aggregates Used in the Field Project

Coarse Aggregate	LA Abrasion Loss (%)	Absorption (%)	Specific Gravity			Soundness % Loss at 5 Cycles		Sand Equivalent	Hardness
			Dry (BLK)	SSD (BLK)	Apparent	3/4 to 3/8	3/8 to #4		
Jefferson	36	0.90	2.570	2.600	2.640	0.5	0.6	38	5
Fine Aggregate	Fineness Modulus	Absorption (%)		SSD (BLK)		Soundness % Loss			
Jefferson	2.88	0.40		2.640		1.0			

Table 7-2 Summary of Mix Designs for Field Project

Aggregate	Virgin binder	Aged binder (%)	OBC (%)	MSG	BSG	VMA (%)	VFA (%)	Dust/Asphalt ratio
		<15	4.5-6.0	-	-	>14.5	70-80	0.6-1.2
Jefferson	SBS	15	4.7	2.468	2.374	14.6	74.1	0.65
	H7205	15	4.8	2.463	2.372	14.7	74.9	0.64
	H7205+SBS	15	4.8	2.447	2.356	14.7	74.5	0.64
	H7686	15	4.8	2.466	2.381	14.5	76.2	0.64
	H7686 (No lime)	15	4.9	2.459	2.368	14.9	75.2	0.62
	PG 64-22	23	5.4	2.434	2.334	16.3	74.8	0.68

Field Project: Laboratory Investigation

In this section of the report, the laboratory testing results of the mixtures obtained from the field portion of the research work are reported. These materials included both samples compacted at the quality control lab at the plant at the time of production as well as samples made from materials sampled and bagged randomly from the trucks delivering the mix to the job site and taken back to the laboratory for later testing and analysis. The specimens that were sampled from the trucks and compacted later are labeled "lab-prepared" in this report. The specimens made with each night's materials at the time of production are referred to as "plant-compacted" in this report.

Materials

The laboratory experimental design detailed herein includes the use of four polymers (referred to as 1, 2, 3 and 1+3). Polymer 1 is control (SBS), polymer 2 is an Ethene homopolymer white powder material, polymer 3 is an oxidized polyethylene wax-like powder, and polymer 1+3 is a combination of polymer 1 (SBS) and polymer 3. In this study, the following polymer percentages by weight of the asphalt binder were used: a) 2.5% polymer 3; b) 1% polymer 3 plus 2% SBS, and c) 2.5% polymer 2. The polymers were blended with virgin PG 64-22 binders at a temperature of 150^{o}C. In the laboratory, the blend was mixed at 800 rpm for up to 20 minutes to produce the PG 76-22 binder. The control SBS binder has approximately 3.5% SBS polymer. The produced binders satisfied the requirements of a typical PG 76-22 binder at both high and low temperatures. The polymer-modified binders 3 and 1+3 exhibited similar rheological properties to SBS-modified binder. Polymer 2 is also known to function as a warm mix additive, as a compaction aide, and as an anti-strip additive (ASA). These properties were investigated in this study as well. The liquid anti-strips used in this part of the research project were prepared at the manufacturer's recommended dosage, and for the mixtures containing hydrated lime, the lime was added at 1% by weight of the aggregate.

Two aggregate sources (designated as I and II) commonly used in South Carolina for interstate and high-volume primary route projects were utilized in this research. The engineering properties of the aggregate sources were shown earlier in this report in Table 7.1. Three ASAs, including hydrated lime (a0) and two liquid ASAs (referred to as a1 and a2), were used for sample preparation. In addition, two different amounts of RAP materials (0% and 15% aged binder) were utilized in this portion of the study. There were a total of 11 Superpave mix designs included in this portion of the project.

Mix Design, Laboratory Sample Fabrication and Testing

The mix designs were 12.5 mm mixtures that satisfied the specifications set forth by the South Carolina Department of Transportation (SCDOT)) for a Surface Type A mixture ($N_{design} = 100$). The gradations for each aggregate source (I and II) are shown in Figure 7.6. In addition, the gradation of the RAPs (-#4) is also shown in Figure 7.6. The design aggregate gradations for each mixture remained constant for each polymer-modified asphalt (PMA) binder, regardless of whether they contained lime or one of the two liquid ASAs.

Based on the recommendations from the suppliers, the mixing and compaction temperatures of PMA mixtures made with polymers 1 (SBS), 1+3, and 3 were set to be 163°C and 152°C, respectively. Mixtures made with polymer 2 were prepared and compacted at approximately 20°C lower than the other mixtures.

In this study, the optimum binder content (OBC) was defined as the amount of binder required to achieve 4.0% air voids. A summary of all of the mix designs for these PMA mixtures are shown in Table 7.3. After the mix designs were completed, for each aggregate / binder / ASA / RAP combination, four Superpave gyratory compacted (SGC) specimens were prepared and tested for ITS (SC-T-70: 7 ± 1% air voids), and six SGC specimens were prepared and tested for rutting using the asphalt pavement analyzer (APA) (AASHTO 63: 4 ± 1.0% air voids). A total of 88 ITS samples and 132 APA samples were tested in this portion of the study.

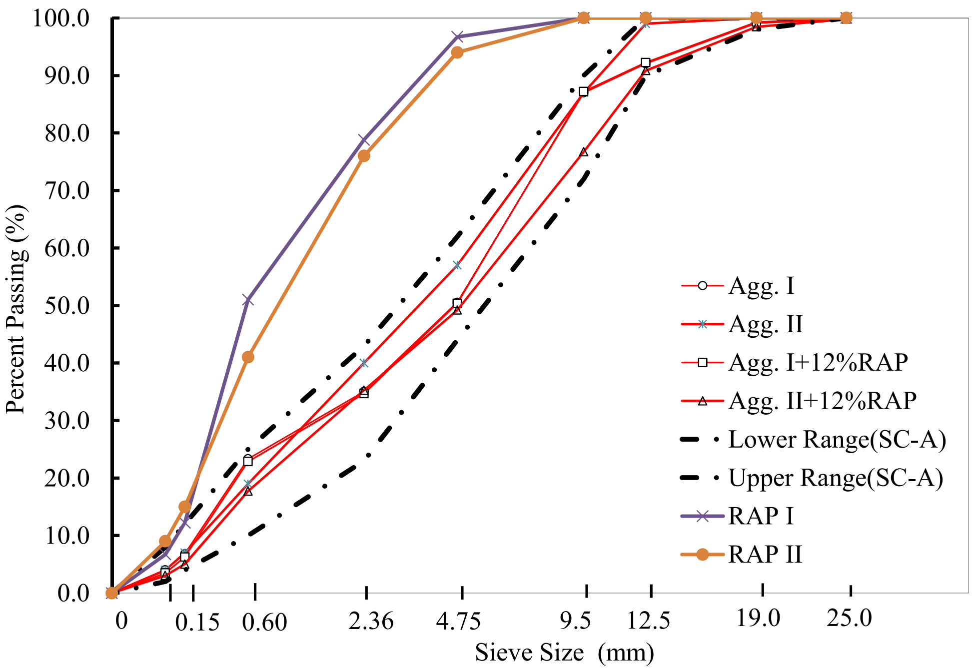


Figure 7-6 Gradations of Aggregates and Two RAP Sources

For this portion of the project, the dynamic modulus of various mixtures was obtained. As described earlier in this report, the dynamic modulus test is a strain-controlled test on cylindrical specimens that are 100 mm in diameter and 150 mm in height. The cored cylindrical specimen with 7.0 ± 1.0% air voids is subjected to a continuous haversine axial compressive load. Prior to testing, all samples were examined for air voids in accordance with AASHTO T 269. Three replicated samples were prepared and tested for each mixture.

Analysis of Results: Mix Designs

As shown in Table 7.3, eleven Superpave mix designs, including seven using aggregate I and four containing aggregate II, were performed for the aforementioned PMA mixtures. For polymers 1 (SBS) and 3, 0% and 15% RAP were used for mix designs, respectively, while the other two polymers (1+3 and 2) were mixed with 15% RAP. All of the mixtures included some type of ASAs except for the one containing only polymer 2. As show in Table 7.3, the optimum binder contents of the various mixtures were between 4.7 and 4.9% (Specifications: 4.5 to 6.0%). The voids in mineral aggregate (VMA), voids filled with asphalt (VFA), and dust/asphalt (D/A) ratios were also in the range of the specifications set forth by SCDOT. For these mix designs, the optimum binder contents were almost identical.

Table 7-3 Mix Designs of Surface Type A Mixtures

Aggregate	Virgin binder	Aged binder (%)	OBC (%)	MSG	BSG	VMA (%)	VFA (%)	Dust/Asp ratio
		<15	4.5-6.0	-	-	>14.5	70-80	0.6-1.2
Agg. I	1	0	4.8	2.456	2.371	14.5	76.1	0.93
	3	0	4.8	2.458	2.371	14.6	75.4	0.93
	1	15	4.7	2.468	2.374	14.6	74.1	0.65
	3	15	4.8	2.463	2.372	14.7	74.9	0.64
	1+3	15	4.8	2.447	2.356	14.7	74.5	0.64
	2	15	4.8	2.466	2.381	14.5	76.2	0.64
	2 (no lime)	15	4.9	2.459	2.368	14.9	75.2	0.62
Agg. II	1	0	4.7	2.479	2.386	14.6	74.4	0.86
	3	0	4.8	2.474	2.382	14.8	75.0	0.84
	1	15	4.8	2.473	2.386	14.7	76.0	0.73
	3	15	4.8	2.473	2.381	14.8	74.7	0.73

Analysis of Results: Air Voids

The air voids of compacted samples are usually used to verify the compaction capability of an asphalt plant mixture considering various factors including, but not limited to, the type of asphalt binder, mixing temperature and compaction temperature. It can be observed in Figure 7.7 that in all cases except for one, the air voids in the lab-compacted specimens were almost identical to the plant-compacted specimens. In addition, the air voids of five polymer-modified mixtures were generally similar, showing approximately 4.0% at 100 gyrations (Surface Type A mixture). It is noted that the polymer 2 samples were compacted at 130 °C and the others at 152 °C.

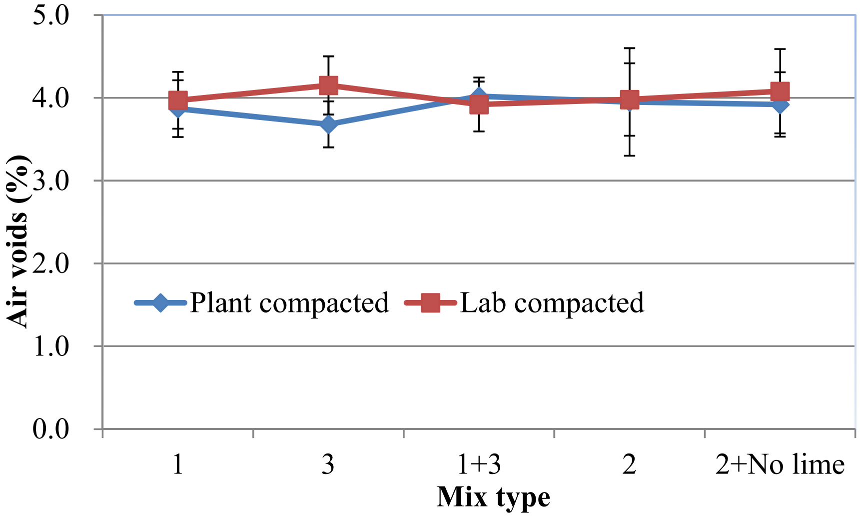
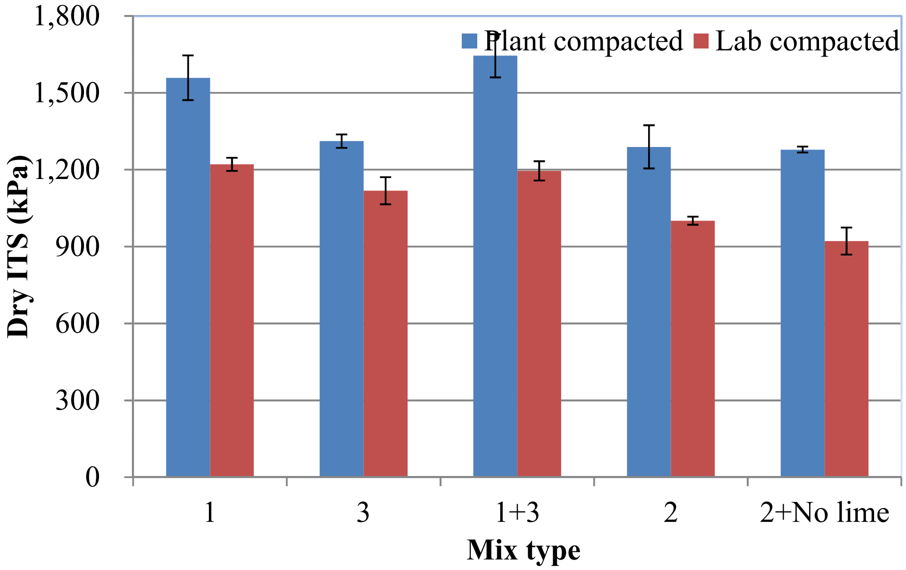


Figure 7-7 Comparisons of Air Void Between Plant and Lab Compacted Mixtures

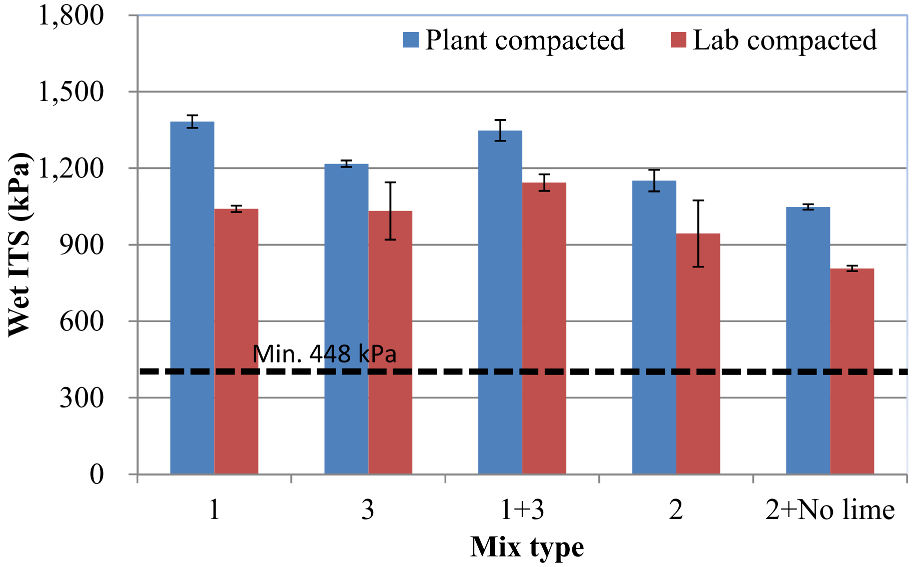
Analysis of Results: Dry Indirect Tensile Strength (ITS)

The dry ITS values were compared and the results are shown in Figure 7.8a. It is shown that the ITS values of hot mix asphalt (HMA) mixtures prepared in the laboratory were generally less than those of HMA mixtures produced in the asphalt plant, regardless of polymer type. All mixtures produced ITS values greater than 900 kPa. The mixtures containing SBS (1 only and 1+3) had slightly higher dry ITS values than mixes made with polymers 2 and 3 only. The mixtures made with polymer 1+3 produced a slightly higher dry ITS value compared to the conventional SBS mixture. Moreover, the indices of various polymerized mixtures compared to SBS mixtures, shown in Table 7.4, were less than 1.00 for samples prepared with polymers 2 and 3.

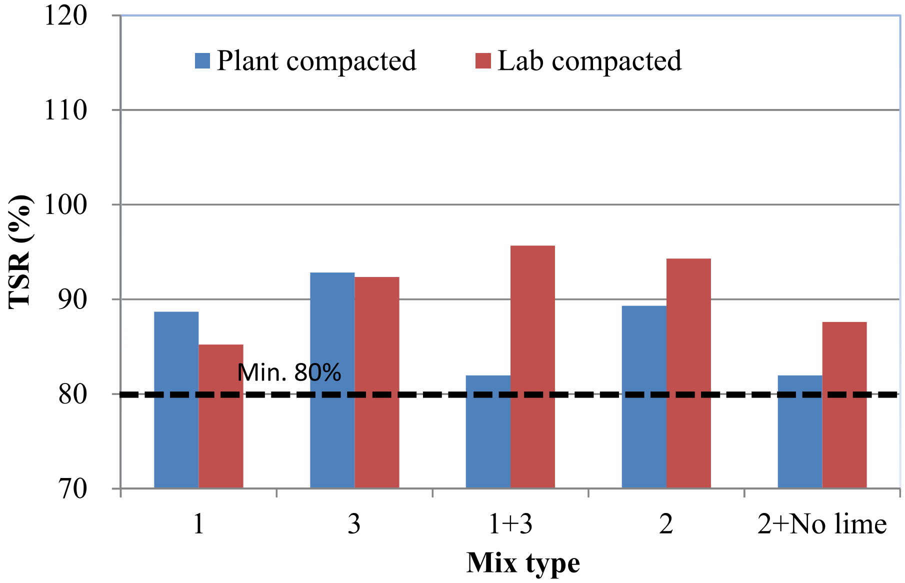
To compare the effects of two different liquid anti-strip additives versus lime, additional lab-only samples were prepared using lab-produced PMA mixtures using the two aggregate sources. As shown in Figure 7.9, the dry ITS values of SBS mixtures from aggregate II were similar to those values of the polymer 3 mixture regardless of ASA type. The SBS mixtures with hydrated lime had slightly higher dry ITS values than the SBS mixtures containing the liquid ASAs for both aggregate sources. However, the dry ITS values were very comparable for various ASA mixtures when using polymer 3. The polymer-modified mixtures from aggregate source I show different trends. The mixtures containing liquid a2 ASA have lower dry ITS values regardless of polymer type, while SBS mixtures with hydrated lime have the highest dry ITS values.



(a)



(b)



(c)

Figure 7-8 ITS and TSR Values of Plant and Lab Compacted Mixtures, (a) Dry ITS Values; (b) Wet ITS Values; (c) TSR Values

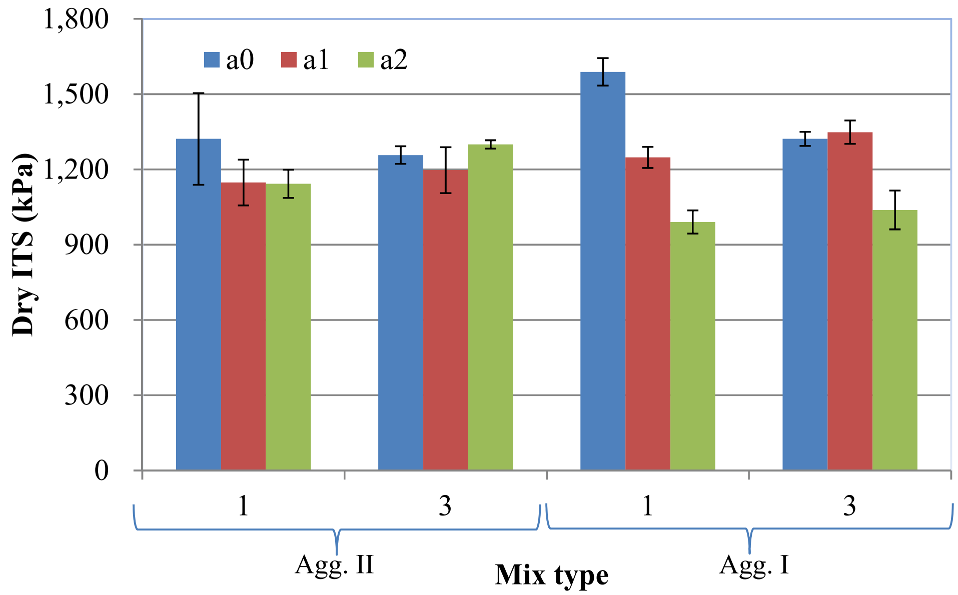


Figure 7-9 Comparisons of Dry ITS Among Mixtures Containing Various ASAs

Table 7-4 Indices of Various Polymerized Mixtures Compared to SBS Mixtures, (A) Plant and Lab Compacted; (B) Various ASAs

(a)

Test results	1	3	1+3	2	2+No lime
Dry ITS	1.00	0.88	1.02	0.82	0.79
Wet ITS	1.00	0.94	1.04	0.87	0.77
Dry flow	1.00	0.95	1.01	0.91	0.97
Wet flow	1.00	0.97	0.97	0.92	0.95
Rut depth	1.00	0.61	1.39	1.45	1.59
Flow number	1.00	3.12	2.13	0.90	0.60

(b)

Test results	1+a0	1+a1	1+a2	3+a0	3+a1	3+a2
Dry ITS	1.00	0.82	0.73	0.89	0.87	0.80
Wet ITS	1.00	0.72	0.63	0.74	0.70	0.66

Dry flow	1.00	1.06	1.14	1.03	1.04	0.99
Wet flow	1.00	0.96	1.02	1.02	0.98	0.97
Rut depth	1.00	1.09	1.40	0.98	1.14	1.28
Dry dissipated energy	1.00	0.80	0.85	0.72	0.98	0.76
Wet dissipated energy	1.00	0.70	0.78	0.68	0.72	0.65
Flow number	1.00	0.89	0.73	0.87	0.51	0.64

Analysis of Results: Wet Indirect Tensile Strength (ITS)

As shown in Figure 7.8b, similar to the dry ITS values, the wet ITS values of the laboratory-produced samples were lower than the ITS values of the plant-produced samples, although they were still much higher than 448 kPa, which is the minimum wet ITS value set by SCDOT's specification. All of the polymer-modified mixtures had similar wet ITS values, except for the polymer 2 mixture that did not contain hydrated lime. The wet ITS value for that mixture was slightly lower.

The wet ITS values shown in Figure 7.10 indicate that the mixtures produced with SBS-modified binder and hydrated lime had the highest wet ITS values amongst the polymerized mixtures for both aggregate sources. For aggregate II, all mixtures containing liquid ASAs (a1 and a2) had approximately the same wet ITS values. It can be observed that for mixtures produced with aggregate source I, the wet ITS value of the SBS mixture containing hydrated lime is higher than any other mixture regardless of ASA and polymer type. In addition, for aggregate source I, polymer-modified mixtures containing liquid ASA a2 showed lower wet ITS values compared to the other mixtures regardless of polymer type. However, these lowest wet ITS values were still twice the 448 kPa minimum specification limit. Therefore, it can be concluded that the polymers and liquid ASAs utilized in this research project can be used to resist the moisture damage of asphalt mixtures.

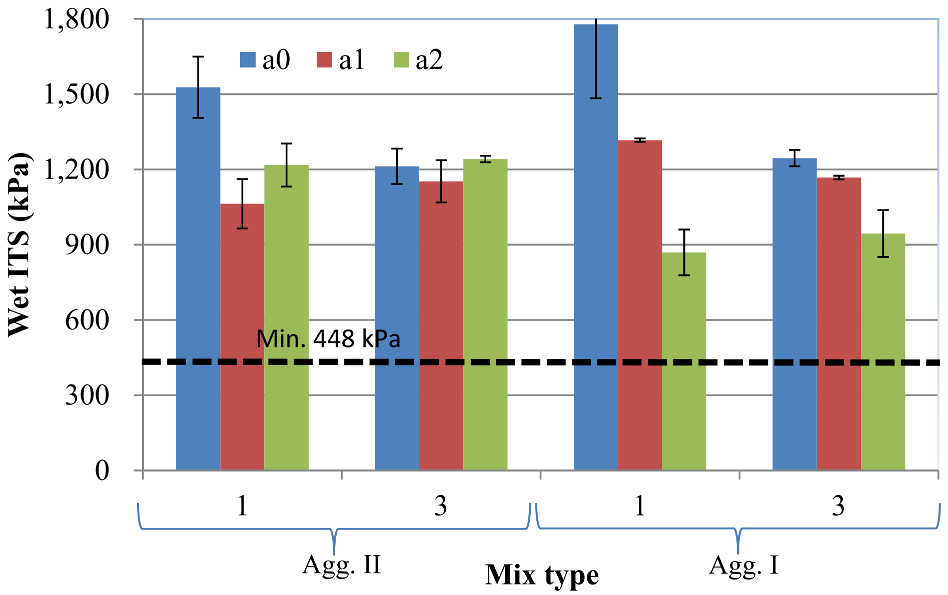


Figure 7-10 Comparisons of Wet ITS Among Mixtures Containing Various ASAs

Analysis of Results: Tensile Strength Ratio (TSR)

The TSR results of plant- and laboratory-produced samples are presented in Figure 7.8c. All of the specimens had TSR values higher than 80%, which is the minimum specification value set forth by many states in the US. The other mixtures had higher TSR values than the SBS mixtures, with the exception of the plant-produced hybrid sample and the polymer 2 plant-produced sample without lime. Compared with the SBS mixture, the samples containing polymer 2 without lime had higher lab-based TSR values and lower plant–based TSR values. It should be noted that the samples made with polymer 2 were the only specimens produced without lime.

As shown in Figure 7.11, the TSR values of all mixtures were greater than 80% regardless of polymer type, aggregate source, and ASA type. In most cases, SBS mixtures had relatively higher TSR values than the mixtures made with polymer 3. In addition, the polymerized mixtures with hydrated lime generally produced slightly higher TRS values than those with liquid ASAs regardless of the aggregate source.

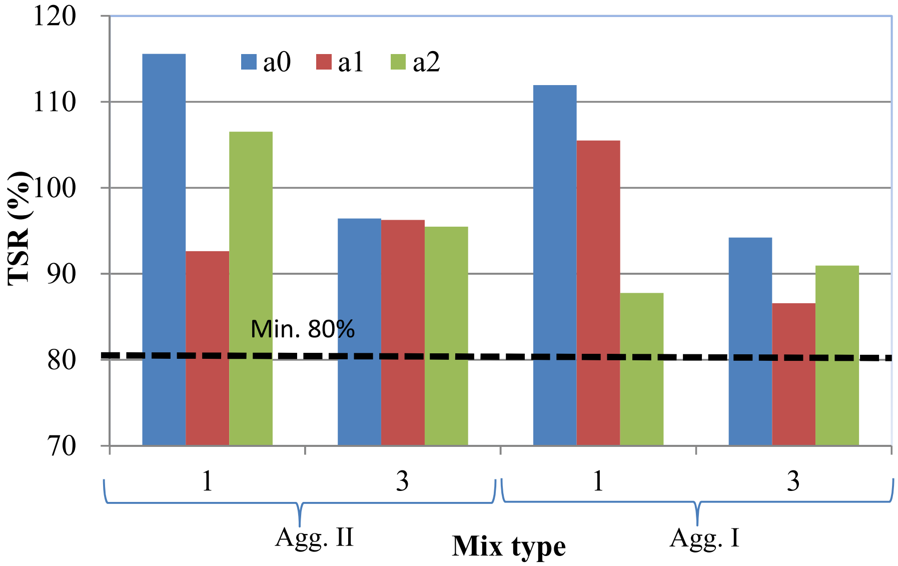
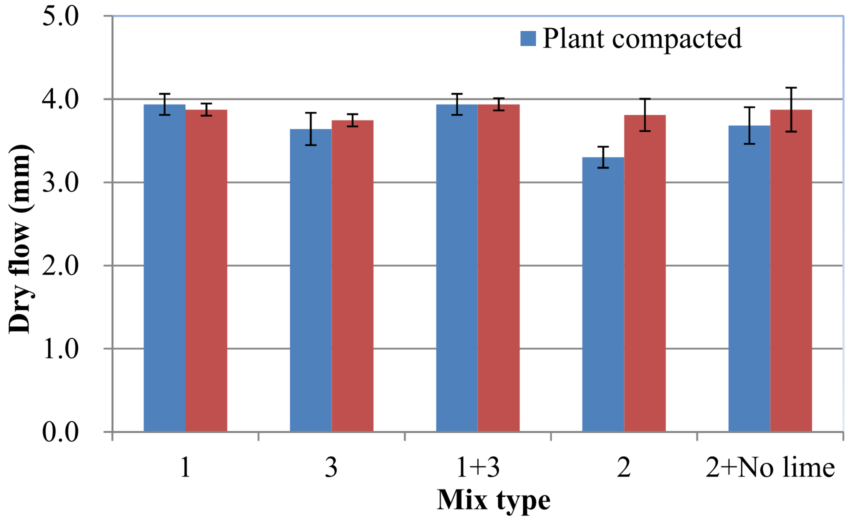


Figure 7-11 Comparisons of TSR Among Mixtures Containing Various ASAs

Analysis of Results: Deformation (Flow)

The deformation (flow) resistance of ITS specimens, which is a measure of the material's resistance to permanent deformation in service, is also used to gauge the moisture susceptibility of the mixtures. In Figure 7.12, the deformation results show that the dry flow values were, in general, comparable for all of the polymer materials. The specimens produced at the asphalt plant generally had relatively lower deformations than the lab-compacted samples regardless of wet or dry samples. In Table 7.4, the indices of dry and wet flow of all of the alternate polymer-modified mixtures exceeded 0.90, indicating the effectiveness of these materials compared to the SBS materials.

With respect to the effect of ASA and aggregate source on deformation resistance, Figure 7.13 shows that all dry and wet flow values were close to 4 mm. The SBS mixtures had flow values similar to the mixtures produced with polymer 1 regardless of aggregate source and ASA type. In addition, Table 7.4 shows that the indices of dry and wet flow for all of the liquid ASAs were greater than 0.96, and some of them were even greater than 1.00 (SBS). Moreover, the mixtures with liquid ASAs did not have noticeably lower dry or wet flow values, in general. Thus, it can be concluded that the polymer-modified mixtures generally had similar deformation resistance regardless of aggregate source and ASA type for the materials used in this study.



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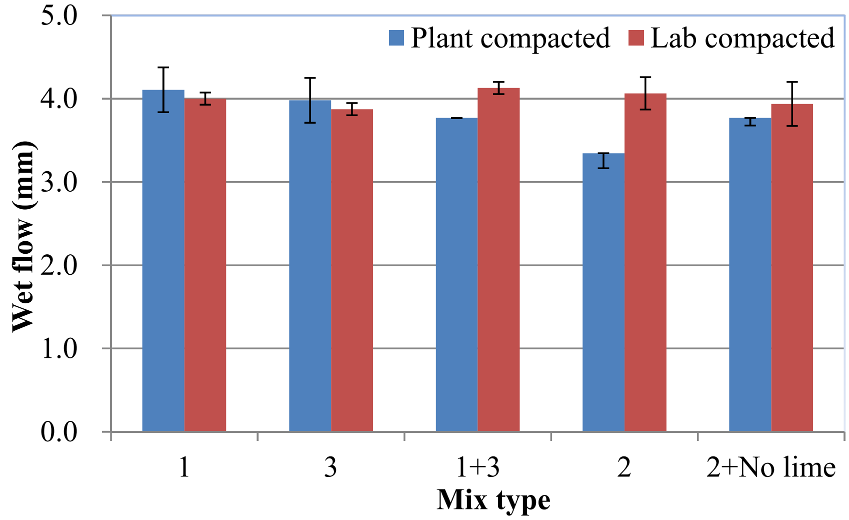
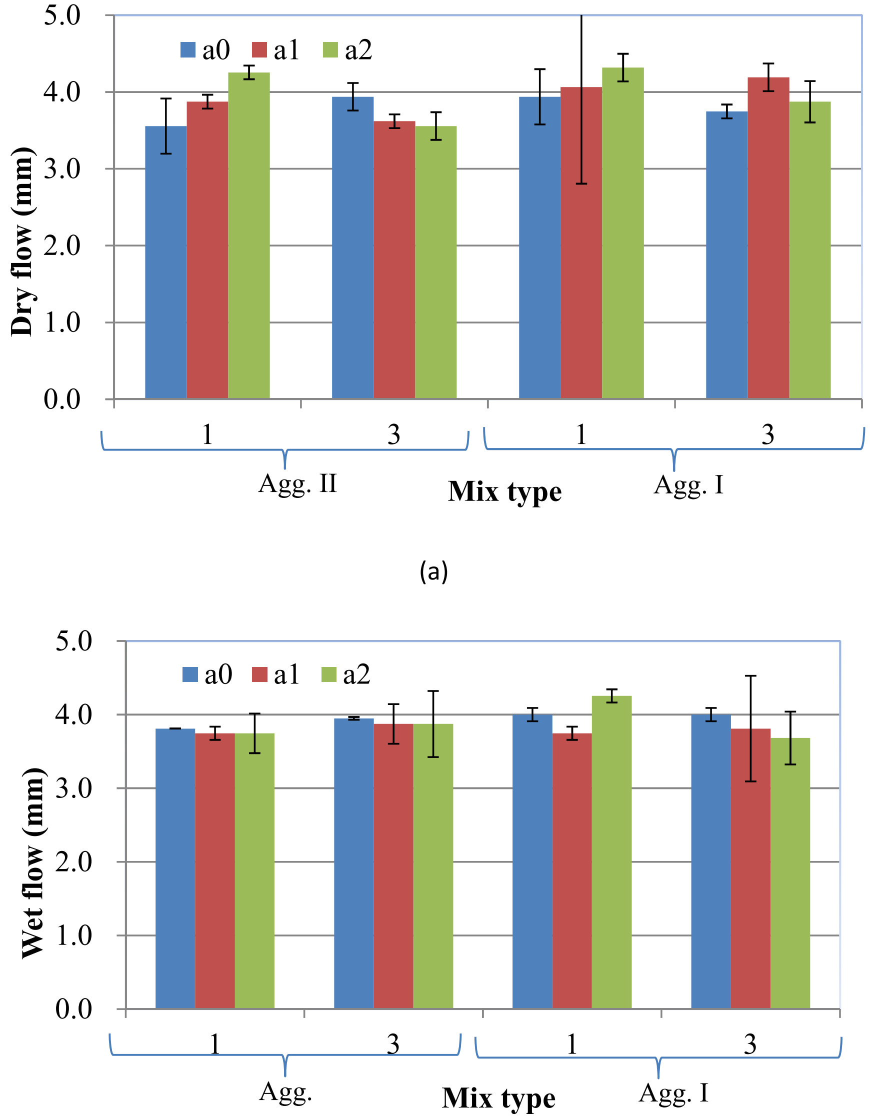


(b)

Figure 7-12 Flow Values of Mixtures Containing Various Polymers, (a) Dry Flow Values, (b) Wet Flow Values



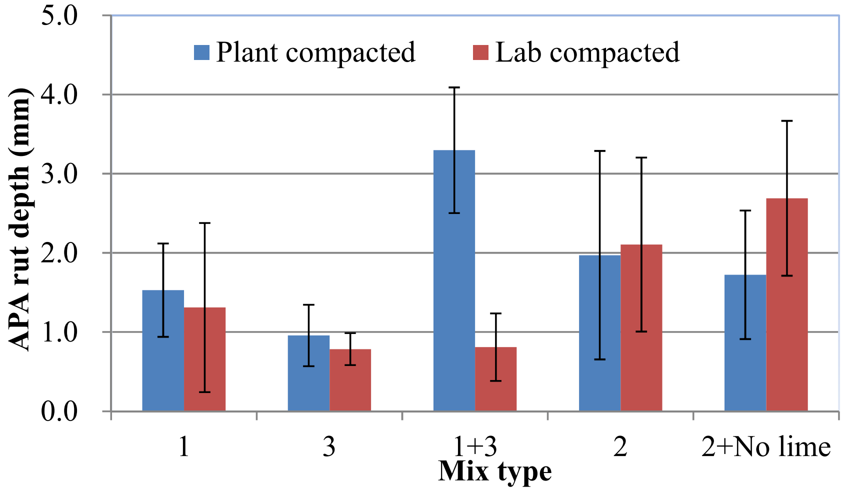
(a)

(b)

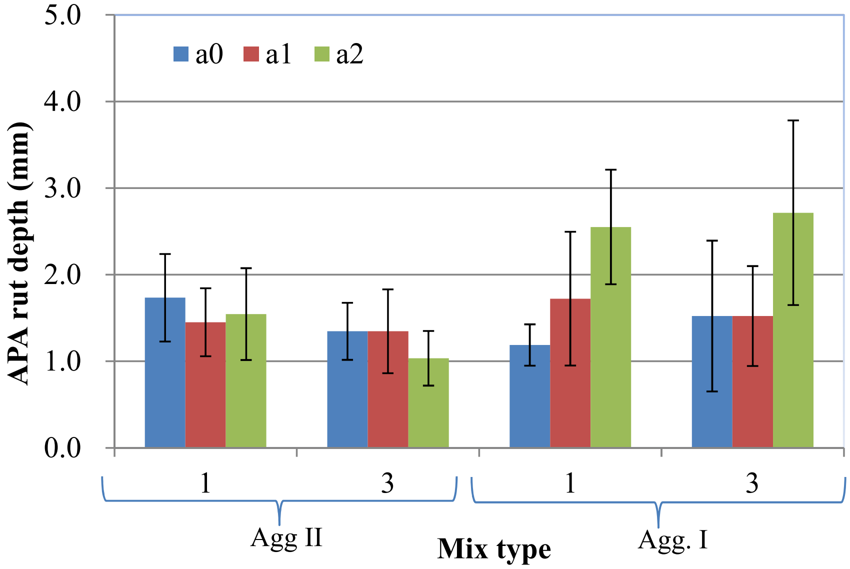
Figure 7-13 Flow Values of Mixtures Containing Various ASAs, (a) Dry Flow Values; (b) Wet Flow Values

Analysis of Results: Asphalt Pavement Analyzer (APA) Rut Depth

The APA results shown in Figure 7.14 indicate that the rut depths of all plant and laboratory mixtures were generally less than 3 mm regardless of polymer type. The mixtures made with polymer 3 had slightly lower rut depth values compared to other mixtures. In addition, the WMA mixtures made with polymer 2 both with and without lime generally had relatively higher rut depths, which is possibly due to their lower compaction temperature; however, the rut depths for those mixtures were still less than 3 mm. The rut depths of all mixtures from aggregate source II generally had relatively lower rut depths compared to aggregate source I, although all rut depths were still less than 3 mm.



(a)



(b)

Figure 7-14 Rut Depth Values of Various Mixtures, (a) Plant and Lab Compacted; (b) Various ASAs

Analysis of Results: Fracture Energy/Dissipated Energy

Previous research illustrated that fracture energy is effective in determining the total dissipated energy of asphalt mixture before failure occurs under traffic loading. The fracture energy values of the various mixtures are shown in Figure 7.15. The results show that the wet samples stored less fracture energy than the dry samples before they were damaged regardless of the polymer type (Figure 7.15a). The samples made with polymer 1 (SBS) and polymer 1+3 generally had higher dissipated energy than other polymer-modified samples and thus may result in better fracture resistance.

In addition, it can be noted that the dry mixtures did not show higher fracture energy than the wet mixtures when using the same materials. The dissipated energy values generally ranged from 40 J to 60 J. No obvious trends could be found regarding the effects of aggregate source, polymer type, and ASA type for the materials used in this research study.

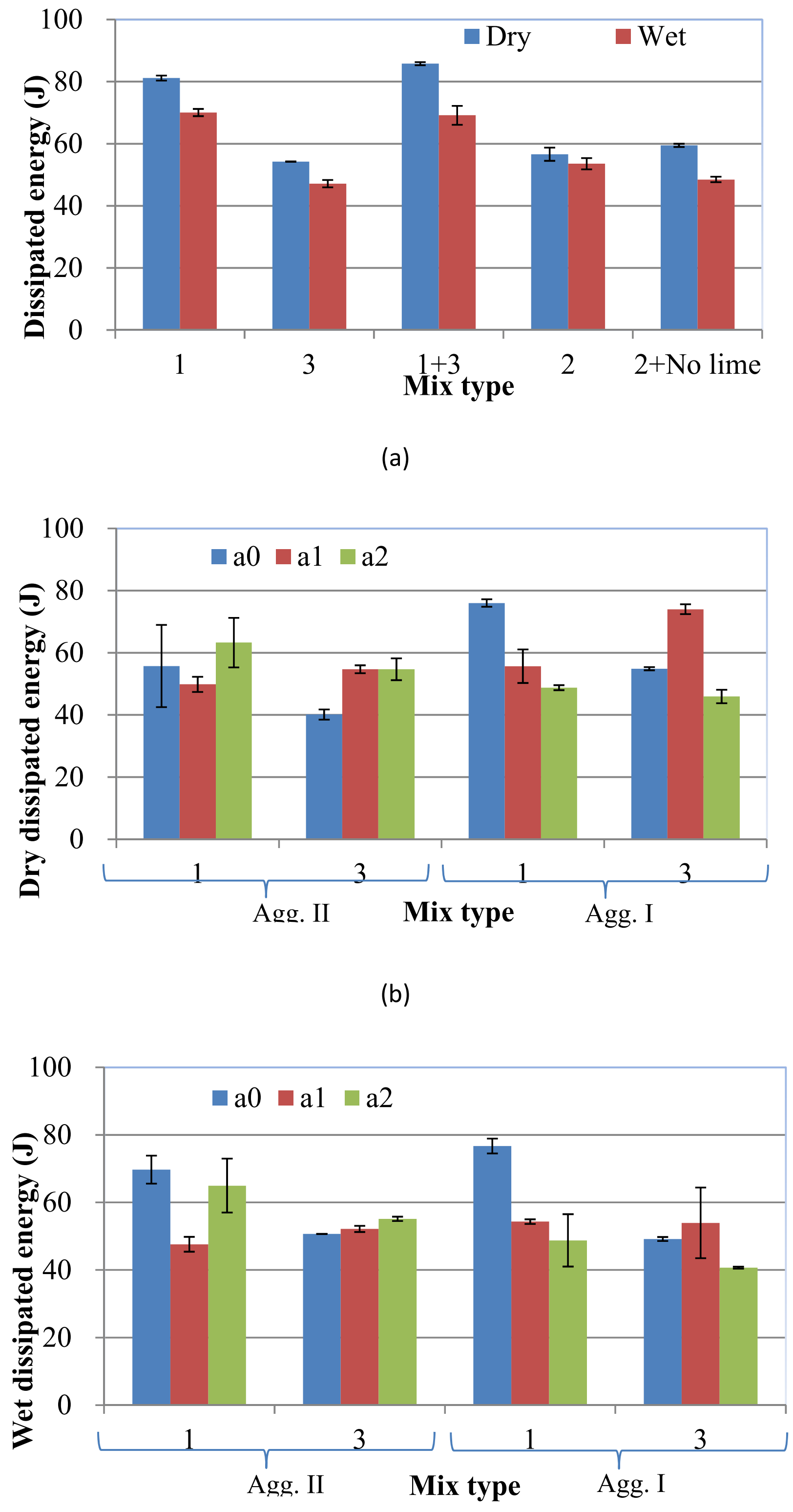


Figure 7-15 Dissipated Energy of Various Mixtures, (a) Plant Compacted Samples, (b) Dry Lab Samples, and (c) Wet Lab Samples

Analysis of Results: Dynamic Modulus, Phase Angle and Flow Number

Complex dynamic modulus, |E*|, testing was conducted to determine the changes in mixture stiffness as a result of the incorporation of different polymers in specimens compacted from the asphalt plant-produced mixtures (Aggregate I). The specimens were conditioned to the test temperatures of 4°C, 20°C, and 45°C in a calibrated environmental chamber before testing. The detailed description of test procedure can be found in AASHTO TP 79. Three replicate dynamic modulus specimens for each mixture were fabricated and tested for this study.

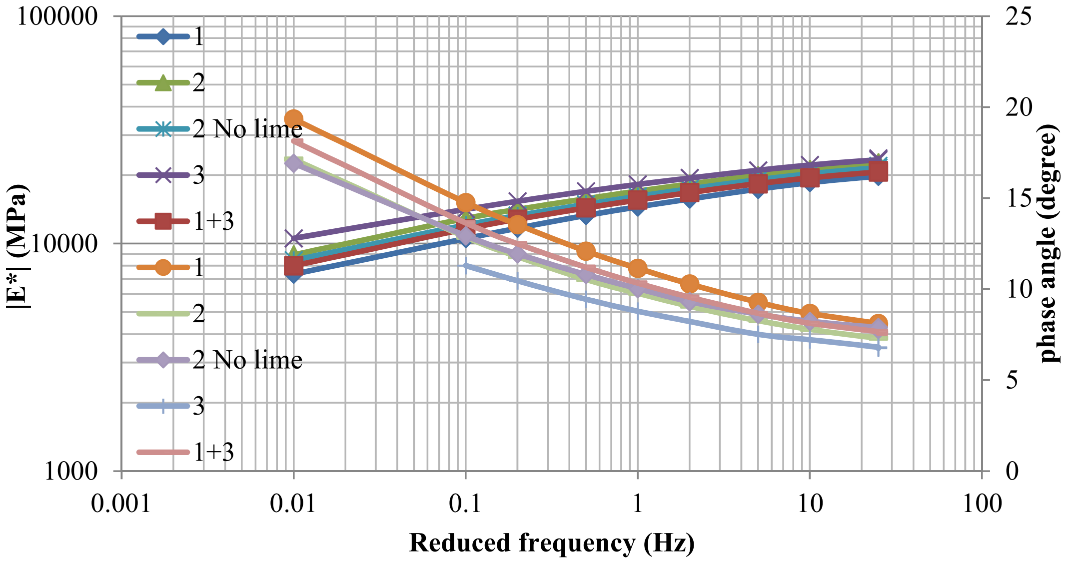
As shown in Figure 7.16a, at 4°C, the samples containing SBS had the lowest |E*| values at varying frequencies, and the samples containing polymer 3 had the highest |E*| values. Therefore, it could be concluded that the mixture produced with polymer 3 may have better elastic recovery than the other mixtures during the loading process due to the effects of the bond between the modified binder and the aggregate. In addition, Figure 7.16a shows that increased frequency resulted in an increase of |E*| value regardless of polymer type.

In Figure 7.16a, it is also observed that as the loading frequency increased at 4°C, the phase angle values decreased for all of the polymer mixtures. In addition, all mixtures at 4°C had similar trends regardless of polymer type. The mixture containing SBS had the highest phase angle value at varying frequencies, while the mixture made with polymer 1 showed the lowest value, and thus has relatively lower viscous properties.

The |E*| and phase angle values of the plant-compacted samples at 20°C are shown in Figure 7.16b. It can be observed that, similar to the test results at 4°C, increased frequency resulted in an increase of the |E*| value and a reduction in phase angle for all mixtures. In addition, the samples made with binder containing polymer 3 had the highest |E*| values and the lowest phase angles, but the polymer 1 (SBS) samples had the lowest |E*| values and the highest phase angles. However, the rate of phase angle reduction resulting from increased frequency at 20°C was slower than that at 4°C.

In addition, the results in Figure 7.16c indicate that at 45°C, the increased frequency resulted in the increase of |E*| values of all mixtures, and the samples containing polymer 3 had the highest |E*| values while polymer 1 (SBS) had the lowest ones. However, at 45°C, the phase angles of all mixtures increased when the loading frequency increased. This trend at 45°C is opposite to the phase angle trends at 4°C and 20°C. In addition, it can be noted that, as expected, higher |E*| values and lower phase angles were obtained when the mixtures were tested at a relatively lower temperature.

The flow number test is used to measure the rutting potential of asphalt concrete mixtures at a test temperature of 59°C according to the LTPPBind 3.1 software. As shown in Figure 7.16d, the lowest flow number value (208) was obtained from the mixture containing polymer 2 without lime, while the highest value (1076) was produced from the mixture containing polymer 3. The flow number values of all polymer-modified mixtures were higher than 190, which is a minimum value set by AASHTO TP 79 for a traffic level of 10 to 30 million ESALs. In addition, Table 7.4 indicates that the indices of flow numbers obtained from mixtures made with binders containing polymers 3 and 3+1 were greater than 1.0, while the indices of mixtures made with polymer 2, both with and without hydrated lime, were less than 1.00. Consequently, it can be concluded that the mixtures containing polymer 2 had the weakest resistance to permanent deformation. In addition, the results of APA rut depth values presented previously indicated similar trends since the mixture containing polymer 3 had the lowest rut depths while the mixtures made with polymer 2 had the highest rut depths.



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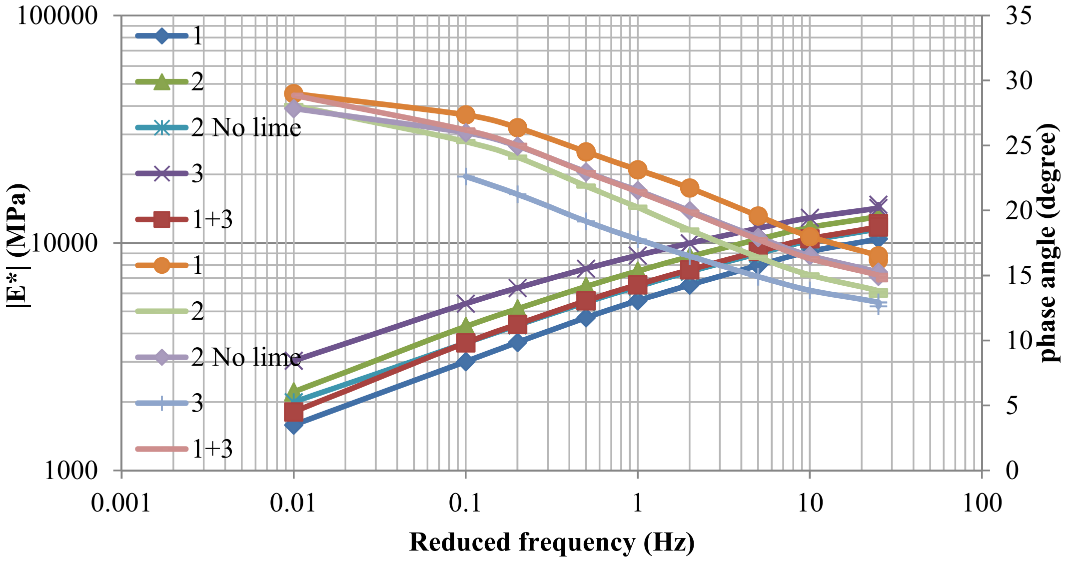

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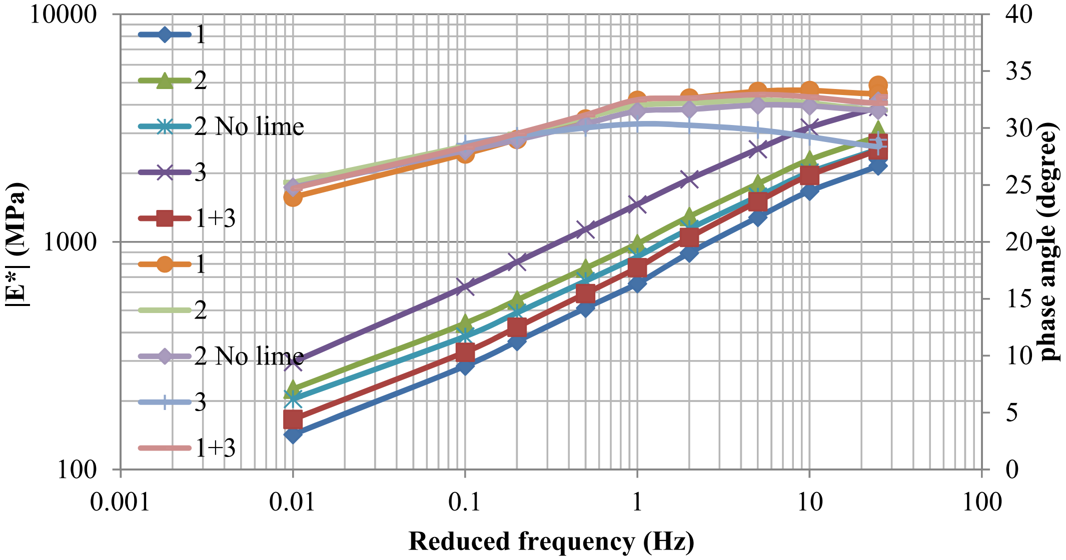

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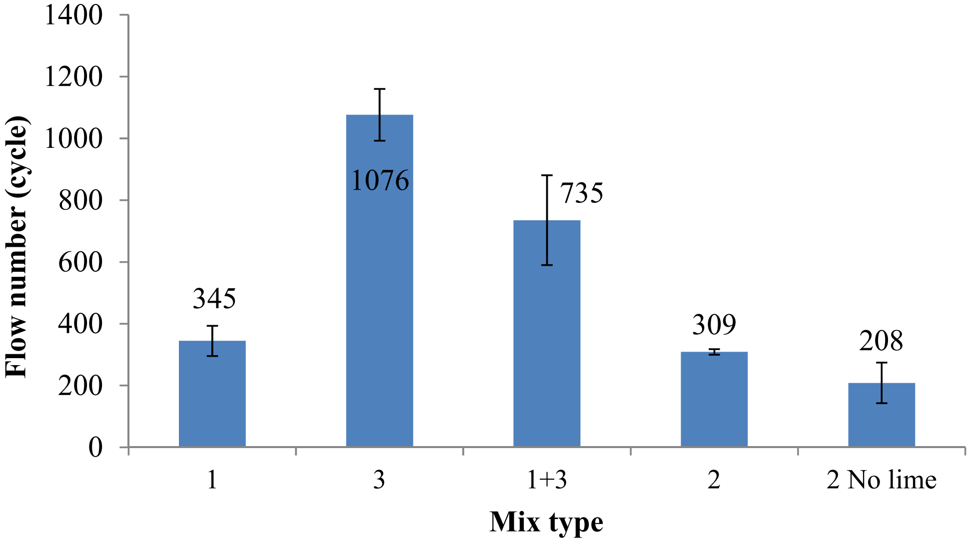


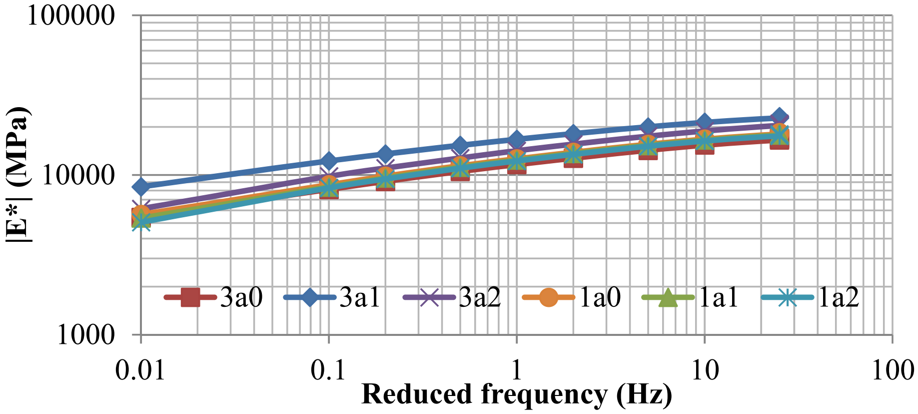
(d)

Figure 7-16 The |E*| And Phase Angle Values of Plant Compacted Samples, (a) at 4°C, (b) at 20°C, (c) at 45°C, and (d) at 59°C

The |E*| and phase angle values of polymer-modified mixtures from aggregate I with various ASAs are presented in Figures 7.17 and 7.18, respectively. The flow numbers of these modified mixtures are shown in Figure 7.19. The results indicate that the |E*| values increased when the frequency increased, while phase angle values reduced regardless of polymer and ASA type for materials used in this research project. The phase angles from polymer 1 (SBS) samples with hydrated lime were generally higher than those from other mixtures, while the |E*| values of these samples were the lowest. In addition, the samples containing polymer 3 and ASA a1 had the highest |E*| values and the lowest phase angles.

Similar to the plant-compacted samples, at the relatively high testing temperature of 45°C, the |E*| values of all mixtures increased with an increasing frequency, but their phase angles also increased when the loading frequency increased. The polymer 3 mixture containing ASA a1 had the highest |E*| values, indicating more elastic characteristics, while polymer 1 (SBS) mixture with hydrated lime generally exhibited more viscous behavior for the materials used in this study. Additionally, it can be noted that higher test temperatures resulted in lower |E*| values and higher phase angles. Similar trends can be obtained from those mixtures from aggregate source II.

Flow number values of these polymer-modified mixtures with various ASAs are shown in Figure 7.19. It can be found that the polymer-modified mixtures containing ASA a2 had the lowest flow numbers regardless of polymer type and aggregate source. In most cases, the mixtures with ASA a1 had the highest flow numbers. The indices shown in Table 7.4 illustrate that SBS mixture containing hydrated lime had higher flow numbers than the other mixtures since their indices were all less than 1.0. These indices were generally similar to the rut depth results obtained from APA tests.



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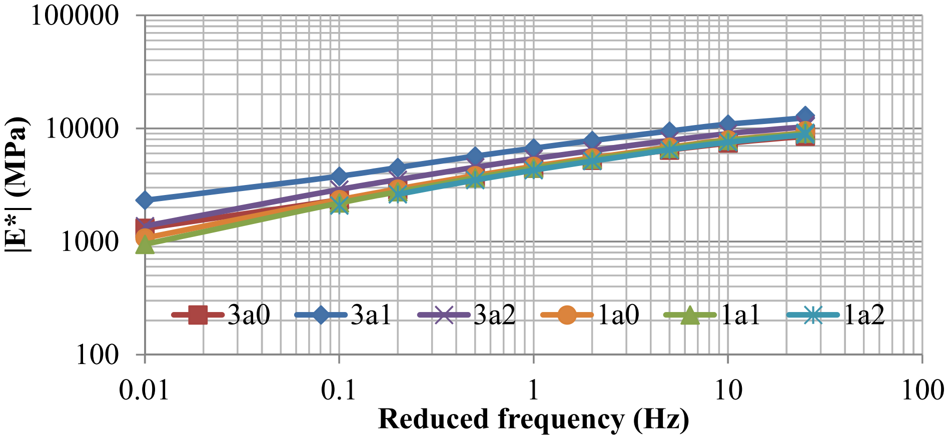

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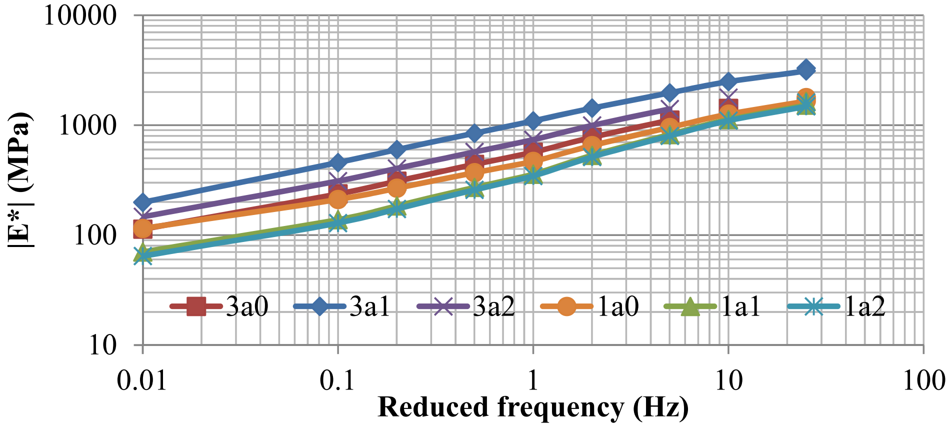
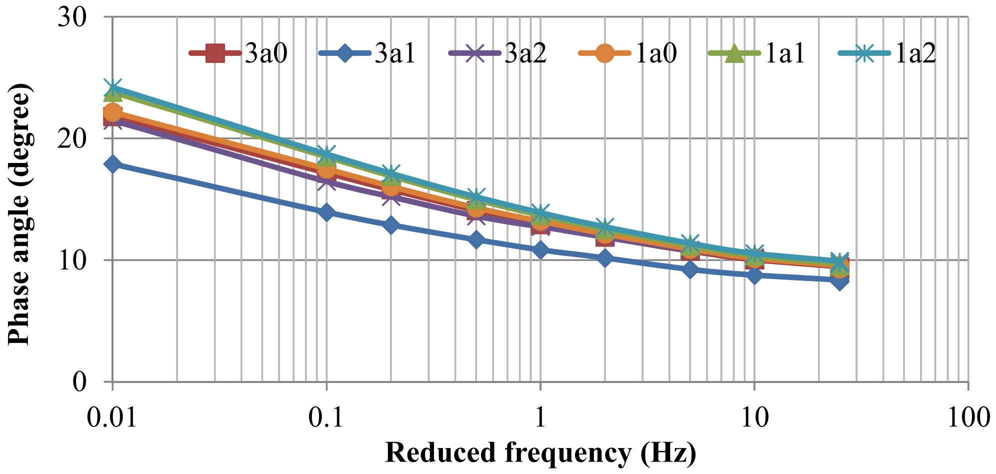


(c)

Figure 7-17 The |E*| Values of Various ASA Samples, (a) at 4°C, (b) at 20°C, and (c) At 45°C



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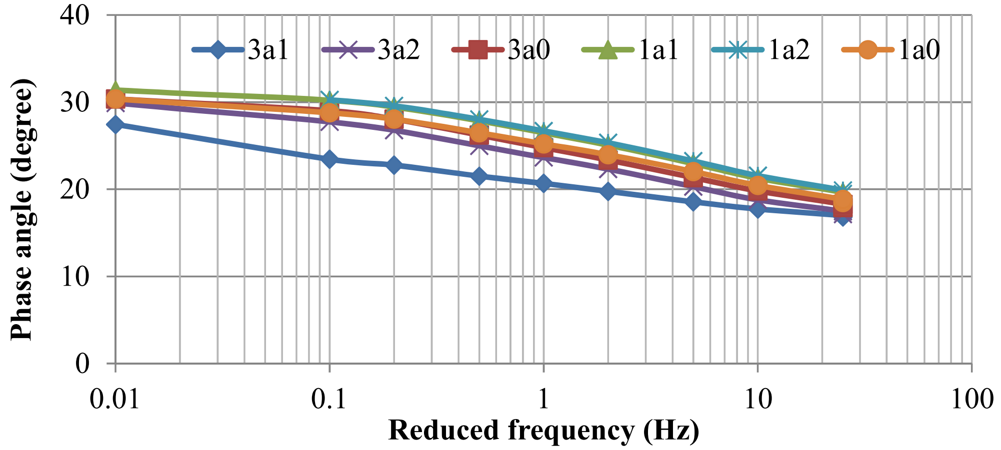

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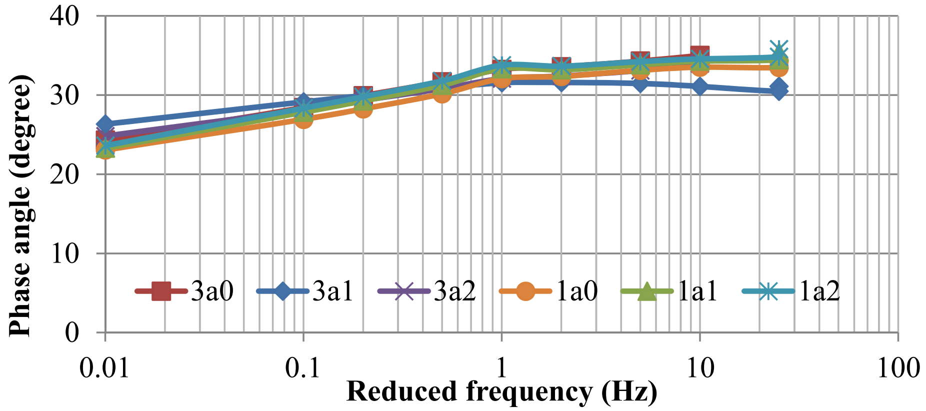


(c)

Figure 7-18 Phase Angle Values of Various ASA Samples, (a) at 4°C, (b) at 20°C, and (c) at 45°C

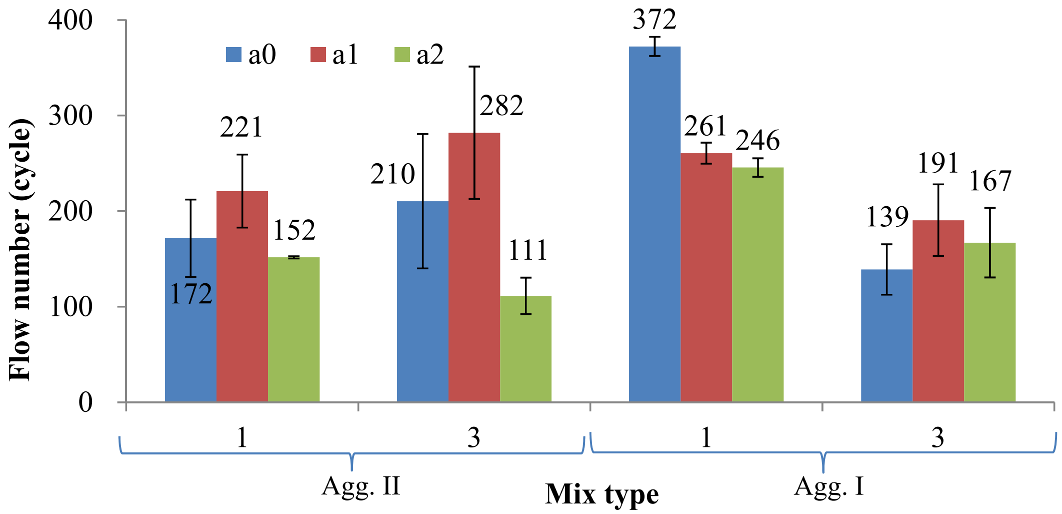


Figure 7-19 Flow numbers of Various ASA Samples at 59°C

Analysis of Results: Falling Weight Deflectometer (FWD) Analysis

A falling weight deflectometer (FWD) is a testing device used by many agencies to evaluate the physical properties of a pavement. FWD data is primarily used to estimate pavement structural capacity for 1) overlay design and 2) to determine if a pavement is being overloaded. This technique is being used for highways, local roads, airport pavements, and railway tracks. To evaluate highways, the machine is usually contained within a trailer that can be towed to a location. The FWD simulates a moving vehicle's wheel load by using a falling-weight loading system to create a temporary deflection basin on the tested surface. Highway engineers use these surface deflection measurements to perform structural analysis, evaluate service life, and identify areas in need of repair.

The FWD is designed to apply a load pulse to the pavement surface which simulates the load produced by a rolling vehicle wheel. The load is produced by dropping a large weight, and transmitted to the pavement through a circular load plate - typically 300mm diameter. A load cell mounted on top of the load plate measures the load applied to the pavement surface. Deflection sensors (geophones; force-balance seismometers) mounted radially from the center of the load plate measure the deformation of the pavement in response to the load.

FWD data is most often used to calculate stiffness-related parameters of a pavement structure. The process of calculating the elastic moduli of individual layers in a multi-layer system (e.g. asphalt concrete, base course, subgrade) based on surface deflections is known as "back-calculation" since there is no closed-form solution. In this case, initial moduli are assumed, surface deflections are calculated, and then the moduli are adjusted in an iterative fashion to converge on the measured deflections.

FWD data can also be used to calculate the degree of load transfer between adjacent concrete slabs, and to detect voids under slabs. The test materials are described in ASTM D 4694, and the test method is defined in ASTM D 4695.

The Eastbound and Westbound test sections were analyzed using this technique, and the results are shown in Figures 7.20 and 7.21, respectively. The FWD will be used after several years to compare the results after several years of traffic on the newly-constructed surface. The results will be used for the next several years to follow the performance of the mixtures. The testing was conducted by SCDOT and the results were provided to the PI after the completion of the test process.

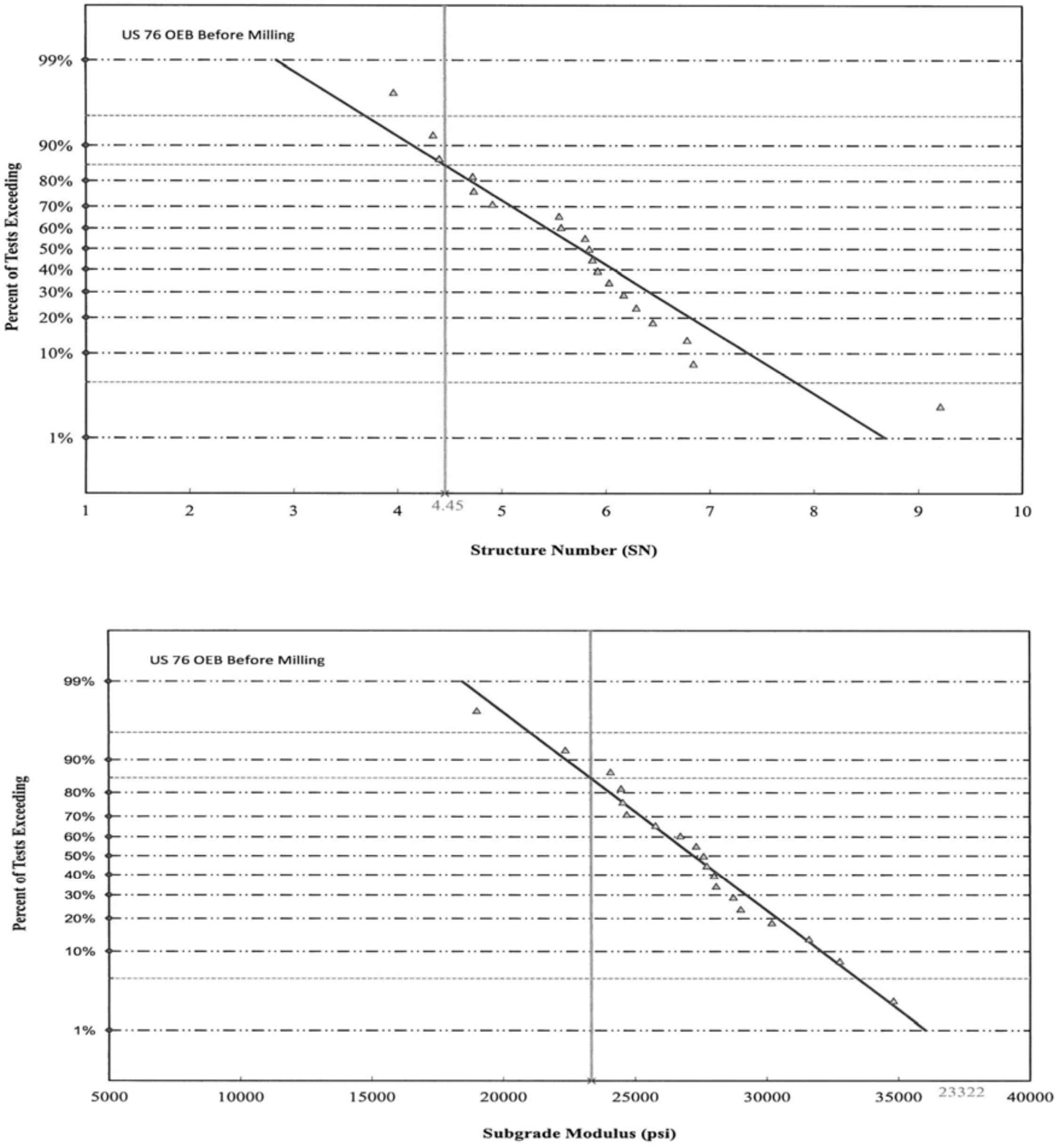
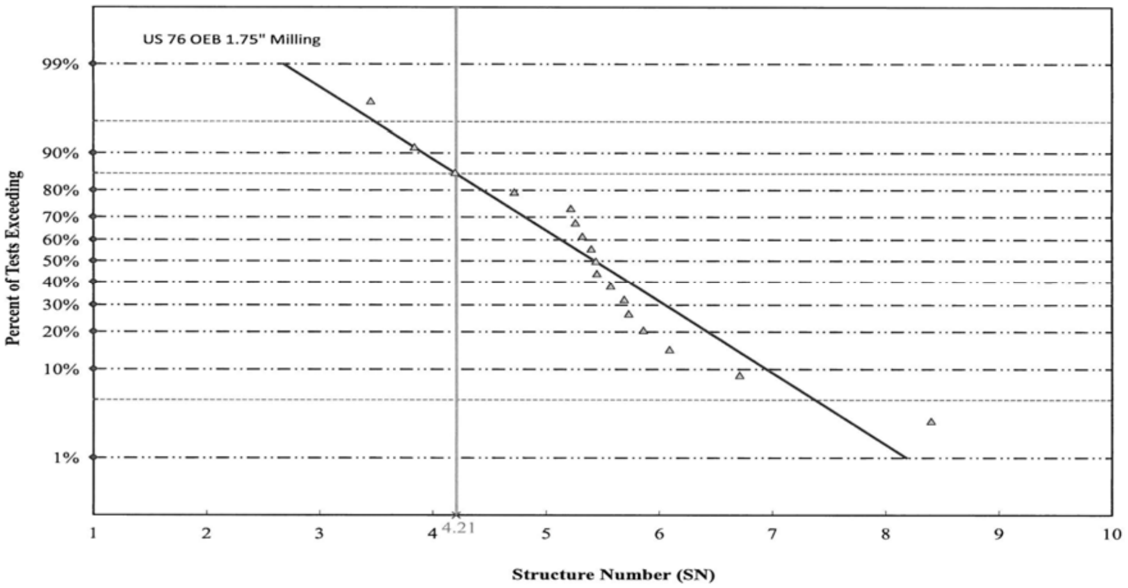


Figure 7-20 FWD Results: Eastbound, US 76 Marion County, SC



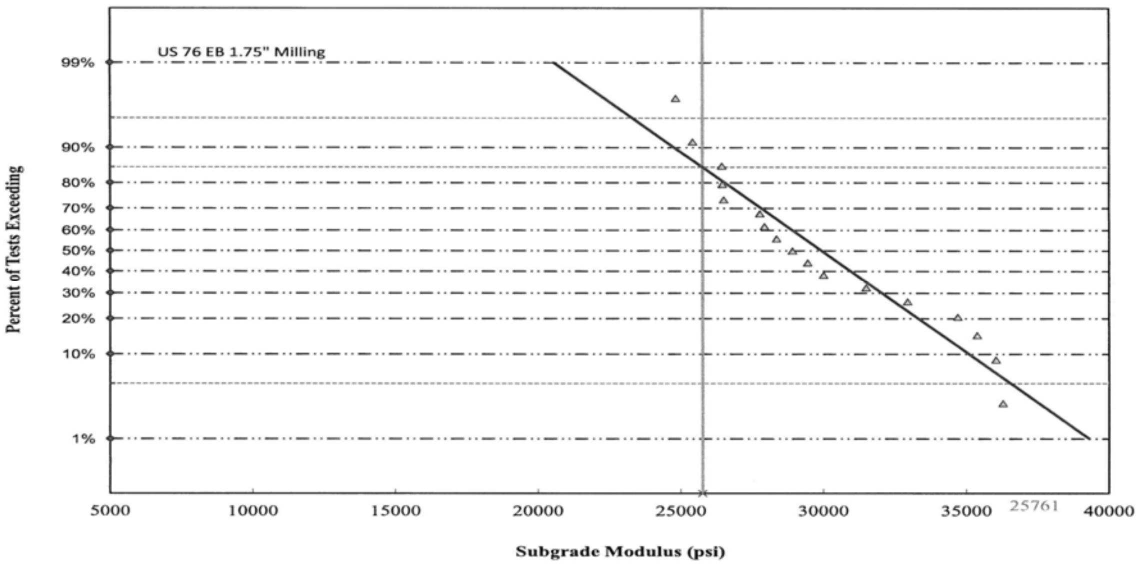
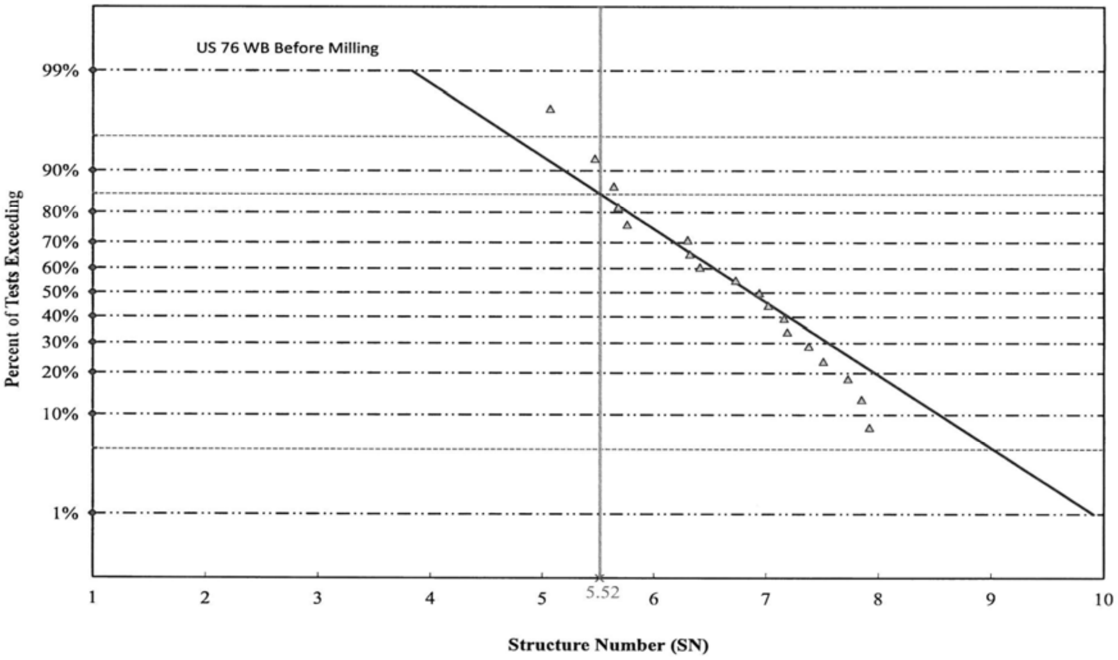


Figure 7.20 (Continued)



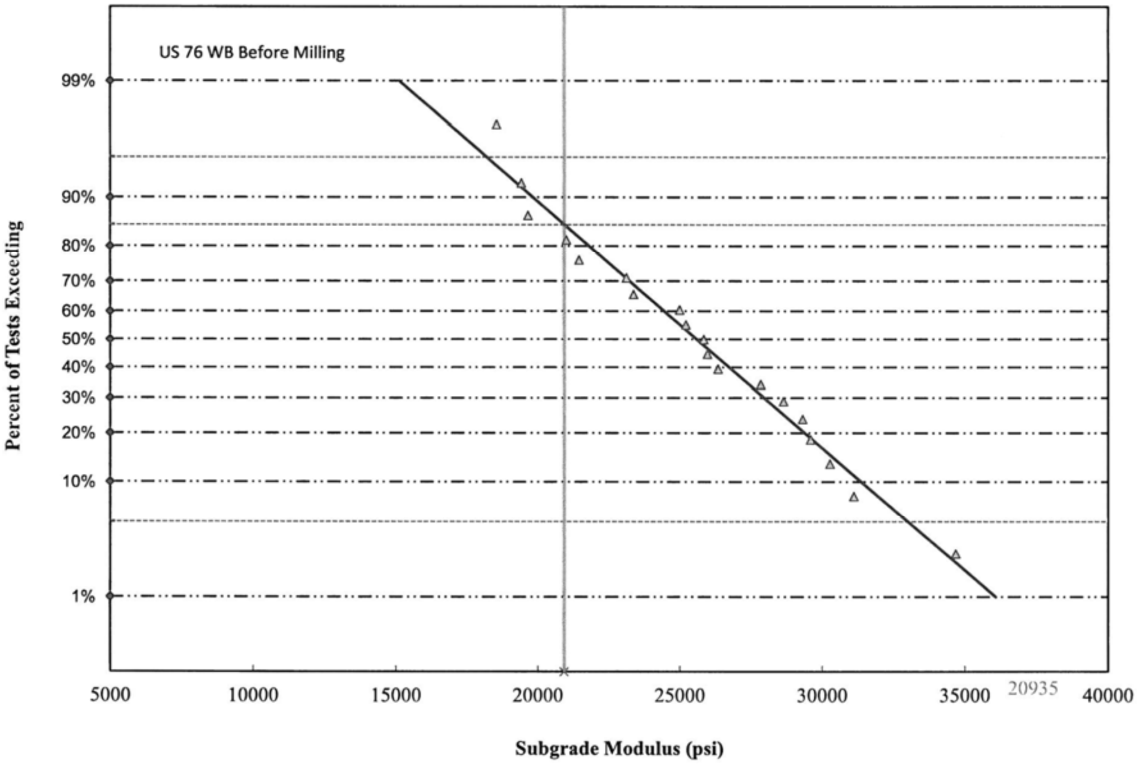
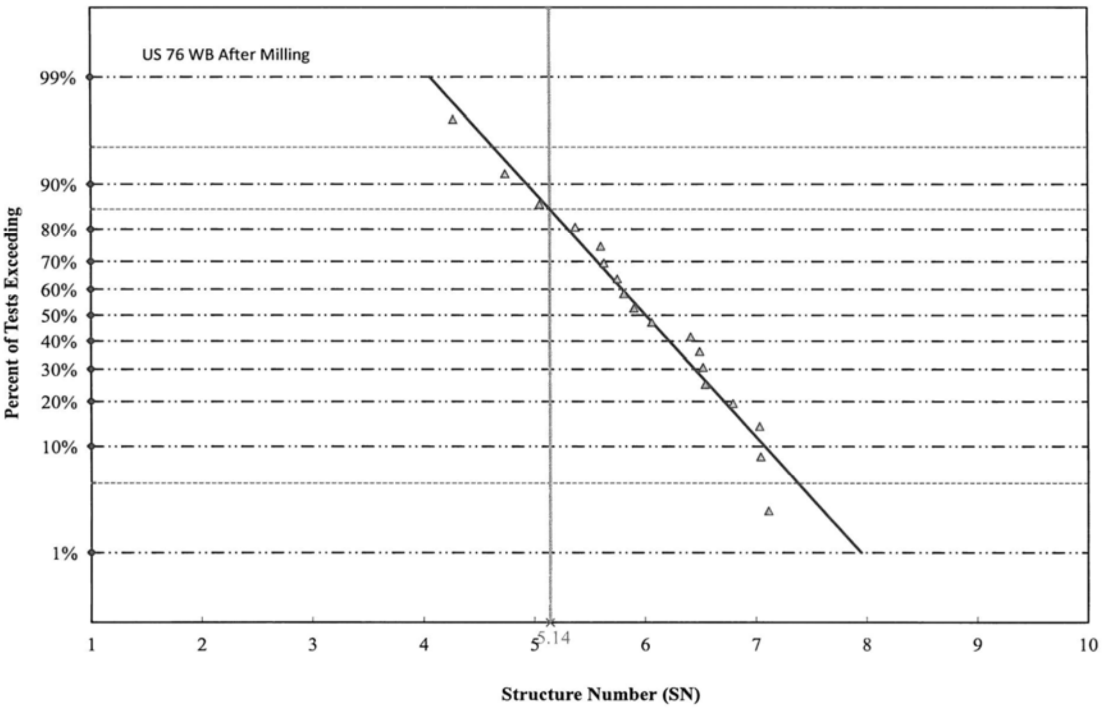


Figure 7-21 FWD Results: Westbound, US 76 Marion County, SC



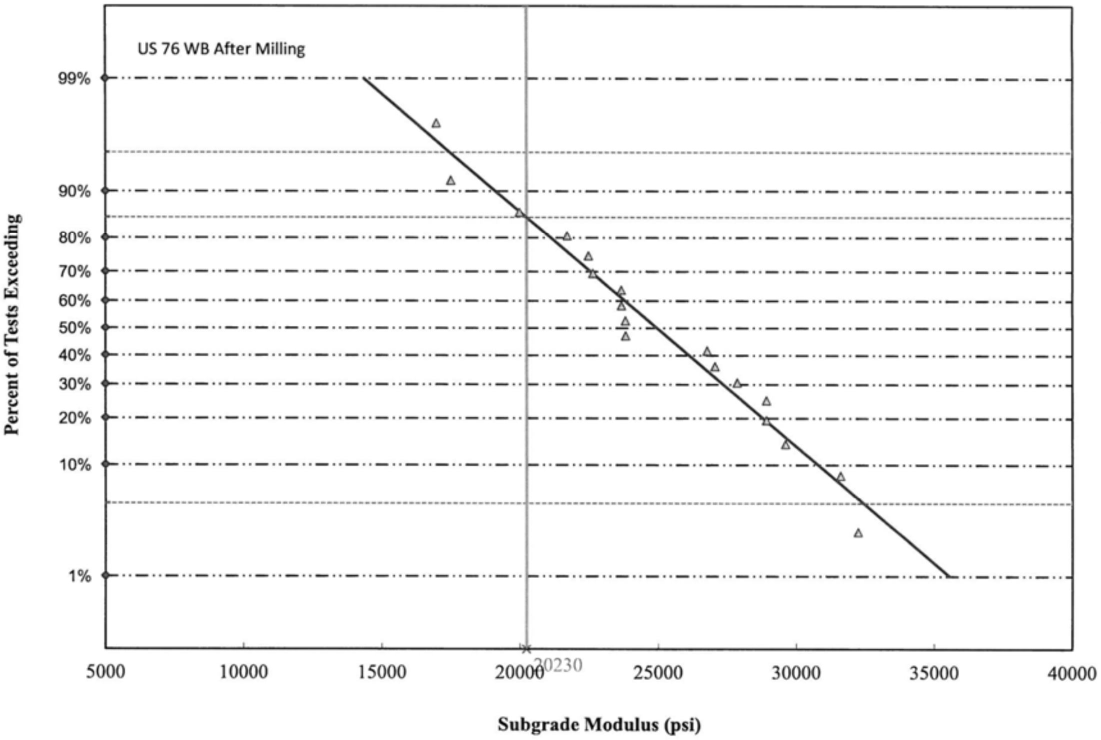


Figure 7.21 (Continued)

Analysis of Results: Hamburg Wheel-Tracking Rut Depth

The Hamburg test results of plant-compacted samples are presented in Figure 7.22. It can been observed that all HWT rut depths were less than 2.0 mm. The mixtures containing polymer 2 (with lime) and polymer 3 had HWT rut depths less than 1.0 mm. In addition, no moisture damage was found during the HWT test. Therefore, it can been concluded that polymers 1, 2 and 3 can improve the performance rut and moisture resistance of the asphalt mixture at a higher testing temperature.

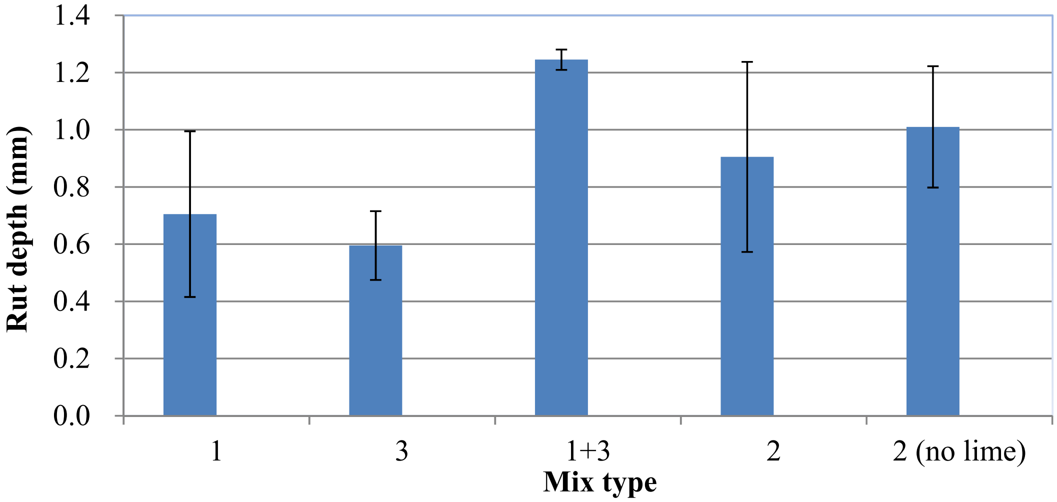


Figure 7-22 HWT rut depths of field samples (plant compacted) at 50°C

Summary

The following findings and conclusions were drawn based upon the laboratory investigation of various polymer mixtures obtained from an asphalt plant and laboratory-fabricated specimens:

(1) The optimum binder contents of various polymer-modified mixtures were very similar using Superpave mix design protocols and the same gradations, aggregate and RAP sources. The binder content, VMA, VFA, and dust/asphalt ratio values of all mixtures met the requirements of SCDOT's specifications. Therefore, it can be concluded that these various polymers did not affect the volumetric characteristics of the mixtures while satisfying the SCDOT's specifications.

(2) All of the polymers used for this study produced wet ITS values higher than 448 kPa, including polymer 2 without an ASA. Additionally, TSR values of all mixtures were greater than 80% regardless of polymer type, aggregate source, and ASA type. Consequently, these polymers and liquid ASAs could

be used to resist the moisture damage of a typical asphalt pavement regardless of aggregate source used in this study.

(3) The average rut depths of all mixtures were generally less than 3 mm regardless of polymer type, aggregate source, and ASA type. In addition, the mixtures containing polymer 2 both with and without lime generally had relatively weaker resistance to permanent deformation in this study.

(4) The dissipated energy results indicated that most of the polymers produced very similar results, and there were no obvious trends among the data.

(5) The polymer 3 mixture had the highest |E*| values while the polymer 1 (SBS) mixture had the lowest |E*| values . In addition, increased frequency resulted in an increase of |E*| value regardless of polymer type.

(6) The mixture containing polymer 1 (SBS) had the highest phase angle values at varying frequencies while the polymer 3 mixture had the lowest ones and thus had relatively lower viscous properties. In addition, all mixtures had similar trends at varying loading frequencies regardless of polymer type.

(7) Flow number results indicated that the mixture containing ASA a2 had the weakest resistance to permanent deformation. Additionally, APA rut depth results showed similar trends to the flow number test results in this research. However, all mixtures satisfied the APA rut depth criteria set forth by SCDOT specifications.

(8) HWT results showed that polymers 1, 2 and 3 can all improve the rut and moisture resistance of an asphalt mixture at a high performance temperature.

Chapter 8 – Summary, Findings, Conclusions and Recommendations

Summary

The laboratory phase of this research project was divided into three major sections. The first phase of the research included the evaluation of alternate binder modifiers (compared to SBS) with respect to rheological properties of these binders and engineering properties of the mixtures made with these binders. In these mixtures, recycled asphalt pavement (RAP) materials were utilized and their effects on engineering properties were investigated. The second part of the work included the evaluation of the performance of liquid ASAs in conventional SBS-modified asphalt mixtures as well as evaluating the compatibility of alternatively-modified binders with both hydrated lime and liquid ASAs. The mixtures were tested for moisture susceptibility, and other performance properties were evaluated both with and without RAP materials. The third phase of the project included the evaluation of the moisture susceptibility and other performance properties of asphalt mixtures made with natural sands. For this portion of the project, all of the natural sand mixtures to be tested included RAP, and the moisture susceptibility testing included hydrated lime and liquid ASAs.

Over 30 Superpave mix designs were conducted to accomplish the objectives of the research project. Several discussions and meetings were held with the interested parties and the suppliers of the polymers ensuring that many technical issues were addressed before initiating the activities of the project. Several hundreds of gyratory samples were made and tested for moisture susceptibility, APA, Hamburg, and AMPT testing. During the project, the AASHTO, ASTM or SCDOT testing procedures were followed for all of the tests conducted.

In addition to the laboratory portion of the project, a field test portion was conducted to investigate the performance of a plastomer compared to SBS and PG 64-22 in the field. The test section included 6 sections (over 2 miles), and the performance is still under evaluation. The field test section was paved in 2012.

Findings and Conclusions

Alternate Modified Binders

There were a total of 16 binder combinations including 2 base binders (PG 64-22). All of these binders were tested using various Superpave binder testing procedures. The findings and the conclusions regarding the binder testing are as follows:

1) The results indicated that, in general, binder A is more viscous than binder B.
2) In general, ground tire rubber (GTR) binders, either lab-produced (A4 or B4) or terminally-blended (TB), produced the highest viscosity values compared to all other binders.

3) The TB and lab-produced GTR binders produced approximately 25% and 20% higher viscosity values compared to SBS binders for binder sources A and B, respectively.
4) The results indicated that the SBS binder for source A produced viscosity values that were lower than the lab-produced GTR, TB GTR, elastomer and PPA+SBS binders.
5) The DSR results indicated that all of the binders, except for the lab-prepared GTR binder with source B, produced a PG 76-22 binder after the modifications with the various polymers.
6) Base binder source A had a higher DSR high failure temperature than base binder source B.
7) Terminally-blended (TB) GTR binder produced the highest DSR failure temperature compared to all other binders, regardless of the binder source.
8) In general, the phase angle of the GTR binders, regardless of the binder source, was the lowest among all binders. As expected, the highest phase angle value was the base binder (PG 64-22) for both sources.
9) The DSR failure temperatures of binder sources A and B after RTFO aging indicated that for binder source A, the binders containing polymer 1 (SBS) and polymer 4 produced the highest failure temperatures. However, for binder B, polymers 1 and 6 produced the highest failure temperatures. The statistical analyses indicated that there were statistical differences among the polymers.
10) The SBS-modified asphalt binders after RTFO aging generally had the highest recovery percentage from MSCR testing; thus, they exhibited better elastic-viscous properties in this study.
11) After long-term aging (PAV aging), all G*sin δ values of the various alternate modified binders were less than 5,000 kPa, and all m-values were greater than 3.00, except for the plastomer-modified binders using binder source B.

The moisture susceptibility of various mixtures containing various modified binders, two different aggregate sources, and three ASAs were investigated, and the conclusions are shown below:

1) The results indicate that the mixtures made with SBS containing hydrated lime produced the highest dry and wet ITS values. However, the mixtures containing the lab-prepared GTR and lime produced the highest TSR values.
2) The mixtures with plastomer modified binders and liquid ASAs 1 and 2 produced the second and third highest TSR values, respectively.
3) All of the TSR values, with exception of lab-prepared GTR modified binder with liquid ASA 1, were greater than 85%.
4) The mixtures made with the lab-prepared GTR and lime produced the second highest wet ITS value.
5) In most cases, the hydrated lime produced statistically-significant higher dry and wet ITS values than the samples containing the liquid ASAs. However, in most cases, the samples prepared with terminally-blended (TB) GTR and the

liquid ASAs produced statistically-significant higher TSR values compared to the samples containing TB GTR and hydrated lime.

6) In many cases, the mixtures made with liquid ASA 2 (a2) produced dry and wet ITS and TSR values that were greater than those of liquid ASA 1 (a1).

The rut resistance of various mixtures containing various modified binders, two different aggregate sources, and three ASAs were investigated using the Asphalt Pavement Analyzer (APA), and the conclusions are shown below:

1) All of the samples produced rut depth less than 3 mm, regardless of the aggregate source, modified binder and ASA type used for this phase of the research.
2) A clear trend could not be established to identify the effects of different variables used to test the samples.
3) The mixtures containing an elastomer produced the lowest rut depths compared to all other mixtures.
4) The samples made with aggregate source I and liquid ASAs produced rut depths that were higher than those made with hydrated lime. However, this was not the case for the aggregate source II.

The dynamic modulus and flow numbers of various mixtures containing various modified binders, two different aggregate sources, and three ASAs were investigated using the Asphalt Material Performance Tester (AMPT), and the conclusions are shown below:

1) The results, in general, indicate that with the exception of one case (aggregate II, lime and lab-blended GTR), all other flow numbers were greater than 50, which is the criteria set for a traffic loading of 3 million to less than 10 million ESALs.
2) The results also indicate that the flow numbers of samples made with aggregate source I, different ASAs, and SBS produced flow numbers that were greater than 190, which is the AASHTO minimum requirement for a traffic loading of 10 million to less than 30 million ESALs.
3) The samples made with aggregate source II, different ASAs, and SBS produced only one case of a flow number greater than 190 (liquid ASA 1, a1).
4) In general, there was no clear trend regarding the flow numbers. For example, samples made with aggregate source I, terminally-blended GTR and all ASAs produced flow numbers that were all greater than 190; however, none of the flow numbers for aggregate source II for those same mixtures produced any values greater than 110. In most cases, the flow numbers for aggregate source I were greater than those of aggregate source II.

The Hamburg Wheel Tracker (HWT) rut depths of various mixtures containing various modified binders, two different aggregate sources, and three ASAs were investigated using the HWT device, and the conclusions are shown below:

(1) For the Surface Type A mixtures made with various alternate modified binders, aggregate source, ASA type, and polymer type generally had no effect on the HWT values of various mixtures.
(2) The HWT rut depths of these mixtures were generally less than 3 mm, which satisfies the requirement of rut depths for all Surface Type A mixtures. The only mixture that exhibited a rut depth of more than 3 mm was the lab-blended GTR binder with aggregate source II and hydrated lime.

Natural Sand

The effects of the use of natural sand in several mixtures were investigated. Several binders, ASAs, and RAP percentages were used in this phase of the research work. The following is a summary of the findings:

1) The optimum binder contents of Surface Type B or C mixtures made with aggregates I and II were the same when using similar gradations, the same natural sand and RAP. In addition, the binder content, VMA, VFA, and dust/asphalt ratio values of these various mixtures met the requirements of SCDOT specifications. Therefore, it can be concluded that for the materials used, the effects of natural sand and aggregate source on the volumetric characteristics of Superpave mix design can be ignored.
2) The Surface Type B and C mixtures containing 20% natural sand all exhibited wet ITS values much higher than 448 kPa. Consequently, it can be concluded that hydrated lime and liquid ASAs can both be used to resist the moisture damage of asphalt mixtures with 20% natural sand regardless of aggregate source and mixture type for the materials tested in this study.
3) TSR values of all of the mixtures were greater than 80% regardless of mixture type, aggregate source, and ASA type. In most cases, the mixtures with hydrated lime had relatively higher TSR values than those with the liquid ASAs. However, based on the test results, other liquid ASAs also are recommended for use in Surface Type B and C mixtures containing 20% natural sand for the materials tested in this study.
4) The rut depths of the Surface Type B mixtures were generally less than 5 mm regardless of aggregate source and ASA type. However, the Surface Type C mixtures made with aggregate II generally had relatively weaker resistance to permanent deformation.
5) There were no significant differences found in fracture energy of dry samples when using various ASAs, aggregate sources, and surface mixture types, but these factors slightly affected the dissipated energy of wet samples.
6) There were some correlations between dissipated energy values and ITS values in this study; however, more research is recommended to obtain the ideal relationships in terms of aggregate source and surface type.
7) The increase of frequency resulted in an increase of dynamic modulus and a reduction of phase angle at the testing temperatures of 4°C and 20°C, but it resulted in an increase of phase angle at 45°C regardless of surface type,

aggregate source, and ASA type. The dynamic modulus values were comparable for the various mixtures. There were some differences in phase angles when tested at a higher temperature.

8) Flow numbers were slightly different in general when using different aggregate sources, ASAs or surface mixture types. In most cases, flow numbers were greater than 30, which satisfies the AASHTO requirement of flow number for mixtures with lower traffic levels.
9) For Surface Type B mixtures, all mixtures had HWT rut depths less than 5 mm regardless of aggregate source and ASA type. In addition, no moisture damage could be observed during the HWT test. Therefore, Surface Type B mixtures containing 20% natural sand were considered to adequately resist permanent deformation for the materials used in this study.
10) For Surface Type C mixtures, liquid ASA should be used cautiously because failures in moisture and permanent deformation were exhibited during HWT testing. However, there are currently no SCDOT requirements for rut resistance for Surface Type C mixtures.

Field Project – Laboratory Investigation

The following findings and conclusions were drawn based upon the laboratory investigation of various polymer-modified asphalt compacted samples obtained from an asphalt plant (the field test sections) and laboratory-fabricated specimens from materials obtained from the plant:

(1) The optimized binder contents of various polymer-modified mixtures were very similar using Superpave mix design protocols and using the same gradations, aggregate sources and RAP sources. The binder content, VMA, VFA, and dust/asphalt ratio values of all mixtures met the requirements of SCDOT's specifications. Therefore, it can be concluded that these various polymers did not affect the volumetric characteristics of the mixtures while satisfying SCDOT's specifications.

(2) All of the polymers used for this study produced wet ITS values higher than 448 kPa, including polymer 3 without an ASA. Consequently, these polymers and liquid ASAs can be used to resist the moisture damage of a typical asphalt pavement regardless of aggregate source used in this study. TSR values of all mixtures were greater than 80% regardless of polymer type, aggregate source, and ASA type.

(3) The average rut depths of all mixtures are generally less than 3 mm regardless of polymer type, aggregate source, and ASA type. In addition, the mixtures containing polymer 2 (both with and without lime) generally had relatively weaker resistance to permanent deformation in this study.

(4) The dissipated energy results indicated that most of the polymers produced very similar results, and there were no obvious trends among the data.

(5) The polymer 3 mixtures exhibited elastic properties that are better than other mixtures during the loading process due to the effects of the bond between this

binder and aggregate. In addition, increased frequency resulted in an increase of |E*| value regardless of polymer type.

(6) The mixture containing SBS had the highest phase angle values at varying frequencies, while the polymer 3 mixture showed the lowest ones, and thus has relatively lower viscous properties. In addition, all mixtures had similar trends at varying loading frequency regardless of polymer type.

(7) Flow number results indicated that the mixture containing ASA a2 might have the weakest resistance to permanent deformation. Additionally, APA rut depth results showed similar trends to the flow number test results in this research.

(8) The HWT rut depths of field samples were less than 2 mm, indicating that polymers 1, 2 or 3 can improve the rut and moisture resistance of an asphalt mixture at a high performance temperature.

It should be noted that in the field, special care should be taken to ensure proper dosage and compatibility of all additives including polymer content, lime, and liquid ASA to ensure that pavement performance is similar to lab results.

Recommendations

The following recommendations are made after the completion of this research:

1) Conduct other laboratory studies to evaluate the effects of other aggregate sources on the engineering properties of the mixtures.
2) Evaluate the cost effectiveness of all of the modified binders used in this study.
3) Construct several field test sections with various modified binders and evaluate the performance of these mixtures in-place.
4) Evaluate the effectiveness of other liquid ASAs with various aggregate sources using a laboratory experimental design that includes different binder sources.
5) Evaluate the effectiveness of the liquid ASAs in the field by constructing several test sections and monitoring the performance of these mixes.

Chapter 9 – Appendices

APPENDIX A – Laboratory Mix Designs: Alternate Modified Binders

Table A-1 Job Mix Formula of Surface A PG 76-22 (SBS) without RAP-Aggregate II

PLANT LOCATION: 0 MIX DESIGN LAB NO.: 0 JOB MIX NO.: **0**
TYPE MIX: Aggregate II DATE APPROVED:
CONTRACTOR: 0 DATE OF LAST REV.: NO. OF REVISIONS:
CONTROL METHOD: DATE VOID:

	Source of Aggregate	**Type of Aggregate**	**% Agg.**	**Ap. Sp. Gr.**
1	Aggregate II	57	10	2.63
2	Aggregate II	789	49	2.63
3	Aggregate II	MS	20	2.63
4	Aggregate II	RS	20	2.63
5	Hydrated Lime	Lime	1	
6	-4RAP	0	0	

SIEVE	**GRADATION**						**COMB.**		
	1	**2**	**3**	**4**	**5**	**6**	**GRAD.**	**TARGET**	**LIMITS**
1 1/2" / 37.5 mm	100	100	100	100	0	0	100	0	100 - 100
1" / 25.0 mm	100	100	100	100	0	0	100	0	100 - 100
3/4" / 19.0 mm	92.994	100	100	100	0	0	99	0	98 - 100
1/2" / 12.5 mm	31.753	98.139	100	100	0	0	92	0	90 - 100
3/8" / 9.5 mm	10.541	92.134	100	100	0	0	87	0	-7 - 7
#4 / 4.75 mm	1.2511	19.732	99.945	99.8866	0	0	51	0	-7 7
#8 / 2.36 mm	1.0863	2.0501	81.105	84.5641	0	0	35	0	-7 - 7
#30 / 0.60 mm	0.9886	1.3023	50.588	58.4153	0	0	23	0	-6 - 6
#100 / 0.150 mm	0.5489	0.7291	7.4396	20.5701	0	0	6.8	0.0	-4 4
#200 / 0.075 mm	0.3835	0.4976	2.3023	12.5267	0	0	4.05	0.00	-2 - 2
OPTIMUM BINDER CONTENT,%								4.7	4.30 - 5.10
% AIR VOIDS								3.73	2.80 - 5.20
% VMA								14.57	13.37 - 15.77

PERCENT BINDER	4.5	5.0	5.5	6.0
MAXIMUM SPECIFIC GRAVITY	2.486	2.468	2.450	2.432
BULK SPECIFIC GRAVITY	2.376	2.402	2.422	2.419
% AIR VOIDS IN TOTAL MIX	4.4	2.7	1.1	0.6
% V. M. A.	14.8	14.3	14.0	14.6
% VOIDS FILLED	70.0	81.3	91.8	96.2

EFFEC. SPECIFIC GRAVITY: 2.662 TSR(%): 115.6 WET TS:(kPa) 1503.3
TYPE AND GRADE OF BINDER: Surface A -SCDOT BINDER SPEC. GR.: 1.034
DESIGN DUST TO ASPHALT RATIO: 0.86
4.7 % Asphalt recommended with permissible variation of: 0.4 This mix is satisfactory and meets SCDOT Specs
specification for use in Aggregate II
REMARKS: Recommended: mixing temp - 325F; compaction temp - 305F; Sample size - 4705 g; ITS size - 3755 g
NOTE → #N/A

Table A-2 Job Mix Formula of Surface A PG 76-22 (Plastomer 2) without RAP-Aggregate II

PLANT LOCATION: 0	MIX DESIGN LAB NO.: 0	JOB MIX NO.: **0**
TYPE MIX: Aggregate II	DATE APPROVED:	
CONTRACTOR: 0	DATE OF LAST REV.:	NO. OF REVISIONS:
CONTROL METHOD:	DATE VOID:	

	Source of Aggregate	Type of Aggregate	% Agg.	Ap. Sp. Gr.
1	Aggregate II	57	10	2.63
2	Aggregate II	789	49	2.63
3	Aggregate II	MS	20	2.63
4	Aggregate II	RS	20	2.63
5	Hydrated Lime	Lime	1	
6	-4RAP	0	0	

SIEVE	GRADATION						COMB.		
	1	2	3	4	5	6	GRAD.	TARGET	LIMITS
1 1/2" / 37.5 mm	100	100	100	100	0	0	100	0	100 - 100
1" / 25.0 mm	100	100	100	100	0	0	100	0	100 - 100
3/4" / 19.0 mm	92.994	100	100	100	0	0	99	0	98 - 100
1/2" / 12.5 mm	31.753	98.139	100	100	0	0	92	0	90 - 100
3/8" / 9.5 mm	10.541	92.134	100	100	0	0	87	0	-7 - 7
#4 / 4.75 mm	1.2511	19.732	99.945	99.8866	0	0	51	0	-7 7
#8 / 2.36 mm	1.0863	2.0501	81.105	84.5641	0	0	35	0	-7 - 7
#30 / 0.60 mm	0.9886	1.3023	50.588	58.4153	0	0	23	0	-6 - 6
#100 / 0.150 mm	0.5489	0.7291	7.4396	20.5701	0	0	6.8	0.0	-4 4
#200 / 0.075 mm	0.3835	0.4976	2.3023	12.5267	0	0	4.05	0.00	-2 - 2

OPTIMUM BINDER CONTENT,%	4.8	4.40 - 5.20
% AIR VOIDS	3.69	2.80 - 5.20
% VMA	14.75	13.55 - 15.95

PERCENT BINDER	4.5	5.0	5.5	6.0
MAXIMUM SPECIFIC GRAVITY	2.484	2.466	2.449	2.431
BULK SPECIFIC GRAVITY	2.382	2.382	2.424	2.421
% AIR VOIDS IN TOTAL MIX	4.1	3.4	1.0	0.4
% V. M. A.	14.5	14.9	13.9	14.5
% VOIDS FILLED	71.6	77.2	92.9	97.2

EFFEC. SPECIFIC GRAVITY: 2.660 TSR(%): 96.4 WET TS:(kPa) 1193.2

TYPE AND GRADE OF BINDER: Surface A -SCDOT BINDER SPEC. GR.: 1.034

DESIGN DUST TO ASPHALT RATIO: 0.84

4.8 % Asphalt recommended with permissible variation of: 0.4 This mix is satisfactory and meets SCDOT Specs

specification for use in Aggregate II

REMARKS: Recommended: mixing temp - 325F; compaction temp - 305F; Sample size - 4706 g; ITS size - 3775 g

NOTE → #N/A

Table A-3 Job Mix Formula of Surface A PG 76-22 (PPA+SBS) without RAP- Aggregate II

PLANT LOCATION:	0	MIX DESIGN LAB NO.:	0	JOB MIX NO.:	**0**
TYPE MIX:	Aggregate II	DATE APPROVED:			
CONTRACTOR:	0	DATE OF LAST REV.:		NO. OF REVISIONS:	
CONTROL METHOD:		DATE VOID:			

	Source of Aggregate	**Type of Aggregate**	**% Agg.**	**Ap. Sp. Gr.**
1	Aggregate II	57	10	2.63
2	Aggregate II	789	49	2.63
3	Aggregate II	MS	20	2.63
4	Aggregate II	RS	20	2.63
5	Hydrated Lime	Lime	1	
6	-4RAP	0	0	

SIEVE			**GRADATION**						**COMB.**				
			1	**2**	**3**	**4**	**5**	**6**	**GRAD.**	**TARGET**	**LIMITS**		
1 1/2"	/	37.5 mm	100	100	100	100	0	0	100	0	100	-	100
1"	/	25.0 mm	100	100	100	100	0	0	100	0	100	-	100
3/4"	/	19.0 mm	92.994	100	100	100	0	0	99	0	98	-	100
1/2"	/	12.5 mm	31.753	98.139	100	100	0	0	92	0	90	-	100
3/8"	/	9.5 mm	10.541	92.134	100	100	0	0	87	0	-7	-	7
#4	/	4.75 mm	1.2511	19.732	99.945	99.8866	0	0	51	0	-7		7
#8	/	2.36 mm	1.0863	2.0501	81.105	84.5641	0	0	35	0	-7	-	7
#30	/	0.60 mm	0.9886	1.3023	50.588	58.4153	0	0	23	0	-6	-	6
#100	/	0.150 mm	0.5489	0.7291	7.4396	20.5701	0	0	6.8	0.0	-4		4
#200	/	0.075 mm	0.3835	0.4976	2.3023	12.5267	0	0	4.05	0.00	-2	-	2
OPTIMUM BINDER CONTENT,%										4.7	4.30	-	5.10
% AIR VOIDS										3.62	2.80	-	5.20
% VMA										14.52	13.32	-	15.72

PERCENT BINDER	4.5	5.0	5.5	6.0
MAXIMUM SPECIFIC GRAVITY	2.496	2.478	2.460	2.442
BULK SPECIFIC GRAVITY	2.398	2.400	2.427	2.426
% AIR VOIDS IN TOTAL MIX	3.9	3.1	1.3	0.7
% V. M. A.	14.4	14.8	14.2	14.7
% VOIDS FILLED	72.6	78.7	90.8	95.5

EFFEC. SPECIFIC GRAVITY:	2.674	TSR(%):	#VALUE!	WET TS:(kPa)	#VALUE!
TYPE AND GRADE OF BINDER:	Surface A PPA+SBS	BINDER SPEC. GR.:	1.034		
DESIGN DUST TO ASPHALT RATIO:	0.86				
4.7	% Asphalt recommended with permissible variation of:	0.4	This mix is satisfactory and meets SCDOT Specs		
specification for use in	Aggregate II				
REMARKS:					
			NOTE →	#N/A	

Table A-4 Job Mix Formula of Surface A PG 76-22 (Terminal-Blended GTR) without RAP- Aggregate II

PLANT LOCATION: 0	MIX DESIGN LAB NO.: 0	JOB MIX NO.: **0**
TYPE MIX: Aggregate II	DATE APPROVED:	
CONTRACTOR: 0	DATE OF LAST REV.:	NO. OF REVISIONS:
CONTROL METHOD:	DATE VOID:	

	Source of Aggregate	**Type of Aggregate**	**% Agg.**	**Ap. Sp. Gr.**
1	Aggregate II	57	10	2.63
2	Aggregate II	789	49	2.63
3	Aggregate II	MS	20	2.63
4	Aggregate II	RS	20	2.63
5	Hydrated Lime	Lime	1	
6	-4RAP	0	0	

SIEVE		**GRADATION**						**COMB.**		
		1	**2**	**3**	**4**	**5**	**6**	**GRAD.**	**TARGET**	**LIMITS**
1 1/2"	/ 37.5 mm	100	100	100	100	0	0	100	100	100 - 100
1"	/ 25.0 mm	100	100	100	100	0	0	100	100	100 - 100
3/4"	/ 19.0 mm	92.994	100	100	100	0	0	99	99	98 - 100
1/2"	/ 12.5 mm	31.753	98.139	100	100	0	0	92	92	90 - 100
3/8"	/ 9.5 mm	10.541	92.134	100	100	0	0	87	87	80 - 94
#4	/ 4.75 mm	1.2511	19.732	99.945	99.8866	0	0	51	51	44 58
#8	/ 2.36 mm	1.0863	2.0501	81.105	84.5641	0	0	35	35	28 - 42
#30	/ 0.60 mm	0.9886	1.3023	50.588	58.4153	0	0	23	23	17 - 30
#100	/ 0.150 mm	0.5489	0.7291	7.4396	20.5701	0	0	6.8	6.5	2 11
#200	/ 0.075 mm	0.3835	0.4976	2.3023	12.5267	0	0	4.05	4.00	2 - 6

OPTIMUM BINDER CONTENT,%	4.9	4.50 - 5.30
% AIR VOIDS	3.90	2.80 - 5.20
% VMA	15.21	14.01 - 16.41

PERCENT BINDER	4.5	5.0	5.5	6.0
MAXIMUM SPECIFIC GRAVITY	2.500	2.481	2.463	2.445
BULK SPECIFIC GRAVITY	2.371	2.392	2.405	2.413
% AIR VOIDS IN TOTAL MIX	5.2	3.6	2.3	1.3
% V. M. A.	15.5	15.1	15.1	15.3
% VOIDS FILLED	66.8	76.4	84.5	91.4

EFFEC. SPECIFIC GRAVITY: 2.678	TSR(%): #VALUE!	WET TS:(kPa) #VALUE!
TYPE AND GRADE OF BINDER: Surface A -TB-GTR	BINDER SPEC. GR.: 1.034	
DESIGN DUST TO ASPHALT RATIO: 0.83		
4.9 % Asphalt recommended with permissible variation of: 0.4	This mix is satisfactory and meets SCDOT Specs	
specification for use in Aggregate II		
REMARKS:		
	NOTE → #N/A	

Table A-5 Job Mix Formula of Surface A PG 76-22 (Lab-Blended GTR) without RAP-Aggregate II

PLANT LOCATION: 0 MIX DESIGN LAB NO.: 0 JOB MIX NO.: **0**

TYPE MIX: Aggregate II DATE APPROVED:

CONTRACTOR: 0 DATE OF LAST REV.: NO. OF REVISIONS:

CONTROL METHOD: DATE VOID:

	Source of Aggregate	**Type of Aggregate**	**% Agg.**	**Ap. Sp. Gr.**
1	Aggregate II	57	10	2.63
2	Aggregate II	789	49	2.63
3	Aggregate II	MS	20	2.63
4	Aggregate II	RS	20	2.63
5	Hydrated Lime	Lime	1	
6	-4RAP	0	0	

SIEVE	**GRADATION**						**COMB.**		
	1	**2**	**3**	**4**	**5**	**6**	**GRAD.**	**TARGET**	**LIMITS**
1 1/2" / 37.5 mm	100	100	100	100	0	0	100	100	100 - 100
1" / 25.0 mm	100	100	100	100	0	0	100	100	100 - 100
3/4" / 19.0 mm	92.994	100	100	100	0	0	99	99	98 - 100
1/2" / 12.5 mm	31.753	98.139	100	100	0	0	92	92	90 - 100
3/8" / 9.5 mm	10.541	92.134	100	100	0	0	87	87	80 - 94
#4 / 4.75 mm	1.2511	19.732	99.945	99.8866	0	0	51	51	44 58
#8 / 2.36 mm	1.0863	2.0501	81.105	84.5641	0	0	35	35	28 - 42
#30 / 0.60 mm	0.9886	1.3023	50.588	58.4153	0	0	23	23	17 - 30
#100 / 0.150 mm	0.5489	0.7291	7.4396	20.5701	0	0	6.8	6.5	2 11
#200 / 0.075 mm	0.3835	0.4976	2.3023	12.5267	0	0	4.05	4.00	2 - 6

OPTIMUM BINDER CONTENT,%	4.9	4.50 - 5.30
% AIR VOIDS	3.51	2.80 - 5.20
% VMA	14.89	13.69 - 16.09

PERCENT BINDER	4.5	5.0	5.5	6.0
MAXIMUM SPECIFIC GRAVITY	2.505	2.486	2.468	2.450
BULK SPECIFIC GRAVITY	2.387	2.406	2.429	2.427
% AIR VOIDS IN TOTAL MIX	4.7	3.2	1.6	0.9
% V. M. A.	15.1	14.8	14.5	15.0
% VOIDS FILLED	68.9	78.4	89.1	93.9

EFFEC. SPECIFIC GRAVITY: 2.685 TSR(%): #VALUE! WET TS:(kPa) #VALUE!

TYPE AND GRADE OF BINDER: Surface A -Nustar 64-22+10%rubber BINDER SPEC. GR.: 1.034

DESIGN DUST TO ASPHALT RATIO: 0.83

4.9 % Asphalt recommended with permissible variation of: 0.4 This mix is satisfactory and meets SCDOT Specs

specification for use in Aggregate II

REMARKS:

Table A-6 Job Mix Formula of Surface A PG 76-22 (Elastomer) without RAP- Aggregate II

PLANT LOCATION: 0	MIX DESIGN LAB NO.: 0	JOB MIX NO.: **0**
TYPE MIX: Aggregate II	DATE APPROVED:	
CONTRACTOR: 0	DATE OF LAST REV.:	NO. OF REVISIONS:
CONTROL METHOD:	DATE VOID:	

	Source of Aggregate	**Type of Aggregate**	**% Agg.**	**Ap. Sp. Gr.**
1	Aggregate II	57	10	2.63
2	Aggregate II	789	49	2.63
3	Aggregate II	MS	20	2.63
4	Aggregate II	RS	20	2.63
5	Hydrated Lime	Lime	1	
6	-4RAP	0	0	

SIEVE	**GRADATION**						**COMB.**		
	1	**2**	**3**	**4**	**5**	**6**	**GRAD.**	**TARGET**	**LIMITS**
1 1/2" / 37.5 mm	100	100	100	100	0	0	100	0	100 - 100
1" / 25.0 mm	100	100	100	100	0	0	100	0	100 - 100
3/4" / 19.0 mm	92.994	100	100	100	0	0	99	0	98 - 100
1/2" / 12.5 mm	31.753	98.139	100	100	0	0	92	0	90 - 100
3/8" / 9.5 mm	10.541	92.134	100	100	0	0	87	0	-7 - 7
#4 / 4.75 mm	1.2511	19.732	99.945	99.8866	0	0	51	0	-7 7
#8 / 2.36 mm	1.0863	2.0501	81.105	84.5641	0	0	35	0	-7 - 7
#30 / 0.60 mm	0.9886	1.3023	50.588	58.4153	0	0	23	0	-6 - 6
#100 / 0.150 mm	0.5489	0.7291	7.4396	20.5701	0	0	6.8	0.0	-4 4
#200 / 0.075 mm	0.3835	0.4976	2.3023	12.5267	0	0	4.05	0.00	-2 - 2

OPTIMUM BINDER CONTENT,%	5.1	4.70 - 5.50
% AIR VOIDS	3.94	2.80 - 5.20
% VMA	15.55	14.35 - 16.75

PERCENT BINDER	4.0	4.5	5.0	5.5
MAXIMUM SPECIFIC GRAVITY	2.508	2.490	2.472	2.454
BULK SPECIFIC GRAVITY	2.286	2.303	2.351	2.363
% AIR VOIDS IN TOTAL MIX	8.8	7.5	4.9	3.7
% V. M. A.	17.7	17.5	16.3	16.2
% VOIDS FILLED	50.0	57.2	70.0	77.4

EFFEC. SPECIFIC GRAVITY: 2.645 TSR(%): #VALUE! WET TS:(kPa) #VALUE!

TYPE AND GRADE OF BINDER: Surface A -Nustar Elastomer BINDER SPEC. GR.: 1.034

DESIGN DUST TO ASPHALT RATIO: 0.79

5.1 % Asphalt recommended with permissible variation of: 0.4 This mix is satisfactory and meets SCDOT Specs

specification for use in Aggregate II

REMARKS:

NOTE → #N/A

Table A-7 Job Mix Formula of Surface A PG 76-22 (SBS) +RAP-Aggregate II

PLANT LOCATION: 0 MIX DESIGN LAB NO.: 0 JOB MIX NO.: **0**

TYPE MIX: Aggregate II DATE APPROVED:

CONTRACTOR: 0 DATE OF LAST REV.: NO. OF REVISIONS:

CONTROL METHOD: DATE VOID:

	Source of Aggregate	**Type of Aggregate**	**% Agg.**	**Ap. Sp. Gr.**
1	Aggregate II	57	10	2.63
2	Aggregate II	789	49	2.63
3	Aggregate II	MS	12	2.63
4	Aggregate II	RS	17	2.63
5	Hydrated Lime	Lime	0	
6	-4RAP	-4RAP	12	

SIEVE	**GRADATION**						**COMB.**		
	1	**2**	**3**	**4**	**5**	**6**	**GRAD.**	**TARGET**	**LIMITS**
1 1/2" / 37.5 mm	100	100	100	100	100	0	100	0	100 - 100
1" / 25.0 mm	100	100	100	100	100	0	100	0	100 - 100
3/4" / 19.0 mm	92.994	100	100	100	100	0	99	0	98 - 100
1/2" / 12.5 mm	31.753	98.139	100	100	100	0	92	0	90 - 100
3/8" / 9.5 mm	10.541	92.134	100	100	100	0	87	0	-7 - 7
#4 / 4.75 mm	1.2511	19.732	99.945	99.8866	96.7016	0	50	0	-7 7
#8 / 2.36 mm	1.0863	2.0501	81.105	84.5641	78.8199	0	35	0	-7 - 7
#30 / 0.60 mm	0.9886	1.3023	50.588	58.4153	51.0181	0	23	0	-6 - 6
#100 / 0.150 mm	0.5489	0.7291	7.4396	20.5701	12.218	0	6.3	0.0	-4 4
#200 / 0.075 mm	0.3835	0.4976	2.3023	12.5267	6.72414	0	3.49	0.00	-2 - 2

OPTIMUM BINDER CONTENT,%	4.8	4.40 - 5.20
% AIR VOIDS	3.50	2.80 - 5.20
% VMA	14.57	13.37 - 15.77

PERCENT BINDER	4.5	5.0	5.5	6.0
MAXIMUM SPECIFIC GRAVITY	2.484	2.466	2.448	2.430
BULK SPECIFIC GRAVITY	2.378	2.392	2.408	2.410
% AIR VOIDS IN TOTAL MIX	4.3	3.0	1.6	0.8
% V. M. A.	14.6	14.5	14.4	14.8
% VOIDS FILLED	70.8	79.7	88.8	94.4

EFFEC. SPECIFIC GRAVITY: 2.659 TSR(%): 92.6 WET TS:(kPa) 1046.5

TYPE AND GRADE OF BINDER: Surface A -SCDOT BINDER SPEC. GR.: 1.034

DESIGN DUST TO ASPHALT RATIO: 0.73

4.8 % Asphalt recommended with permissible variation of: 0.4 This mix is satisfactory and meets SCDOT Specs

specification for use in Aggregate II

REMARKS: Recommended: mixing temp - 325F; compaction temp - 305F; Sample size - 4706 g; ITS size - 3775 g

NOTE → #N/A

Table A-8 Job Mix Formula of Surface A PG 76-22 (Plastomer 2) +RAP-Aggregate II

PLANT LOCATION: 0 MIX DESIGN LAB NO.: 0 JOB MIX NO.: **0**
TYPE MIX: Aggregate II DATE APPROVED:
CONTRACTOR: 0 DATE OF LAST REV.: NO. OF REVISIONS:
CONTROL METHOD: DATE VOID:

	Source of Aggregate	**Type of Aggregate**	**% Agg.**	**Ap. Sp. Gr.**
1	Aggregate II	57	10	2.63
2	Aggregate II	789	49	2.63
3	Aggregate II	MS	12	2.63
4	Aggregate II	RS	17	2.63
5	Hydrated Lime	Lime	0	
6	-4RAP	-4RAP	12	

SIEVE	**GRADATION**						**COMB.**		
	1	**2**	**3**	**4**	**5**	**6**	**GRAD.**	**TARGET**	**LIMITS**
1 1/2" / 37.5 mm	100	100	100	100	100	0	100	0	100 - 100
1" / 25.0 mm	100	100	100	100	100	0	100	0	100 - 100
3/4" / 19.0 mm	92.994	100	100	100	100	0	99	0	98 - 100
1/2" / 12.5 mm	31.753	98.139	100	100	100	0	92	0	90 - 100
3/8" / 9.5 mm	10.541	92.134	100	100	100	0	87	0	-7 - 7
#4 / 4.75 mm	1.2511	19.732	99.945	99.8866	96.7016	0	50	0	-7 7
#8 / 2.36 mm	1.0863	2.0501	81.105	84.5641	78.8199	0	35	0	-7 - 7
#30 / 0.60 mm	0.9886	1.3023	50.588	58.4153	51.0181	0	23	0	-6 - 6
#100 / 0.150 mm	0.5489	0.7291	7.4396	20.5701	12.218	0	6.3	0.0	-4 4
#200 / 0.075 mm	0.3835	0.4976	2.3023	12.5267	6.72414	0	3.49	0.00	-2 - 2

OPTIMUM BINDER CONTENT,%	4.8	4.40 - 5.20
% AIR VOIDS	3.73	2.80 - 5.20
% VMA	14.79	13.59 - 15.99

PERCENT BINDER	4.5	5.0	5.5	6.0
MAXIMUM SPECIFIC GRAVITY	2.484	2.466	2.448	2.430
BULK SPECIFIC GRAVITY	2.367	2.390	2.403	2.402
% AIR VOIDS IN TOTAL MIX	4.7	3.1	1.9	1.2
% V. M. A.	15.0	14.6	14.6	15.1
% VOIDS FILLED	68.7	79.0	87.4	92.1

EFFEC. SPECIFIC GRAVITY: 2.660 TSR(%): 96.3 WET TS:(kPa) 1134.5
TYPE AND GRADE OF BINDER: Surface A -SCDOT BINDER SPEC. GR.: 1.034
DESIGN DUST TO ASPHALT RATIO: 0.73
4.8 % Asphalt recommended with permissible variation of: 0.4 This mix is satisfactory and meets SCDOT Specs
specification for use in Aggregate II
REMARKS: Recommended: mixing temp - 325F; compaction temp - 305F; Sample size - 4706 g; ITS size - 3775g
NOTE → #N/A

Table A-9 Job Mix Formula of Surface A PG 76-22 (PPA+SBS) +RAP-Aggregate II

PLANT LOCATION: 0 MIX DESIGN LAB NO.: 0 JOB MIX NO.: **0**

TYPE MIX: Aggregate II DATE APPROVED:

CONTRACTOR: 0 DATE OF LAST REV.: NO. OF REVISIONS:

CONTROL METHOD: DATE VOID:

	Source of Aggregate	**Type of Aggregate**	**% Agg.**	**Ap. Sp. Gr.**
1	Aggregate II	57	10	2.63
2	Aggregate II	789	49	2.63
3	Aggregate II	MS	12	2.63
4	Aggregate II	RS	17	2.63
5	Hydrated Lime	Lime	0	
6	-4RAP	-4RAP	12	

SIEVE	**GRADATION**						**COMB.**				
	1	**2**	**3**	**4**	**5**	**6**	**GRAD.**	**TARGET**	**LIMITS**		
1 1/2" / 37.5 mm	100	100	100	100	100	0	100	0	100	-	100
1" / 25.0 mm	100	100	100	100	100	0	100	0	100	-	100
3/4" / 19.0 mm	92.994	100	100	100	100	0	99	0	98	-	100
1/2" / 12.5 mm	31.753	98.139	100	100	100	0	92	0	90	-	100
3/8" / 9.5 mm	10.541	92.134	100	100	100	0	87	0	-7	-	7
#4 / 4.75 mm	1.2511	19.732	99.945	99.8866	96.7016	0	50	0	-7		7
#8 / 2.36 mm	1.0863	2.0501	81.105	84.5641	78.8199	0	35	0	-7	-	7
#30 / 0.60 mm	0.9886	1.3023	50.588	58.4153	51.0181	0	23	0	-6	-	6
#100 / 0.150 mm	0.5489	0.7291	7.4396	20.5701	12.218	0	6.3	0.0	-4		4
#200 / 0.075 mm	0.3835	0.4976	2.3023	12.5267	6.72414	0	3.49	0.00	-2	-	2

OPTIMUM BINDER CONTENT,%	4.8	4.40 - 5.20
% AIR VOIDS	4.25	2.80 - 5.20
% VMA	15.28	14.08 - 16.48

PERCENT BINDER	4.5	5.0	5.5	6.0
MAXIMUM SPECIFIC GRAVITY	2.493	2.475	2.457	2.439
BULK SPECIFIC GRAVITY	2.366	2.383	2.408	2.422
% AIR VOIDS IN TOTAL MIX	5.1	3.7	2.0	0.7
% V. M. A.	15.4	15.2	14.8	14.7
% VOIDS FILLED	67.0	75.7	86.7	95.3

EFFEC. SPECIFIC GRAVITY: 2.670 TSR(%): #VALUE! WET TS:(kPa) #VALUE!

TYPE AND GRADE OF BINDER: Surface A -SBS+PPA BINDER SPEC. GR.: 1.034

DESIGN DUST TO ASPHALT RATIO: 0.73

4.8 % Asphalt recommended with permissible variation of: 0.4 This mix is satisfactory and meets SCDOT Specs

specification for use in Aggregate II

REMARKS:

NOTE → #N/A

Table A-10 Job Mix Formula of Surface A PG 76-22 (Terminal-Blended GTR) +RAP-Aggregate II

PLANT LOCATION: 0	MIX DESIGN LAB NO.: 0	JOB MIX NO.: **0**
TYPE MIX: Aggregate II	DATE APPROVED:	
CONTRACTOR: 0	DATE OF LAST REV.:	NO. OF REVISIONS:
CONTROL METHOD:	DATE VOID:	

	Source of Aggregate	**Type of Aggregate**	**% Agg.**	**Ap. Sp. Gr.**
1	Aggregate II	57	10	2.63
2	Aggregate II	789	49	2.63
3	Aggregate II	MS	12	2.63
4	Aggregate II	RS	16	2.63
5	-200 fine	-200 fine	1	
6	-4RAP	-4RAP	12	

SIEVE	**GRADATION**						**COMB.**		
	1	**2**	**3**	**4**	**5**	**6**	**GRAD.**	**TARGET**	**LIMITS**
1 1/2" / 37.5 mm	100	100	100	100	100	0	100	100	100 - 100
1" / 25.0 mm	100	100	100	100	100	0	100	100	100 - 100
3/4" / 19.0 mm	92.994	100	100	100	100	0	99	99	98 - 100
1/2" / 12.5 mm	31.753	98.139	100	100	100	0	92	92	90 - 100
3/8" / 9.5 mm	10.541	92.134	100	100	100	0	87	87	80 - 94
#4 / 4.75 mm	1.2511	19.732	99.945	99.8866	96.7016	0	50	50	43 57
#8 / 2.36 mm	1.0863	2.0501	81.105	84.5641	78.8199	0	35	35	28 - 42
#30 / 0.60 mm	0.9886	1.3023	50.588	58.4153	51.0181	0	23	23	17 - 29
#100 / 0.150 mm	0.5489	0.7291	7.4396	20.5701	12.218	0	6.9	6.5	2 11
#200 / 0.075 mm	0.3835	0.4976	2.3023	12.5267	6.72414	0	4.17	4.00	2 - 6

OPTIMUM BINDER CONTENT,%	5.3	4.90 - 5.70
% AIR VOIDS	3.97	2.80 - 5.20
% VMA	16.12	14.92 - 17.32

PERCENT BINDER	4.5	5.0	5.5	6.0
MAXIMUM SPECIFIC GRAVITY	2.498	2.480	2.461	2.444
BULK SPECIFIC GRAVITY	2.329	2.368	2.373	2.413
% AIR VOIDS IN TOTAL MIX	6.8	4.5	3.6	1.2
% V. M. A.	16.9	16.0	16.2	15.2
% VOIDS FILLED	60.0	71.7	77.8	91.8

EFFEC. SPECIFIC GRAVITY: 2.677 TSR(%): #VALUE! WET TS:(kPa) #VALUE!

TYPE AND GRADE OF BINDER: Surface A -TB-GTR BINDER SPEC. GR.: 1.034

DESIGN DUST TO ASPHALT RATIO: 0.79

5.3 % Asphalt recommended with permissible variation of: 0.4 This mix is satisfactory and meets SCDOT Specs

specification for use in Aggregate II

REMARKS:

NOTE → #N/A

Table A-11 Job Mix Formula of Surface A PG 76-22 (Lab-Blended GTR) +RAP-Aggregate II

PLANT LOCATION: 0 MIX DESIGN LAB NO.: 0 JOB MIX NO.: **0**
TYPE MIX: Aggregate II DATE APPROVED:
CONTRACTOR: 0 DATE OF LAST REV.: NO. OF REVISIONS:
CONTROL METHOD: DATE VOID:

	Source of Aggregate	**Type of Aggregate**	**% Agg.**	**Ap. Sp. Gr.**
1	Aggregate II	57	10	2.63
2	Aggregate II	789	49	2.63
3	Aggregate II	MS	12	2.63
4	Aggregate II	RS	17	2.63
5	Hydrated Lime	Lime	0	
6	-4RAP	-4RAP	12	

SIEVE	**GRADATION**						**COMB.**		
	1	**2**	**3**	**4**	**5**	**6**	**GRAD.**	**TARGET**	**LIMITS**
1 1/2" / 37.5 mm	100	100	100	100	100	0	100	0	100 - 100
1" / 25.0 mm	100	100	100	100	100	0	100	0	100 - 100
3/4" / 19.0 mm	92.994	100	100	100	100	0	99	0	98 - 100
1/2" / 12.5 mm	31.753	98.139	100	100	100	0	92	0	90 - 100
3/8" / 9.5 mm	10.541	92.134	100	100	100	0	87	0	-7 - 7
#4 / 4.75 mm	1.2511	19.732	99.945	99.8866	96.7016	0	50	0	-7 7
#8 / 2.36 mm	1.0863	2.0501	81.105	84.5641	78.8199	0	35	0	-7 - 7
#30 / 0.60 mm	0.9886	1.3023	50.588	58.4153	51.0181	0	23	0	-6 - 6
#100 / 0.150 mm	0.5489	0.7291	7.4396	20.5701	12.218	0	6.3	0.0	-4 4
#200 / 0.075 mm	0.3835	0.4976	2.3023	12.5267	6.72414	0	3.49	0.00	-2 - 2

OPTIMUM BINDER CONTENT,%	5.4	5.00 - 5.80
% AIR VOIDS	4.40	2.80 - 5.20
% VMA	16.71	15.51 - 17.91

PERCENT BINDER	4.5	5.0	5.5	6.0
MAXIMUM SPECIFIC GRAVITY	2.498	2.480	2.462	2.444
BULK SPECIFIC GRAVITY	2.336	2.363	2.355	2.379
% AIR VOIDS IN TOTAL MIX	6.5	4.7	4.3	2.7
% V. M. A.	16.6	16.1	16.9	16.5
% VOIDS FILLED	61.1	70.7	74.3	83.9

EFFEC. SPECIFIC GRAVITY: 2.677 TSR(%): #VALUE! WET TS:(kPa) #VALUE!
TYPE AND GRADE OF BINDER: Surface A -Nustar 64-22+10%rubber BINDER SPEC. GR.: 1.034
DESIGN DUST TO ASPHALT RATIO: 0.65
5.4 % Asphalt recommended with permissible variation of: 0.4 This mix is satisfactory and meets SCDOT Specs
specification for use in Aggregate II
REMARKS:
NOTE → #N/A

Table A-12 Job Mix Formula of Surface A PG 76-22 (Elastomer) +RAP-Aggregate II

PLANT LOCATION: 0　MIX DESIGN LAB NO.: 0　JOB MIX NO.: **0**
TYPE MIX: Aggregate II　DATE APPROVED:
CONTRACTOR: 0　DATE OF LAST REV.:　NO. OF REVISIONS:
CONTROL METHOD:　DATE VOID:

	Source of Aggregate	**Type of Aggregate**	**% Agg.**	**Ap. Sp. Gr.**
1	Aggregate II	57	10	2.63
2	Aggregate II	789	49	2.63
3	Aggregate II	MS	12	2.63
4	Aggregate II	RS	17	2.63
5	Hydrated Lime	Lime	0	
6	-4RAP	-4RAP	12	

SIEVE	**GRADATION**						**COMB.**		
	1	**2**	**3**	**4**	**5**	**6**	**GRAD.**	**TARGET**	**LIMITS**
1 1/2" / 37.5 mm	100	100	100	100	100	0	100	0	100 - 100
1" / 25.0 mm	100	100	100	100	100	0	100	0	100 - 100
3/4" / 19.0 mm	92.994	100	100	100	100	0	99	0	98 - 100
1/2" / 12.5 mm	31.753	98.139	100	100	100	0	92	0	90 - 100
3/8" / 9.5 mm	10.541	92.134	100	100	100	0	87	0	-7 - 7
#4 / 4.75 mm	1.2511	19.732	99.945	99.8866	96.7016	0	50	0	-7 7
#8 / 2.36 mm	1.0863	2.0501	81.105	84.5641	78.8199	0	35	0	-7 - 7
#30 / 0.60 mm	0.9886	1.3023	50.588	58.4153	51.0181	0	23	0	-6 - 6
#100 / 0.150 mm	0.5489	0.7291	7.4396	20.5701	12.218	0	6.3	0.0	-4 4
#200 / 0.075 mm	0.3835	0.4976	2.3023	12.5267	6.72414	0	3.49	0.00	-2 - 2

OPTIMUM BINDER CONTENT,%	5.1	4.70 - 5.50
% AIR VOIDS	4.16	2.80 - 5.20
% VMA	15.81	14.61 - 17.01

PERCENT BINDER	4.0	4.5	5.0	5.5
MAXIMUM SPECIFIC GRAVITY	2.505	2.487	2.468	2.451
BULK SPECIFIC GRAVITY	2.324	2.344	2.357	2.383
% AIR VOIDS IN TOTAL MIX	7.2	5.7	4.5	2.8
% V. M. A.	16.2	15.9	15.9	15.4
% VOIDS FILLED	55.5	64.1	71.7	82.2

EFFEC. SPECIFIC GRAVITY: 2.663　TSR(%): #VALUE!　WET TS:(kPa) #VALUE!
TYPE AND GRADE OF BINDER: Surface A -Nustar64-22+Elastomer　BINDER SPEC. GR.: 1.034
DESIGN DUST TO ASPHALT RATIO: 0.69
5.1 % Asphalt recommended with permissible variation of: 0.4 This mix is satisfactory and meets SCDOT Specs
specification for use in Aggregate II
REMARKS: Recommended: mixing temp - 325F; compaction temp - 305F; Sample size - 4706 g; ITS size - 3775 g
NOTE → #N/A

Table A-13 Job Mix Formula of Surface A PG 76-22 (SBS) without RAP- Aggregate I

PLANT LOCATION: 0	MIX DESIGN LAB NO.: 0	JOB MIX NO.: **0**
TYPE MIX: Aggregate I	DATE APPROVED:	
CONTRACTOR: 0	DATE OF LAST REV.:	NO. OF REVISIONS:
CONTROL METHOD:	DATE VOID:	

	Source of Aggregate	**Type of Aggregate**	**% Agg.**	**Ap. Sp. Gr.**
1	Aggregate I	0	0	2.63
2	Aggregate I	789	56	2.63
3	Aggregate I	MS	15	2.63
4	Aggregate I	RS	28	2.63
5	Hydrated Lime	Lime	1	
6	-4RAP	0	0	

SIEVE			**GRADATION**					**COMB.**		
		1	**2**	**3**	**4**	**5**	**6**	**GRAD.**	**TARGET**	**LIMITS**
1 1/2"	37.5 mm	0	100	100	100	100	0	100	100	100 - 100
1"	25.0 mm	0	100	100	100	100	0	100	100	100 - 100
3/4"	19.0 mm	0	100	100	100	100	0	100	100	98 - 100
1/2"	12.5 mm	0	98	100	100	100	0	99	99	90 - 100
3/8"	9.5 mm	0	78	100	100	100	0	87	87	80 - 94
#4	4.75 mm	0	25	99	99	94	0	57	57	50 64
#8	2.36 mm	0	6	85	82	76	0	40	40	33 - 47
#30	0.60 mm	0	2	37	40	41	0	19	19	13 - 25
#100	0.150 mm	0	1	10	16	15	0	7.3	7.0	3 11
#200	0.075 mm	0	0.7	3	10	9	0	4.44	4.00	2 - 6

OPTIMUM BINDER CONTENT,%	4.8	4.40 - 5.20
% AIR VOIDS	3.46	2.80 - 5.20
% VMA	14.47	13.27 - 15.67

PERCENT BINDER	4.5	5.0	5.5	6.0
MAXIMUM SPECIFIC GRAVITY	2.467	2.449	2.432	2.411
BULK SPECIFIC GRAVITY	2.359	2.379	2.398	2.395
% AIR VOIDS IN TOTAL MIX	4.4	2.9	1.4	0.7
% V. M. A.	14.6	14.4	14.2	14.6
% VOIDS FILLED	70.1	80.2	90.1	95.4

EFFEC. SPECIFIC GRAVITY: 2.639 TSR(%): 111.9 WET TS:(kPa) 1750.7

TYPE AND GRADE OF BINDER: Surface A -SCDOT BINDER SPEC. GR.: 1.034

DESIGN DUST TO ASPHALT RATIO: 0.93

4.8 % Asphalt recommended with permissible variation of: 0.4 This mix is satisfactory and meets SCDOT Specs

specification for use in Aggregate I

REMARKS: Recommended: mixing temp - 325F; compaction temp - 305F; Sample size - 4706 g; ITS size - 3775 g

NOTE → #N/A

Table A-14 Job Mix Formula of Surface A PG 76-22 (Plastomer 2) without RAP-Aggregate I

PLANT LOCATION: 0	MIX DESIGN LAB NO.: 0	JOB MIX NO.: **0**
TYPE MIX: Aggregate I	DATE APPROVED:	
CONTRACTOR: 0	DATE OF LAST REV.:	NO. OF REVISIONS:
CONTROL METHOD:	DATE VOID:	

	Source of Aggregate	**Type of Aggregate**	**% Agg.**	**Ap. Sp. Gr.**
1	Aggregate I	0	0	2.63
2	Aggregate I	789	56	2.63
3	Aggregate I	MS	15	2.63
4	Aggregate I	RS	28	2.63
5	Hydrated Lime	Lime	1	
6	-4RAP	0	0	

SIEVE	**GRADATION**						**COMB.**		
	1	**2**	**3**	**4**	**5**	**6**	**GRAD.**	**TARGET**	**LIMITS**
1 1/2" / 37.5 mm	0	100	100	100	100	0	100	100	100 - 100
1" / 25.0 mm	0	100	100	100	100	0	100	100	100 - 100
3/4" / 19.0 mm	0	100	100	100	100	0	100	100	98 - 100
1/2" / 12.5 mm	0	98	100	100	100	0	99	99	90 - 100
3/8" / 9.5 mm	0	78	100	100	100	0	87	87	80 - 94
#4 / 4.75 mm	0	25	99	99	94	0	57	57	50 64
#8 / 2.36 mm	0	6	85	82	76	0	40	40	33 - 47
#30 / 0.60 mm	0	2	37	40	41	0	19	19	13 - 25
#100 / 0.150 mm	0	1	10	16	15	0	7.3	7.0	3 11
#200 / 0.075 mm	0	0.7	3	10	9	0	4.44	4.00	2 - 6

OPTIMUM BINDER CONTENT,%	4.8	4.40 - 5.20
% AIR VOIDS	3.58	2.80 - 5.20
% VMA	14.59	13.39 - 15.79

PERCENT BINDER	4.5	5.0	5.5	6.0
MAXIMUM SPECIFIC GRAVITY	2.470	2.452	2.434	2.419
BULK SPECIFIC GRAVITY	2.358	2.379	2.395	2.393
% AIR VOIDS IN TOTAL MIX	4.5	3.0	1.6	1.1
% V. M. A.	14.8	14.5	14.4	15.0
% VOIDS FILLED	69.4	79.6	88.8	92.9

EFFEC. SPECIFIC GRAVITY: 2.642 TSR(%): 94.2 WET TS:(kPa) 1225.5

TYPE AND GRADE OF BINDER: Surface A -SCDOT BINDER SPEC. GR.: 1.034

DESIGN DUST TO ASPHALT RATIO: 0.93

4.8 % Asphalt recommended with permissible variation of: 0.4 This mix is satisfactory and meets SCDOT Specs

specification for use in Aggregate I

REMARKS: Recommended: mixing temp - 325F; compaction temp - 305F; Sample size - 4706 g; ITS size - 3775 g

NOTE → #N/A

Table A-15 Job Mix Formula of Surface A PG 76-22 (Terminal-Blend GTR) without RAP-Aggregate I

PLANT LOCATION: 0	MIX DESIGN LAB NO.: 0	JOB MIX NO.: **0**
TYPE MIX: Aggregate I	DATE APPROVED:	
CONTRACTOR: 0	DATE OF LAST REV.:	NO. OF REVISIONS:
CONTROL METHOD:	DATE VOID:	

	Source of Aggregate	**Type of Aggregate**	**% Agg.**	**Ap. Sp. Gr.**
1	Aggregate I	0	0	2.63
2	Aggregate I	789	56	2.63
3	Aggregate I	MS	15	2.63
4	Aggregate I	RS	28	2.63
5	Hydrated Lime	Lime	1	
6	-4RAP	0	0	

SIEVE	**GRADATION**						**COMB.**		
	1	**2**	**3**	**4**	**5**	**6**	**GRAD.**	**TARGET**	**LIMITS**
1 1/2" / 37.5 mm	0	100	100	100	100	0	100	100	100 - 100
1" / 25.0 mm	0	100	100	100	100	0	100	100	100 - 100
3/4" / 19.0 mm	0	100	100	100	100	0	100	100	98 - 100
1/2" / 12.5 mm	0	98	100	100	100	0	99	99	90 - 100
3/8" / 9.5 mm	0	78	100	100	100	0	87	87	80 - 94
#4 / 4.75 mm	0	25	99	99	94	0	57	57	50 64
#8 / 2.36 mm	0	6	85	82	76	0	40	40	33 - 47
#30 / 0.60 mm	0	2	37	40	41	0	19	19	13 - 25
#100 / 0.150 mm	0	1	10	16	15	0	7.3	7.0	3 11
#200 / 0.075 mm	0	0.7	3	10	9	0	4.44	4.00	2 - 6

OPTIMUM BINDER CONTENT,%	4.8	4.40 - 5.20
% AIR VOIDS	3.95	2.80 - 5.20
% VMA	14.91	13.71 - 16.11

PERCENT BINDER	4.5	5.0	5.5	6.0
MAXIMUM SPECIFIC GRAVITY	2.470	2.453	2.435	2.405
BULK SPECIFIC GRAVITY	2.347	2.373	2.393	2.399
% AIR VOIDS IN TOTAL MIX	5.0	3.3	1.7	0.3
% V. M. A.	15.2	14.7	14.4	14.2
% VOIDS FILLED	67.2	78.0	88.2	98.2

EFFEC. SPECIFIC GRAVITY: 2.644 TSR(%): #VALUE! WET TS:(kPa) #VALUE!

TYPE AND GRADE OF BINDER: Surface A -TB-GTR BINDER SPEC. GR.: 1.034

DESIGN DUST TO ASPHALT RATIO: 0.93

4.8 % Asphalt recommended with permissible variation of: 0.4 This mix is satisfactory and meets SCDOT Specs

specification for use in Aggregate I

REMARKS:

NOTE → #N/A

Table A-16 Job Mix Formula of Surface A PG 76-22 (Lab-Blended GTR) without RAP-Aggregate I

PLANT LOCATION: 0	MIX DESIGN LAB NO.: 0	JOB MIX NO.: **0**
TYPE MIX: Aggregate I	DATE APPROVED:	
CONTRACTOR: 0	DATE OF LAST REV.:	NO. OF REVISIONS:
CONTROL METHOD:	DATE VOID:	

	Source of Aggregate	**Type of Aggregate**	**% Agg.**	**Ap. Sp. Gr.**
1	Aggregate I	0	0	2.63
2	Aggregate I	789	56	2.63
3	Aggregate I	MS	15	2.63
4	Aggregate I	RS	28	2.63
5	Hydrated Lime	Lime	1	
6	-4RAP	0	0	

SIEVE	**GRADATION**						**COMB.**		
	1	**2**	**3**	**4**	**5**	**6**	**GRAD.**	**TARGET**	**LIMITS**
1 1/2" / 37.5 mm	0	100	100	100	100	0	100	100	100 - 100
1" / 25.0 mm	0	100	100	100	100	0	100	100	100 - 100
3/4" / 19.0 mm	0	100	100	100	100	0	100	100	98 - 100
1/2" / 12.5 mm	0	98	100	100	100	0	99	99	90 - 100
3/8" / 9.5 mm	0	78	100	100	100	0	87	87	80 - 94
#4 / 4.75 mm	0	25	99	99	94	0	57	57	50 64
#8 / 2.36 mm	0	6	85	82	76	0	40	40	33 - 47
#30 / 0.60 mm	0	2	37	40	41	0	19	19	13 - 25
#100 / 0.150 mm	0	1	10	16	15	0	7.3	7.0	3 11
#200 / 0.075 mm	0	0.7	3	10	9	0	4.44	4.00	2 - 6

OPTIMUM BINDER CONTENT,%	5.1	4.70 - 5.50
% AIR VOIDS	3.85	2.80 - 5.20
% VMA	15.55	14.35 - 16.75

PERCENT BINDER	4.5	5.0	5.5	6.0
MAXIMUM SPECIFIC GRAVITY	2.488	2.470	2.452	2.434
BULK SPECIFIC GRAVITY	2.318	2.368	2.384	2.375
% AIR VOIDS IN TOTAL MIX	6.8	4.1	2.8	2.4
% V. M. A.	16.9	15.6	15.5	16.2
% VOIDS FILLED	59.6	73.6	82.0	85.2

EFFEC. SPECIFIC GRAVITY: 2.665	TSR(%): #VALUE!	WET TS:(kPa) #VALUE!
TYPE AND GRADE OF BINDER: Surface A -PG64-22+10%GTR	BINDER SPEC. GR.: 1.034	
DESIGN DUST TO ASPHALT RATIO: 0.87		
5.1 % Asphalt recommended with permissible variation of: 0.4	This mix is satisfactory and meets SCDOT Specs	
specification for use in Aggregate I		
REMARKS:		
		NOTE → #N/A

Table A-17 Job Mix Formula of Surface A PG 76-22 (Elastomer) without RAP-Aggregate I

PLANT LOCATION: 0 MIX DESIGN LAB NO.: 0 JOB MIX NO.: **0**
TYPE MIX: Aggregate I DATE APPROVED:
CONTRACTOR: 0 DATE OF LAST REV.: NO. OF REVISIONS:
CONTROL METHOD: DATE VOID:

	Source of Aggregate	**Type of Aggregate**	**% Agg.**	**Ap. Sp. Gr.**
1	Aggregate I	0	0	2.63
2	Aggregate I	789	56	2.63
3	Aggregate I	MS	15	2.63
4	Aggregate I	RS	28	2.63
5	Hydrated Lime	Lime	1	
6	-4RAP	0	0	

SIEVE	**GRADATION**						**COMB.**		
	1	**2**	**3**	**4**	**5**	**6**	**GRAD.**	**TARGET**	**LIMITS**
1 1/2" / 37.5 mm	0	100	100	100	100	0	100	100	100 - 100
1" / 25.0 mm	0	100	100	100	100	0	100	100	100 - 100
3/4" / 19.0 mm	0	100	100	100	100	0	100	100	98 - 100
1/2" / 12.5 mm	0	98	100	100	100	0	99	99	90 - 100
3/8" / 9.5 mm	0	78	100	100	100	0	87	87	80 - 94
#4 / 4.75 mm	0	25	99	99	94	0	57	57	50 64
#8 / 2.36 mm	0	6	85	82	76	0	40	40	33 - 47
#30 / 0.60 mm	0	2	37	40	41	0	19	19	13 - 25
#100 / 0.150 mm	0	1	10	16	15	0	7.3	7.0	3 11
#200 / 0.075 mm	0	0.7	3	10	9	0	4.44	4.00	2 - 6

OPTIMUM BINDER CONTENT,%	5.0	4.60 - 5.40
% AIR VOIDS	4.34	2.80 - 5.20
% VMA	15.73	14.53 - 16.93

PERCENT BINDER	4.0	4.5	5.0	5.5
MAXIMUM SPECIFIC GRAVITY	2.498	2.480	2.462	2.409
BULK SPECIFIC GRAVITY	2.340	2.342	2.355	2.396
% AIR VOIDS IN TOTAL MIX	6.3	5.6	4.3	0.5
% V. M. A.	15.4	15.8	15.7	13.3
% VOIDS FILLED	58.8	64.7	72.4	96.0

EFFEC. SPECIFIC GRAVITY: 2.655 TSR(%): #VALUE! WET TS:(kPa) #VALUE!
TYPE AND GRADE OF BINDER: Surface A -PG64-22+Elastomer BINDER SPEC. GR.: 1.034
DESIGN DUST TO ASPHALT RATIO: 0.89
5.0 % Asphalt recommended with permissible variation of: 0.4 This mix is satisfactory and meets SCDOT Specs
specification for use in Aggregate I
REMARKS: Recommended: mixing temp - 325F; compaction temp - 305F; Sample size - 4706 g; ITS size - 3775 g
NOTE → #N/A

Table A-18 Job Mix Formula of Surface A PG 76-22 (SBS) +RAP-Aggregate I

PLANT LOCATION: 0	MIX DESIGN LAB NO.: 0	JOB MIX NO.: **0**
TYPE MIX: Aggregate I	DATE APPROVED:	
CONTRACTOR: 0	DATE OF LAST REV.:	NO. OF REVISIONS:
CONTROL METHOD:	DATE VOID:	

	Source of Aggregate	**Type of Aggregate**	**% Agg.**	**Ap. Sp. Gr.**
1	Aggregate I	57	10	2.63
2	Aggregate I	789	47	2.63
3	Aggregate I	MS	14	2.63
4	Aggregate I	RS	16	2.63
5	Hydrated Lime	Lime	1	
6	-4 RAP (CR)	-4 RAP	12	

SIEVE	**GRADATION**						**COMB.**		
	1	**2**	**3**	**4**	**5**	**6**	**GRAD.**	**TARGET**	**LIMITS**
1 1/2" / 37.5 mm	100	100	100	100	100	0	100	99.8	100 - 100
1" / 25.0 mm	100	100	100	100	100	0	100	99.8	100 - 100
3/4" / 19.0 mm	86.7	100	100	100	100	0	98	98.5	98 - 100
1/2" / 12.5 mm	35.4	94.7	100	100	100	0	91	90.9	90 - 100
3/8" / 9.5 mm	7.5	70.6	100	100	100	0	77	76.7	70 - 84
#4 / 4.75 mm	0.6	17.4	96.6	97.7	91.8	0	49	49.2	42 56
#8 / 2.36 mm	0.5	3.6	81.0	80.8	70.3	0	35	35.3	28 - 42
#30 / 0.60 mm	0.4	0.9	38.6	41.8	36.2	0	18	17.7	11 - 24
#100 / 0.150 mm	0.3	0.4	6.8	13.3	7.5	0	5.0	5.0	1 9
#200 / 0.075 mm	0.2	0.3	2.6	8.2	3.3	0	3.05	3.0	1 - 5

OPTIMUM BINDER CONTENT,%	4.7	4.30 - 5.10
% AIR VOIDS	3.74	2.80 - 5.20
% VMA	14.52	13.32 - 15.72

PERCENT BINDER	4.5	5.0	5.5	6.0
MAXIMUM SPECIFIC GRAVITY	2.469	2.451	2.434	2.416
BULK SPECIFIC GRAVITY	2.365	2.378	2.386	2.391
% AIR VOIDS IN TOTAL MIX	4.2	3.0	2.0	1.1
% V. M. A.	14.5	14.5	14.7	14.9
% VOIDS FILLED	70.8	79.3	86.6	92.9

EFFEC. SPECIFIC GRAVITY: 2.642 TSR(%): 85.2 WET TS:(kPa) 1024.5

TYPE AND GRADE OF BINDER: Nustar PG 76-22 BINDER SPEC. GR.: 1.034

DESIGN DUST TO ASPHALT RATIO: 0.65

4.7 % Asphalt recommended with permissible variation of: 0.4 This mix is satisfactory and meets SCDOT specs

specification for use in Aggregate I

REMARKS:

NOTE → #N/A

Table A-19 Job Mix Formula of Surface A PG 76-22 (Plastomer 2) +RAP-Aggregate I

PLANT LOCATION: 0 MIX DESIGN LAB NO.: 0 JOB MIX NO.: **0**
TYPE MIX: Aggregate I DATE APPROVED:
CONTRACTOR: 0 DATE OF LAST REV.: NO. OF REVISIONS:
CONTROL METHOD: DATE VOID:

	Source of Aggregate	**Type of Aggregate**	**% Agg.**	**Ap. Sp. Gr.**
1	Aggregate I	57	10	2.63
2	Aggregate I	789	47	2.63
3	Aggregate I	MS	14	2.63
4	Aggregate I	RS	16	2.63
5	Hydrated Lime	Lime	1	
6	-4 RAP (CR)	-4 RAP	12	

SIEVE	**GRADATION**						**COMB.**		
	1	**2**	**3**	**4**	**5**	**6**	**GRAD.**	**TARGET**	**LIMITS**
1 1/2" / 37.5 mm	100	100	100	100	100	0	100	99.8	100 - 100
1" / 25.0 mm	100	100	100	100	100	0	100	99.8	100 - 100
3/4" / 19.0 mm	86.7	100	100	100	100	0	98	98.5	98 - 100
1/2" / 12.5 mm	35.4	94.7	100	100	100	0	91	90.9	90 - 100
3/8" / 9.5 mm	7.5	70.6	100	100	100	0	77	76.7	70 - 84
#4 / 4.75 mm	0.6	17.4	96.6	97.7	91.8	0	49	49.2	42 56
#8 / 2.36 mm	0.5	3.6	81.0	80.8	70.3	0	35	35.3	28 - 42
#30 / 0.60 mm	0.4	0.9	38.6	41.8	36.2	0	18	17.7	11 - 24
#100 / 0.150 mm	0.3	0.4	6.8	13.3	7.5	0	5.0	5.0	1 9
#200 / 0.075 mm	0.2	0.3	2.6	8.2	3.3	0	3.05	3.0	1 - 5
OPTIMUM BINDER CONTENT,%								4.8	4.40 - 5.20
% AIR VOIDS								3.40	2.80 - 5.20
% VMA								14.41	13.21 - 15.61

PERCENT BINDER	4.5	5.0	5.5	6.0
MAXIMUM SPECIFIC GRAVITY	2.466	2.448	2.431	2.414
BULK SPECIFIC GRAVITY	2.360	2.380	2.399	2.399
% AIR VOIDS IN TOTAL MIX	4.3	2.8	1.3	0.6
% V. M. A.	14.6	14.3	14.1	14.5
% VOIDS FILLED	70.5	80.5	90.8	95.7

EFFEC. SPECIFIC GRAVITY: 2.638 TSR(%): #VALUE! WET TS:(kPa) #VALUE!
TYPE AND GRADE OF BINDER: Honeywell 7205 BINDER SPEC. GR.: 1.034
DESIGN DUST TO ASPHALT RATIO: 0.64
4.8 % Asphalt recommended with permissible variation of: 0.4 This mix is satisfactory and meets SCDOT specs
specification for use in Aggregate I
REMARKS:
NOTE → #N/A

Table A-20 Job Mix Formula of Surface A PG 76-22 (Terminal-Blended GTR) +RAP-Aggregate I

PLANT LOCATION: 0 MIX DESIGN LAB NO.: 0 JOB MIX NO.: **0**

TYPE MIX: Aggregate I DATE APPROVED:

CONTRACTOR: 0 DATE OF LAST REV.: NO. OF REVISIONS:

CONTROL METHOD: DATE VOID:

	Source of Aggregate	**Type of Aggregate**	**% Agg.**	**Ap. Sp. Gr.**
1	Aggregate I	57	10	2.63
2	Aggregate I	789	47	2.63
3	Aggregate I	MS	14	2.63
4	Aggregate I	RS	16	2.63
5	-200 fine	-200 fine	1	
6	-4 RAP (CR)	-4 RAP	12	

SIEVE		**GRADATION**						**COMB.**		
		1	**2**	**3**	**4**	**5**	**6**	**GRAD.**	**TARGET**	**LIMITS**
1 1/2"	/ 37.5 mm	100	100	100	100	100	0	100	99.8	100 - 100
1"	/ 25.0 mm	100	100	100	100	100	0	100	99.8	100 - 100
3/4"	/ 19.0 mm	86.7	100	100	100	100	0	98	98.5	98 - 100
1/2"	/ 12.5 mm	35.4	94.7	100	100	100	0	91	90.9	90 - 100
3/8"	/ 9.5 mm	7.5	70.6	100	100	100	0	77	76.7	70 - 84
#4	/ 4.75 mm	0.6	17.4	96.6	97.7	91.8	0	49	49.2	42 56
#8	/ 2.36 mm	0.5	3.6	81.0	80.8	70.3	0	35	35.3	28 - 42
#30	/ 0.60 mm	0.4	0.9	38.6	41.8	36.2	0	18	17.7	11 - 24
#100	/ 0.150 mm	0.3	0.4	6.8	13.3	7.5	0	5.0	5.0	1 9
#200	/ 0.075 mm	0.2	0.3	2.6	8.2	3.3	0	3.05	3.0	1 - 5
OPTIMUM BINDER CONTENT,%									4.7	4.30 - 5.10
% AIR VOIDS									3.72	2.80 - 5.20
% VMA									14.54	13.34 - 15.74

PERCENT BINDER	4.5	5.0	5.5	6.0
MAXIMUM SPECIFIC GRAVITY	2.481	2.463	2.445	2.428
BULK SPECIFIC GRAVITY	2.376	2.390	2.415	2.410
% AIR VOIDS IN TOTAL MIX	4.2	3.0	1.3	0.7
% V. M. A.	14.6	14.5	14.1	14.7
% VOIDS FILLED	71.0	79.7	91.1	95.1

EFFEC. SPECIFIC GRAVITY: 2.656 TSR(%): #VALUE! WET TS:(kPa) #VALUE!

TYPE AND GRADE OF BINDER: Type A TB-GTR BINDER SPEC. GR.: 1.034

DESIGN DUST TO ASPHALT RATIO: 0.65

4.7 % Asphalt recommended with permissible variation of: 0.4 This mix is satisfactory and meets SCDOT specs

specification for use in Aggregate I

REMARKS:

NOTE → #N/A

Table A-21 Job Mix Formula of Surface A PG 76-22 (Lab-Blended GTR) +RAP-Aggregate I

PLANT LOCATION: 0 MIX DESIGN LAB NO.: 0 JOB MIX NO.: **0**
TYPE MIX: Aggregate I DATE APPROVED:
CONTRACTOR: 0 DATE OF LAST REV.: NO. OF REVISIONS:
CONTROL METHOD: DATE VOID:

	Source of Aggregate	**Type of Aggregate**	**% Agg.**	**Ap. Sp. Gr.**
1	Aggregate I	57	10	2.63
2	Aggregate I	789	47	2.63
3	Aggregate I	MS	14	2.63
4	Aggregate I	RS	16	2.63
5	Dust	Dust	1	
6	-4 RAP (CR)	-4 RAP	12	

SIEVE	**GRADATION**						**COMB.**		
	1	**2**	**3**	**4**	**5**	**6**	**GRAD.**	**TARGET**	**LIMITS**
1 1/2" / 37.5 mm	100	100	100	100	100	0	100	99.8	100 - 100
1" / 25.0 mm	100	100	100	100	100	0	100	99.8	100 - 100
3/4" / 19.0 mm	86.7	100	100	100	100	0	98	98.5	98 - 100
1/2" / 12.5 mm	35.4	94.7	100	100	100	0	91	90.9	90 - 100
3/8" / 9.5 mm	7.5	70.6	100	100	100	0	77	76.7	70 - 84
#4 / 4.75 mm	0.6	17.4	96.6	97.7	91.8	0	49	49.2	42 56
#8 / 2.36 mm	0.5	3.6	81.0	80.8	70.3	0	35	35.3	28 - 42
#30 / 0.60 mm	0.4	0.9	38.6	41.8	36.2	0	18	17.7	11 - 24
#100 / 0.150 mm	0.3	0.4	6.8	13.3	7.5	0	5.0	5.0	1 9
#200 / 0.075 mm	0.2	0.3	2.6	8.2	3.3	0	3.05	3.0	1 - 5
OPTIMUM BINDER CONTENT,%								5.1	4.70 - 5.50
% AIR VOIDS								3.97	2.80 - 5.20
% VMA								15.61	14.41 - 16.81

PERCENT BINDER	4.5	5.0	5.5	6.0
MAXIMUM SPECIFIC GRAVITY	2.480	2.462	2.444	2.427
BULK SPECIFIC GRAVITY	2.364	2.361	2.360	2.378
% AIR VOIDS IN TOTAL MIX	4.7	4.1	3.5	2.0
% V. M. A.	15.0	15.5	16.0	15.8
% VOIDS FILLED	68.8	73.6	78.4	87.3

EFFEC. SPECIFIC GRAVITY: 2.655 TSR(%): #VALUE! WET TS:(kPa) #VALUE!
TYPE AND GRADE OF BINDER: Type A PG 64-22+10%rubber BINDER SPEC. GR.: 1.034
DESIGN DUST TO ASPHALT RATIO: 0.60
5.1 % Asphalt recommended with permissible variation of: 0.4 This mix is satisfactory and meets SCDOT specs
specification for use in Aggregate I
REMARKS:
NOTE → #N/A

Table A-22 Job Mix Formula of Surface A PG 76-22 (Elastomer) +RAP-Aggregate I

PLANT LOCATION: 0 MIX DESIGN LAB NO.: 0 JOB MIX NO.: **0**
TYPE MIX: Aggregate I DATE APPROVED:
CONTRACTOR: 0 DATE OF LAST REV.: NO. OF REVISIONS:
CONTROL METHOD: DATE VOID:

	Source of Aggregate	**Type of Aggregate**	**% Agg.**	**Ap. Sp. Gr.**
1	Aggregate I	57	10	2.63
2	Aggregate I	789	47	2.63
3	Aggregate I	MS	14	2.63
4	Aggregate I	RS	16	2.63
5	-200 fine	-200 fine	1	
6	-4 RAP (CR)	-4 RAP	12	

SIEVE	**GRADATION**						**COMB.**		
	1	**2**	**3**	**4**	**5**	**6**	**GRAD.**	**TARGET**	**LIMITS**
1 1/2" / 37.5 mm	100	100	100	100	100	0	100	99.8	100 - 100
1" / 25.0 mm	100	100	100	100	100	0	100	99.8	100 - 100
3/4" / 19.0 mm	86.7	100	100	100	100	0	98	98.5	98 - 100
1/2" / 12.5 mm	35.4	94.7	100	100	100	0	91	90.9	90 - 100
3/8" / 9.5 mm	7.5	70.6	100	100	100	0	77	76.7	70 - 84
#4 / 4.75 mm	0.6	17.4	96.6	97.7	91.8	0	49	49.2	42 56
#8 / 2.36 mm	0.5	3.6	81.0	80.8	70.3	0	35	35.3	28 - 42
#30 / 0.60 mm	0.4	0.9	38.6	41.8	36.2	0	18	17.7	11 - 24
#100 / 0.150 mm	0.3	0.4	6.8	13.3	7.5	0	5.0	5.0	1 9
#200 / 0.075 mm	0.2	0.3	2.6	8.2	3.3	0	3.05	3.0	1 - 5

OPTIMUM BINDER CONTENT,%	4.9	4.50 - 5.30
% AIR VOIDS	3.97	2.80 - 5.20
% VMA	15.17	13.97 - 16.37

PERCENT BINDER	4.5	5.0	5.5	6.0
MAXIMUM SPECIFIC GRAVITY	2.475	2.457	2.439	2.422
BULK SPECIFIC GRAVITY	2.369	2.361	2.407	2.403
% AIR VOIDS IN TOTAL MIX	4.3	3.9	1.3	0.8
% V. M. A.	14.6	15.3	14.1	14.7
% VOIDS FILLED	70.7	74.8	90.7	94.8

EFFEC. SPECIFIC GRAVITY: 2.648 TSR(%): #VALUE! WET TS:(kPa) #VALUE!
TYPE AND GRADE OF BINDER: Type A PG64-22+Elastomer BINDER SPEC. GR.: 1.034
DESIGN DUST TO ASPHALT RATIO: 0.62
4.9 % Asphalt recommended with permissible variation of: 0.4 This mix is satisfactory and meets SCDOT specs
specification for use in Aggregate I
REMARKS:
NOTE → #N/A

APPENDIX B – Laboratory Mix Designs: Natural Sand

Table B-1 Job Mix Formula of Surface B with 25% Aged Binder and Lime - Aggregate II

PLANT LOCATION: 0 MIX DESIGN LAB NO.: 0 JOB MIX NO.: **0**

TYPE MIX: Type B PG 64-22 DATE APPROVED:

CONTRACTOR: 0 DATE OF LAST REV.: NO. OF REVISIONS:

CONTROL METHOD: DATE VOID:

	Source of Aggregate	Type of Aggregate	% Agg.	Ap. Sp. Gr.
1	Aggregate II	789	46	2.63
2	Aggregate II	MS	0	2.63
3	Aggregate II	RS	10	2.63
4	Aggregate II	Lime	1	2.63
5	-4RAP	-4RAP	23	
6	Natrual sand	Natural Sand	20	

SIEVE	GRADATION						COMB.		
	1	2	3	4	5	6	GRAD.	TARGET	LIMITS
1 1/2" / 37.5 mm	100	100	100	100	100	100	95	0	100 - 100
1" / 25.0 mm	100	100	100	100	100	100	95	0	100 - 100
3/4" / 19.0 mm	92.994	100	100	100	100	100	92	0	100 - 100
1/2" / 12.5 mm	31.753	98.139	100	100	100	100	64	0	97 - 100
3/8" / 9.5 mm	10.541	92.134	100	100	100	100	54	0	-7 - 7
#4 / 4.75 mm	1.2511	19.732	99.945	99.8866	96.7016	99.66968	49	0	-7 7
#8 / 2.36 mm	1.0863	2.0501	81.105	84.5641	78.8199	99.56204	44	0	-7 - 7
#30 / 0.60 mm	0.9886	1.3023	50.588	58.4153	51.0181	79.70055	35	0	-6 - 6
#100 / 0.150 mm	0.5489	0.7291	7.4396	20.5701	12.218	2.943911	22.0	0.0	-4 4
#200 / 0.075 mm	0.3835	0.4976	2.3023	12.5267	6.72414	0.92237	20.28	0.00	-2 - 2

OPTIMUM BINDER CONTENT,%	5.7	5.30 - 6.10
% AIR VOIDS	4.06	2.80 - 5.20
% VMA	17.04	15.84 - 18.24

PERCENT BINDER	4.5	5.0	5.5	6.0
MAXIMUM SPECIFIC GRAVITY	2.498	2.480	2.462	2.444
BULK SPECIFIC GRAVITY	2.284	2.314	2.358	2.350
% AIR VOIDS IN TOTAL MIX	8.6	6.7	4.2	3.9
% V. M. A.	18.5	17.9	16.7	17.5
% VOIDS FILLED	53.6	62.7	75.0	78.0

EFFEC. SPECIFIC GRAVITY: 2.677 TSR(%): #VALUE! WET TS:(kPa) #VALUE!

TYPE AND GRADE OF BINDER: Surface B -Nustar PG 64-22 BINDER SPEC. GR.: 1.034

DESIGN DUST TO ASPHALT RATIO: 3.56

5.7 % Asphalt recommended with permissible variation of: 0.4 This mix is satisfactory and meets SCDOT Specs

specification for use in Type B PG 64-22

REMARKS: Recommended: mixing temp - 285F; compaction temp - 245F; Sample size - 4706 g; ITS size - 3729 g

NOTE → #N/A

Table B-2 Job Mix Formula of Surface B with 25% Aged Binder and Lime - Aggregate I

PLANT LOCATION: 0	MIX DESIGN LAB NO.: 0	JOB MIX NO.: **0**
TYPE MIX: Aggregate I	DATE APPROVED:	
CONTRACTOR: 0	DATE OF LAST REV.:	NO. OF REVISIONS:
CONTROL METHOD:	DATE VOID:	

	Source of Aggregate	**Type of Aggregate**	**% Agg.**	**Ap. Sp. Gr.**
1	Aggregate I	789	36	2.63
2	Aggregate I	MS	0	2.63
3	Aggregate I	RS	20	2.63
4	Hydrated lime	Lime	1	2.63
5	-4 RAP (CR)	-4RAP	23	
6	Natrual sand	Natrual sand	20	

SIEVE			**GRADATION**						**COMB.**				
			1	**2**	**3**	**4**	**5**	**6**	**GRAD.**	**TARGET**	**LIMITS**		
1 1/2"	/	37.5 mm	100	100	100	100	100	100	95	0	100	-	100
1"	/	25.0 mm	100	100	100	100	100	100	95	0	100	-	100
3/4"	/	19.0 mm	86.7	100	100	100	100	100	91	0.0	100	-	100
1/2"	/	12.5 mm	35.4	94.7	100	100	100	100	72	0.0	97	-	100
3/8"	/	9.5 mm	7.5	70.6	100	100	100	100	62	0.0	-7	-	7
#4	/	4.75 mm	0.6	17.4	96.6	97.7	91.8	99.67	57	0.0	-7		7
#8	/	2.36 mm	0.5	3.6	81.0	80.8	70.3	99.562	50	0.0	-7	-	7
#30	/	0.60 mm	0.4	0.9	38.6	41.8	36.2	79.701	34	0.0	-6	-	6
#100	/	0.150 mm	0.3	0.4	6.8	13.3	7.5	2.9439	21.5	0.0	-4		4
#200	/	0.075 mm	0.2	0.3	2.6	8.2	3.3	0.9224	19.75	0.0	-2	-	2

OPTIMUM BINDER CONTENT,%	5.7	5.30	-	6.10
% AIR VOIDS	4.33	2.80	-	5.20
% VMA	17.21	16.01	-	18.41

PERCENT BINDER	4.5	5.0	5.5	6.0
MAXIMUM SPECIFIC GRAVITY	2.486	2.468	2.450	2.432
BULK SPECIFIC GRAVITY	2.283	2.323	2.333	2.344
% AIR VOIDS IN TOTAL MIX	8.2	5.9	4.8	3.6
% V. M. A.	18.1	17.1	17.2	17.2
% VOIDS FILLED	54.9	65.7	72.2	79.1

EFFEC. SPECIFIC GRAVITY: 2.662 TSR(%): 85.2 WET TS:(kPa) 1024.5

TYPE AND GRADE OF BINDER: Surface B Nustar PG 64-22 BINDER SPEC. GR.: 1.034

DESIGN DUST TO ASPHALT RATIO: 3.47

5.7 % Asphalt recommended with permissible variation of: 0.4 This mix is satisfactory and meets SCDOT specs

specification for use in Aggregate I

REMARKS:

NOTE → #N/A

Table B-3 Job Mix Formula of Surface C with 30% Aged Binder and Lime - Aggregate II

PLANT LOCATION: 0 MIX DESIGN LAB NO.: 0 JOB MIX NO.: **0**
TYPE MIX: Type CM PG 64-22 DATE APPROVED:
CONTRACTOR: 0 DATE OF LAST REV.: NO. OF REVISIONS:
CONTROL METHOD: DATE VOID:

	Source of Aggregate	**Type of Aggregate**	**% Agg.**	**Ap. Sp. Gr.**
1	Aggregate II	789	42	2.63
2	Aggregate II	MS	0	2.63
3	Aggregate II	RS	10	2.63
4	Hydrated Lime	Lime	1	2.63
5	-4RAP	-4RAP	27	
6	Natrual sand	Natural Sand	20	

SIEVE	**GRADATION**						**COMB.**		
	1	**2**	**3**	**4**	**5**	**6**	**GRAD.**	**TARGET**	**LIMITS**
1 1/2" / 37.5 mm	100	100	100	100	100	100	95	0	100 - 100
1" / 25.0 mm	100	100	100	100	100	100	95	0	100 - 100
3/4" / 19.0 mm	92.994	100	100	100	100	100	92	0	98 - 100
1/2" / 12.5 mm	31.753	98.139	100	100	100	100	66	0	97 - 100
3/8" / 9.5 mm	10.541	92.134	100	100	100	100	57	0	-7 - 7
#4 / 4.75 mm	1.2511	19.732	99.945	99.8866	96.7016	99.66968	52	0	-7 7
#8 / 2.36 mm	1.0863	2.0501	81.105	84.5641	78.8199	99.56204	47	0	-7 - 7
#30 / 0.60 mm	0.9886	1.3023	50.588	58.4153	51.0181	79.70055	38	0	-6 - 6
#100 / 0.150 mm	0.5489	0.7291	7.4396	20.5701	12.218	2.943911	25.2	0.0	-4 4
#200 / 0.075 mm	0.3835	0.4976	2.3023	12.5267	6.72414	0.92237	23.46	0.00	-2 - 2

OPTIMUM BINDER CONTENT,%	6.3	5.90 - 6.70
% AIR VOIDS	4.47	2.80 - 5.20
% VMA	18.66	17.46 - 19.86

PERCENT BINDER	5.0	5.5	6.0	6.5
MAXIMUM SPECIFIC GRAVITY	2.485	2.467	2.449	2.431
BULK SPECIFIC GRAVITY	2.264	2.286	2.312	2.341
% AIR VOIDS IN TOTAL MIX	8.9	7.3	5.6	3.7
% V. M. A.	19.9	19.5	19.0	18.4
% VOIDS FILLED	55.1	62.4	70.5	79.9

EFFEC. SPECIFIC GRAVITY: 2.684 TSR(%): #VALUE! WET TS:(kPa) #VALUE!
TYPE AND GRADE OF BINDER: Surface CM -Nustar PG 64-22 BINDER SPEC. GR.: 1.034
DESIGN DUST TO ASPHALT RATIO: 4.69
6.3 % Asphalt recommended with permissible variation of: 0.4 This mix is satisfactory and meets SCDOT Specs
specification for use in Type CM PG 64-22
REMARKS: Recommended: mixing temp - 285F; compaction temp - 245F; Sample size - 4706 g; ITS size - 3729 g
NOTE → #N/A

Table B-4 Job Mix Formula of Surface C with 30% Aged Binder and Lime – Aggregate I

PLANT LOCATION: 0 MIX DESIGN LAB NO.: 0 JOB MIX NO.: **0**
TYPE MIX: Type CM PG 64-22 DATE APPROVED:
CONTRACTOR: 0 DATE OF LAST REV.: NO. OF REVISIONS:
CONTROL METHOD: DATE VOID:

	Source of Aggregate	**Type of Aggregate**	**% Agg.**	**Ap. Sp. Gr.**
1	Aggregate I	789	28	2.63
2	Aggregate I	MS	0	2.63
3	Aggregate I	RS	24	2.63
4	Hydrated Lime	Lime	1	2.63
5	-4 RAP (CR)	-4 RAP	27	
6	Natrual sand	Natrual sand	20	

SIEVE	**GRADATION**						**COMB.**		
	1	**2**	**3**	**4**	**5**	**6**	**GRAD.**	**TARGET**	**LIMITS**
1 1/2" / 37.5 mm	100	100	100	100	100	100	95	0	100 - 100
1" / 25.0 mm	100	100	100	100	100	100	95	0	100 - 100
3/4" / 19.0 mm	86.7	100	100	100	100	100	91	0.0	98 - 100
1/2" / 12.5 mm	35.4	94.7	100	100	100	100	77	0.0	97 - 100
3/8" / 9.5 mm	7.5	70.6	100	100	100	100	69	0.0	-7 - 7
#4 / 4.75 mm	0.6	17.4	96.6	97.7	91.8	99.67	64	0.0	-7 7
#8 / 2.36 mm	0.5	3.6	81.0	80.8	70.3	99.562	56	0.0	-7 - 7
#30 / 0.60 mm	0.4	0.9	38.6	41.8	36.2	79.701	39	0.0	-6 - 6
#100 / 0.150 mm	0.3	0.4	6.8	13.3	7.5	2.9439	25.0	0.0	-4 4
#200 / 0.075 mm	0.2	0.3	2.6	8.2	3.3	0.9224	23.03	0.0	-2 - 2

OPTIMUM BINDER CONTENT,%	6.3	5.90 - 6.70
% AIR VOIDS	4.38	2.80 - 5.20
% VMA	18.39	17.19 - 19.59

PERCENT BINDER	5.0	5.5	6.0	6.5
MAXIMUM SPECIFIC GRAVITY	2.448	2.414	2.397	2.380
BULK SPECIFIC GRAVITY	2.236	2.272	2.294	2.301
% AIR VOIDS IN TOTAL MIX	8.7	5.9	4.3	3.3
% V. M. A.	19.5	17.9	17.6	17.8
% VOIDS FILLED	55.6	67.4	75.7	81.3

EFFEC. SPECIFIC GRAVITY: 2.638 TSR(%): 85.2 WET TS:(kPa) 1024.5
TYPE AND GRADE OF BINDER: Surface CM Nustar PG 64-22 BINDER SPEC. GR.: 1.034
DESIGN DUST TO ASPHALT RATIO: 3.66
6.3 % Asphalt recommended with permissible variation of: 0.4 This mix is satisfactory and meets SCDOT specs
specification for use in Type CM PG 64-22
REMARKS:
NOTE → #N/A

<u>APPENDIX C – Laboratory Mix Designs: Field Project</u>

Table C-1 Job Mix Formula of Surface B PG 64-22

PLANT LOCATION: 0 MIX DESIGN LAB NO.: 0 JOB MIX NO.: **0**

TYPE MIX: Surface B PG 64-22 DATE APPROVED:

CONTRACTOR: 0 DATE OF LAST REV.: NO. OF REVISIONS:

CONTROL METHOD: DATE VOID:

	Source of Aggregate	**Type of Aggregate**	**% Agg.**	**Ap. Sp. Gr.**
1	Aggregate I	57	0	2.63
2	Aggregate I	789	39	2.63
3	Aggregate I	MS	19	2.63
4	Aggregate I	RS	18	2.63
5	Hydrated Lime	Lime	1	
6	-4 RAP (CR)	-4 RAP	23	

SIEVE	**GRADATION**						**COMB.**		
	1	**2**	**3**	**4**	**5**	**6**	**GRAD.**	**TARGET**	**LIMITS**
1 1/2" / 37.5 mm	100	100	100	100	100	0	100	0	100 - 100
1" / 25.0 mm	100	100	100	100	100	0	100	0	100 - 100
3/4" / 19.0 mm	86.72	100	100	100	100	0	100	0	98 - 100
1/2" / 12.5 mm	35.44	94.70	100	100	100	0	98	0	90 - 100
3/8" / 9.5 mm	7.49	70.57	100	100	100	0	88	0	-7 - 7
#4 / 4.75 mm	0.56	17.40	96.63	97.69	91.83	0	65	0	-7 7
#8 / 2.36 mm	0.48	3.63	81.03	80.78	70.35	0	48	0	-7 - 7
#30 / 0.60 mm	0.43	0.93	38.60	41.80	36.21	0	24	0	-6 - 6
#100 / 0.150 mm	0.33	0.44	6.81	13.35	7.55	0	6.4	0.0	-4 4
#200 / 0.075 mm	0.25	0.31	2.60	8.23	3.29	0	3.66	0.00	-2 - 2

OPTIMUM BINDER CONTENT,%	5.4	5.00 - 5.80
% AIR VOIDS	4.12	2.80 - 5.20
% VMA	16.30	15.10 - 17.50

PERCENT BINDER	4.5	5.0	5.5	6.0
MAXIMUM SPECIFIC GRAVITY	2.466	2.448	2.430	2.413
BULK SPECIFIC GRAVITY	2.290	2.328	2.335	2.355
% AIR VOIDS IN TOTAL MIX	7.1	4.9	3.9	2.4
% V. M. A.	17.1	16.1	16.3	16.1
% VOIDS FILLED	58.3	69.7	76.0	85.0

EFFEC. SPECIFIC GRAVITY: 2.638 TSR(%): 97.8 WET TS:(kPa) 1100.8

TYPE AND GRADE OF BINDER: Nustar PG 64-22 BINDER SPEC. GR.: 1.034

DESIGN DUST TO ASPHALT RATIO: 0.68

5.4 % Asphalt recommended with permissible variation of: 0.4 This mix is satisfactory and meets SCDOT specs

specification for use in Surface B PG 64-22

REMARKS:

NOTE → #N/A

Table C-2 Job Mix Formula of Surface A PG76-22 (SBS)

PLANT LOCATION: 0	MIX DESIGN LAB NO.: 0	JOB MIX NO.: **0**
TYPE MIX: Surface A-PG 76-22 (SBS)	DATE APPROVED:	
CONTRACTOR: 0	DATE OF LAST REV.:	NO. OF REVISIONS:
CONTROL METHOD:	DATE VOID:	

	Source of Aggregate	**Type of Aggregate**	**% Agg.**	**Ap. Sp. Gr.**
1	Aggregate I	57	10	2.63
2	Aggregate I	789	47	2.63
3	Aggregate I	MS	14	2.63
4	Aggregate I	RS	16	2.63
5	Hydrated Lime	Lime	1	
6	-4 RAP (CR)	-4 RAP	12	

SIEVE	**GRADATION**						**COMB.**		
	1	**2**	**3**	**4**	**5**	**6**	**GRAD.**	**TARGET**	**LIMITS**
1 1/2" / 37.5 mm	100	100	100	100	100	0	100	99.8	100 - 100
1" / 25.0 mm	100	100	100	100	100	0	100	99.8	100 - 100
3/4" / 19.0 mm	86.7	100	100	100	100	0	98	98.5	98 - 100
1/2" / 12.5 mm	35.4	94.7	100	100	100	0	91	90.9	90 - 100
3/8" / 9.5 mm	7.5	70.6	100	100	100	0	77	76.7	70 - 84
#4 / 4.75 mm	0.6	17.4	96.6	97.7	91.8	0	49	49.2	42 56
#8 / 2.36 mm	0.5	3.6	81.0	80.8	70.3	0	35	35.3	28 - 42
#30 / 0.60 mm	0.4	0.9	38.6	41.8	36.2	0	18	17.7	11 - 24
#100 / 0.150 mm	0.3	0.4	6.8	13.3	7.5	0	5.0	5.0	1 9
#200 / 0.075 mm	0.2	0.3	2.6	8.2	3.3	0	3.05	3.0	1 - 5

OPTIMUM BINDER CONTENT,%	4.7	4.30 - 5.10
% AIR VOIDS	3.78	2.80 - 5.20
% VMA	14.58	13.38 - 15.78

PERCENT BINDER	4.5	5.0	5.5	6.0
MAXIMUM SPECIFIC GRAVITY	2.475	2.457	2.439	2.422
BULK SPECIFIC GRAVITY	2.366	2.387	2.386	2.391
% AIR VOIDS IN TOTAL MIX	4.4	2.9	2.2	1.3
% V. M. A.	14.7	14.4	14.9	15.2
% VOIDS FILLED	70.1	80.1	85.3	91.5

EFFEC. SPECIFIC GRAVITY: 2.649 TSR(%): 85.2 WET TS:(kPa) 1024.5

TYPE AND GRADE OF BINDER: Nustar PG 76-22 BINDER SPEC. GR.: 1.034

DESIGN DUST TO ASPHALT RATIO: 0.65

4.7 % Asphalt recommended with permissible variation of: 0.4 This mix is satisfactory and meets SCDOT specs

specification for use in Surface A-PG 76-22 (SBS)

REMARKS:

NOTE → #N/A

Table C-3 Job Mix Formula of Surface A PG76-22 (Plastomer 2)

PLANT LOCATION: 0 MIX DESIGN LAB NO.: 0 JOB MIX NO.: **0**

TYPE MIX: Aggregate I DATE APPROVED:

CONTRACTOR: 0 DATE OF LAST REV.: NO. OF REVISIONS:

CONTROL METHOD: DATE VOID:

	Source of Aggregate	**Type of Aggregate**	**% Agg.**	**Ap. Sp. Gr.**
1	Aggregate I	57	10	2.63
2	Aggregate I	789	47	2.63
3	Aggregate I	MS	14	2.63
4	Aggregate I	RS	16	2.63
5	Hydrated Lime	Lime	1	
6	-4 RAP (CR)	-4 RAP	12	

SIEVE	**GRADATION**						**COMB.**		
	1	**2**	**3**	**4**	**5**	**6**	**GRAD.**	**TARGET**	**LIMITS**
1 1/2" / 37.5 mm	100	100	100	100	100	0	100	99.8	100 - 100
1" / 25.0 mm	100	100	100	100	100	0	100	99.8	100 - 100
3/4" / 19.0 mm	86.7	100	100	100	100	0	98	98.5	98 - 100
1/2" / 12.5 mm	35.4	94.7	100	100	100	0	91	90.9	90 - 100
3/8" / 9.5 mm	7.5	70.6	100	100	100	0	77	76.7	70 - 84
#4 / 4.75 mm	0.6	17.4	96.6	97.7	91.8	0	49	49.2	42 56
#8 / 2.36 mm	0.5	3.6	81.0	80.8	70.3	0	35	35.3	28 - 42
#30 / 0.60 mm	0.4	0.9	38.6	41.8	36.2	0	18	17.7	11 - 24
#100 / 0.150 mm	0.3	0.4	6.8	13.3	7.5	0	5.0	5.0	1 9
#200 / 0.075 mm	0.2	0.3	2.6	8.2	3.3	0	3.05	3.0	1 - 5

OPTIMUM BINDER CONTENT,%	4.8	4.40 - 5.20
% AIR VOIDS	3.45	2.80 - 5.20
% VMA	14.50	13.30 - 15.70

PERCENT BINDER	4.5	5.0	5.5	6.0
MAXIMUM SPECIFIC GRAVITY	2.477	2.459	2.441	2.424
BULK SPECIFIC GRAVITY	2.373	2.386	2.393	2.399
% AIR VOIDS IN TOTAL MIX	4.2	3.0	2.0	1.0
% V. M. A.	14.5	14.5	14.7	14.9
% VOIDS FILLED	71.2	79.5	86.6	93.2

EFFEC. SPECIFIC GRAVITY: 2.651 TSR(%): 94.3 WET TS:(kPa) 929.1

TYPE AND GRADE OF BINDER: Honeywell 7686 with Lime BINDER SPEC. GR.: 1.034

DESIGN DUST TO ASPHALT RATIO: 0.64

4.8 % Asphalt recommended with permissible variation of: 0.4 This mix is satisfactory and meets SCDOT specs

specification for use in Aggregate I

REMARKS:

NOTE → #N/A

Table C-4 Job Mix Formula of Surface A PG76-22 (Plastomer 2 without Lime)

PLANT LOCATION:	0	MIX DES	0	JOB MIX	**0**
TYPE MIX:	Aggregate I	DATE APPROVED:			
CONTRACTOR:	0	DATE OF LAST REV.:		NO. OF REVISIONS:	
CONTROL METHOD:		DATE VOID:			

	Source of Aggregate	**Type of Aggregate**	**% Agg.**	**Ap. Sp. Gr.**
1	Aggregate I	57	10	2.63
2	Aggregate I	789	47	2.63
3	Aggregate I	MS	14	2.63
4	Aggregate I	RS	17	2.63
5	Hydrated Lime	Lime	0	
6	-4 RAP (CR)	-4 RAP	12	

SIEVE	**GRADATION**						**COMB.**				
	1	**2**	**3**	**4**	**5**	**6**	**GRAD.**	**TARGET**	**LIMITS**		
1 1/2" / 37.5 mm	100	100	100	100	100	0	100	99.8	100	-	100
1" / 25.0 mm	100	100	100	100	100	0	100	99.8	100	-	100
3/4" / 19.0 mm	86.7	100	100	100	100	0	99	98.5	98	-	100
1/2" / 12.5 mm	35.4	94.7	100	100	100	0	91	90.9	90	-	100
3/8" / 9.5 mm	7.5	70.6	100	100	100	0	77	76.7	70	-	84
#4 / 4.75 mm	0.6	17.4	96.6	97.7	91.8	0	49	49.2	42		56
#8 / 2.36 mm	0.5	3.6	81.0	80.8	70.3	0	35	35.3	28	-	42
#30 / 0.60 mm	0.4	0.9	38.6	41.8	36.2	0	17	17.7	11	-	24
#100 / 0.150 mm	0.3	0.4	6.8	13.3	7.5	0	4.4	5.0	1		9
#200 / 0.075 mm	0.2	0.3	2.6	8.2	3.3	0	2.33	3.1	1	-	5
OPTIMUM BINDER CONTENT,%								4.9	4.50	-	5.30
% AIR VOIDS								3.70	2.80	-	5.20
% VMA								14.92	13.72	-	16.12

PERCENT BINDER	4.5	5.0	5.5	6.0
MAXIMUM SPECIFIC GRAVITY	2.474	2.456	2.438	2.421
BULK SPECIFIC GRAVITY	2.351	2.373	2.388	2.394
% AIR VOIDS IN TOTAL MIX	4.9	3.4	2.1	1.1
% V. M. A.	15.2	14.9	14.8	15.0
% VOIDS FILLED	67.4	77.2	86.0	92.6

EFFEC. SPECIFIC GRAVITY: 2.647 TSR(%): 87.6 WET TS:(k 794.7

TYPE AND GRADE OF BINDER: Honeywell 7686 without Lime BINDER S 1.034

DESIGN DUST TO ASPHALT RATIO: 0.62

4.9 % Asphalt recommended with permissible variation of: 0.4 This mix is satisfactory and meets SCDOT specs

specification for use in Aggregate I

REMARKS:

NOTE → #N/A

Table C-5 Job Mix Formula of Surface A PG76-22 (Plastomer 3)

PLANT LOCATION:	0	MIX DESIGN LAB NO.:	0	JOB MIX NO.:	**0**
TYPE MIX:	Aggregate I	DATE APPROVED:			
CONTRACTOR:	0	DATE OF LAST REV.:		NO. OF REVISIONS:	
CONTROL METHOD:		DATE VOID:			

	Source of Aggregate	**Type of Aggregate**	**% Agg.**	**Ap. Sp. Gr.**
1	Aggregate I	57	10	2.63
2	Aggregate I	789	47	2.63
3	Aggregate I	MS	14	2.63
4	Aggregate I	RS	16	2.63
5	Hydrated Lime	Lime	1	
6	-4 RAP (CR)	-4 RAP	12	

SIEVE	**GRADATION**						**COMB.**		
	1	**2**	**3**	**4**	**5**	**6**	**GRAD.**	**TARGET**	**LIMITS**
1 1/2" / 37.5 mm	100	100	100	100	100	0	100	99.8	100 - 100
1" / 25.0 mm	100	100	100	100	100	0	100	99.8	100 - 100
3/4" / 19.0 mm	86.7	100	100	100	100	0	98	98.5	98 - 100
1/2" / 12.5 mm	35.4	94.7	100	100	100	0	91	90.9	90 - 100
3/8" / 9.5 mm	7.5	70.6	100	100	100	0	77	76.7	70 - 84
#4 / 4.75 mm	0.6	17.4	96.6	97.7	91.8	0	49	49.2	42 56
#8 / 2.36 mm	0.5	3.6	81.0	80.8	70.3	0	35	35.3	28 - 42
#30 / 0.60 mm	0.4	0.9	38.6	41.8	36.2	0	18	17.7	11 - 24
#100 / 0.150 mm	0.3	0.4	6.8	13.3	7.5	0	5.0	5.0	1 9
#200 / 0.075 mm	0.2	0.3	2.6	8.2	3.3	0	3.05	3.0	1 - 5

OPTIMUM BINDER CONTENT,%	4.8	4.40 - 5.20
% AIR VOIDS	3.70	2.80 - 5.20
% VMA	14.71	13.51 - 15.91

PERCENT BINDER	4.5	5.0	5.5	6.0
MAXIMUM SPECIFIC GRAVITY	2.474	2.456	2.438	2.417
BULK SPECIFIC GRAVITY	2.360	2.380	2.399	2.399
% AIR VOIDS IN TOTAL MIX	4.6	3.1	1.6	0.8
% V. M. A.	14.9	14.6	14.4	14.7
% VOIDS FILLED	69.0	78.9	88.9	94.7

EFFEC. SPECIFIC GRAVITY: 2.648 TSR(%): 92.4 WET TS:(kPa) 1016.2

TYPE AND GRADE OF BINDER: Honeywell 7205 BINDER SPEC. GR.: 1.034

DESIGN DUST TO ASPHALT RATIO: 0.64

4.8 % Asphalt recommended with permissible variation of: 0.4 This mix is satisfactory and meets SCDOT specs

specification for use in Aggregate I

REMARKS:

NOTE → #N/A

Table C-6 Job Mix Formula of Surface A PG76-22 (SBS+Plastomer 3)

PLANT LOCATION: 0 MIX DESIGN LAB NO.: 0 JOB MIX NO.: **0**

TYPE MIX: Aggregate I DATE APPROVED:

CONTRACTOR: 0 DATE OF LAST REV.: NO. OF REVISIONS:

CONTROL METHOD: DATE VOID:

	Source of Aggregate	**Type of Aggregate**	**% Agg.**	**Ap. Sp. Gr.**
1	Aggregate I	57	10	2.63
2	Aggregate I	789	47	2.63
3	Aggregate I	MS	14	2.63
4	Aggregate I	RS	16	2.63
5	Hydrated Lime	Lime	1	
6	-4 RAP (CR)	-4 RAP	12	

SIEVE		**GRADATION**						**COMB.**		
		1	**2**	**3**	**4**	**5**	**6**	**GRAD.**	**TARGET**	**LIMITS**
1 1/2"	/ 37.5 mm	100	100	100	100	100	0	100	99.8	100 - 100
1"	/ 25.0 mm	100	100	100	100	100	0	100	99.8	100 - 100
3/4"	/ 19.0 mm	86.7	100	100	100	100	0	98	98.5	98 - 100
1/2"	/ 12.5 mm	35.4	94.7	100	100	100	0	91	90.9	90 - 100
3/8"	/ 9.5 mm	7.5	70.6	100	100	100	0	77	76.7	70 - 84
#4	/ 4.75 mm	0.6	17.4	96.6	97.7	91.8	0	49	49.2	42 56
#8	/ 2.36 mm	0.5	3.6	81.0	80.8	70.3	0	35	35.3	28 - 42
#30	/ 0.60 mm	0.4	0.9	38.6	41.8	36.2	0	18	17.7	11 - 24
#100	/ 0.150 mm	0.3	0.4	6.8	13.3	7.5	0	5.0	5.0	1 9
#200	/ 0.075 mm	0.2	0.3	2.6	8.2	3.3	0	3.05	3.0	1 - 5

OPTIMUM BINDER CONTENT,%	4.8	4.40 - 5.20
% AIR VOIDS	3.74	2.80 - 5.20
% VMA	14.67	13.47 - 15.87

PERCENT BINDER	4.5	5.0	5.5	6.0
MAXIMUM SPECIFIC GRAVITY	2.458	2.440	2.423	2.406
BULK SPECIFIC GRAVITY	2.363	2.351	2.370	2.400
% AIR VOIDS IN TOTAL MIX	3.8	3.7	2.2	0.3
% V. M. A.	14.1	15.0	14.8	14.2
% VOIDS FILLED	72.8	75.6	85.3	98.2

EFFEC. SPECIFIC GRAVITY: 2.628 TSR(%): 95.7 WET TS:(kPa) 1125.7

TYPE AND GRADE OF BINDER: SBS+Honeywell 7205 BINDER SPEC. GR.: 1.034

DESIGN DUST TO ASPHALT RATIO: 0.64

4.8 % Asphalt recommended with permissible variation of: 0.4 This mix is satisfactory and meets SCDOT specs

specification for use in Aggregate I

REMARKS:

NOTE → #N/A

Chapter 10 - References

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