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Laboratory Evaluation of Anti-Strip Additives in Hot Mix Asphalt

FINAL REPORT

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16. Abstract

The use of hydrated lime or other liquid anti-stripping agents (ASA) is the most common method to improve the moisture susceptibility of asphalt mixes. However, most laboratory test conditions used to evaluate the moisture susceptibility of the mixes are only for a short duration of time. This might not be a good representation of the field conditions (i.e., several months or years of service). Thus, a study to evaluate the effects of conditioning the mixes for longer durations was initiated. Also, another problem with the use of the liquid anti-stripping agents is their heat storage stability. This report addresses these two issues, by preparing and testing mixtures made with fresh binder for indirect tensile strength after conditioning the samples for 1, 7, 28, 90 and 180 days, and samples prepared from binder stored for 3 days at 163^{o}C after conditioning them for 1, 28 and 90 days. The results of this study indicated that hydrated lime and the liquid anti-stripping agents were equally effective for the mixes used in this research when conditioned beyond 1 day. In the case of samples prepared from stored binder, there was no significant difference in the effectiveness of hydrated lime and the liquid anti-stripping agents even after conditioning for 1 day. Though it was observed that none of the ASA treatments performed better than others in the case of samples prepared with stored binder, it was also observed that almost all mixes gave significantly similar wet ITS and TSR values as samples prepared from fresh binder.

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DISCLAIMER

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CHAPTER I: INTRODUCTION

Some state highway departments have problems with hot mix asphalt (HMA) pavements failing prematurely due to moisture damage. Moisture damage, also referred to as stripping, occurs due to loss of adhesion between the asphalt binder and aggregate and/or loss of cohesion within the asphalt binder (Hicks 1991). Measures to prevent such failure have included the addition of anti-strip additives (ASAs) to the HMA mixtures. Examples of ASAs include hydrated lime, hydraulic cement, and several liquid ASAs.

Currently, the South Carolina Department of Transportation (SCDOT) specifies the use of hydrated lime as an ASA. This was based on research conducted in the 1980s (Busching *et al* 1986). This research concluded that liquid ASAs were not as effective in preventing moisture damage as hydrated lime since the wet indirect tensile strengths and tensile strength ratios were lower for HMA mixtures containing liquid ASAs as compared to mixtures containing hydrated lime. Also, each particular liquid ASA was not compatible with all asphalt binder and aggregate sources used in South Carolina whereas, hydrated lime performed well with all binder and aggregate sources tested for the research project. Finally, there were storage stability problems and concerns about long-term performance of liquid ASAs that led to the decision to use hydrated lime.

In the past 20 years, new liquid ASAs have been developed that have been shown to be as effective as hydrated lime and more storage stable than earlier liquid ASAs (Tunnicliff 1997, Kennedy and Ping 1991, and Mazuch and Jeffery 1995). Due to these developments, a new evaluation of anti-strip additives was needed to determine the suitability for liquid ASA usage in South Carolina.

The major objective of this study was to investigate the use of ASAs in HMA in the laboratory. The specific objectives of this study included the following:

A. Conducting a literature survey of the latest uses of anti-strip additives in hot mix asphalt. This included a survey of the several southeastern state highway departments (North Carolina, Georgia, Florida, Tennessee, Alabama, and Virginia). This survey included the states that have evaluated in-place stripping. A survey of current users of the StripScan™ *Anti-Strip Measurement System* for determining the quantity of liquid ASA content of HMA mixtures was also conducted to evaluate the potential use by the SCDOT.

B. Conducting SCDOT Surface Type B mix designs using three aggregate sources (micaceous granite, granite, and marble schist), PG 64-22 asphalt binder from two sources, and the following ASAs:

    1. Hydrated lime
    2. Liquid ASA 1
    3. Liquid ASA 2
    4. Liquid ASA 3
    5. Control (no ASA)

C. Determining the heat and storage stability of the liquid ASAs when blended with asphalt binder by conducting moisture susceptibility tests per SC-T-70 (see D.1. below) and conducting the following binder tests on each binder containing each ASA (fresh and after storage):

    1. Rotational viscosity (original)
    2. Dynamic shear rheometer (original, RTFO aged, and PAV aged)
    3. Bending beam rheometer (PAV aged)
    4. Gel permeation chromatography (GPC)

D. Evaluating the moisture susceptibility of mixtures using the following tests:

    1. Tensile strength ratio (SC-T-70, *Modified AASHTO T 283*)
        a. 1-day conditioning (SC-T-70): (n = 4)
        b. 7-day conditioning (SC-T-70): (n = 4)
        c. 28-day conditioning (SC-T-70): (n = 4)
        d. 90-day conditioning (SC-T-70): (n = 4)
        e. 180-day conditioning (SC-T-70): (n = 4)
    2. Boil test (ASTM D 3625) (n = 3)

E. Evaluating the effects of ASAs on the asphalt binder content determined by the ignition oven. Methods of qualitatively and quantitatively determining the hydrated lime content in HMA mixtures after being tested in the ignition oven were also surveyed.

F. Providing the recommendations regarding the following:

    1. Potential changes to mix design procedures when liquid ASAs are used,
    2. Additional test methods to be used to evaluate stripping in HMA mixtures, and
    3. Potential specifications for laboratory and field implementation of liquid ASAs.

Background and Significance of the Work

Premature failure of hot mix asphalt pavements due to stripping has been a major problem for state highway departments since the 1970s. The increase in stripping occurrences since the 1970s has been attributed to many factors (Kandhal and Rickards 2001), but the state highway departments have been able to minimize the moisture damage to most pavements through a proper pavement design, asphalt mix design (addition of ASAs), and quality control measures. In South Carolina, after an extensive research project, the SCDOT implemented the use of hydrated lime in all SCDOT approved mixtures (Busching *et al* 1986). This implementation came after stripping continued to be a significant problem through the 1980s despite the routine use of liquid ASAs. The use of hydrated lime has resulted in a major reduction in stripping occurrences in South Carolina.

The material selection stage of the mix design process has shown to be crucial in preventing stripping in pavements. When selecting materials, technicians conducting mix designs have the ability to exclude strip-prone aggregates or select appropriate anti-strip additives in order to prevent stripping. A variety of ASAs have been utilized for this purpose by many states. There are several liquid ASAs that may be effective in preventing stripping in South Carolina pavements, but there are many issues that must be addressed prior to allowing the use of such materials in asphalt mix designs.

Benefits

There are many different types of ASAs available that have the potential to be effective in preventing stripping of asphalt mixtures. While hydrated lime is the most popular ASA in many states, liquid ASAs may prove to be cost effective alternatives for stripping protection. Also, liquid ASAs can be terminally blended, which could simplify production at asphalt plants. Liquid ASAs may have the possibility of being considered as a feasible alternative to hydrated lime in South Carolina depending on the results of this study.

CHAPTER II: LITERATURE REVIEW

The best efforts of highway engineers in the design and construction of asphalt pavements are often undermined by environmental factors such as water, temperature variations, sunlight, etc. These individual factors are not individually harmful, but when coupled with large volumes of traffic, they frequently lead to significant problems with the durability of the pavements. In this case, moisture can be a major environmental contributor to the premature deterioration of asphalt pavements. Its effects can be minimized – in some cases, eliminated – by proper construction practices that emphasize good design, mixing, and compaction. Despite these efforts, when a highway failure occurs, many times water is cited as the prime suspect. In addition, many other factors such the material's characteristics affect the performance of the mixtures. Some binder/aggregate combinations are simply more susceptible to moisture induced damage.

Water affects asphalt concrete in various ways. It may act directly and literally strip binder from the aggregate. However, generally, the effects are more subtle. Water weakens the structure to a point where the mix can no longer sustain the traffic it was designed to support, and finally fails under the repeated loading.

Stripping produces several forms of distress, including localized bleeding, rutting, shoving, etc., and ultimately the complete failure of the asphalt pavement. Although it is not completely understood why stripping occurs in some pavements and not in others, it is not hard to conclude that stripping reduces the pavement's performance, increases its maintenance cost, produces an inferior ride quality, and ultimately produces an overall higher life cycle cost. For this reason, many highway agencies are requiring the use of ASAs in the asphalt pavements to prevent the moisture induced damages. For many years, hydrated lime was widely used as an ASA to reduce the problem of stripping in the HMA. Liquid ASAs, such as Redicote 82-S and Tall Oil Z-940 have also been reported to produce results comparable to the hydrated lime, with easier application, safer operation and lower costs (Selim 1997). 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 anti-stripping additive (Busching *et al* 1986). Also, the heat stability of liquid ASAs at the time was an issue. 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 was needed to select the most effective ASA properties for use in South Carolina.

Moisture Susceptibility

Moisture susceptibility is the tendency of HMA toward stripping. The loss of integrity of an HMA mix through the weakening of the bond between the aggregate and the binder is known as stripping. Stripping usually begins at the bottom of the HMA layer, and gradually travels upward. A typical situation is the gradual loss of strength over the years, which causes many surface manifestations like rutting, corrugations, shoving, raveling, cracking, etc. (Roberts *et al* 1996). This makes identification of stripping very difficult. Also, it may take many years for the surface indicators to appear. To prevent moisture susceptibility, proper mix design is essential. However, even with a proper mix design, if the mix is not compacted properly, it may still be susceptible to moisture damage. Thus, HMA should be tested in a situation where moisture can infiltrate into the air voids of the mixture. For this reason, the tests for moisture susceptibility are done on mixes containing 7 ± 1 percent air voids (Hunter and Ksaibati 2002).

Causes of Stripping

Several mechanisms contributing to stripping have been identified. These mechanisms include emulsification, detachment, displacement, pore pressure, film rupture, etc. Research conducted at the National Center for Asphalt Technology (NCAT) under the Strategic Highway Research Program (SHRP) A-003B Project has shown that the physicochemical surface properties of mineral aggregate are more important for moisture induced stripping of the HMA compared to the properties of the binder. Some of the aggregates are inherently susceptible to stripping. However, there are also other external factors and in-place properties that lead to the deterioration of the HMA. Some of the other factors for the moisture induced stripping of the HMA are as follows (Kandhal 1994).

Inadequate Pavement Drainage

Inadequate surfaces or subsurfaces produce water or moisture vapor, which is the necessary catalyst to induce stripping. There have been case histories where stripping was not a general phenomenon occurring on the entire project site but only in areas that were over-saturated with water due to inadequate drainage (Kandhal 1994).

Water can enter the HMA pavement in many ways. It can enter as surface runoff from cracks and other openings. It can also enter from the sides and the bottom as seepage from ditches or from a high water table. Water often moves upward by the capillary action from the bottom of the pavement. Many sub-bases and sub-grades in the existing highways lack the desired permeability, and are therefore, saturated with capillary moisture. The air voids in the HMA can become saturated with water, even from the vapor condensation from water in the sub-grade and the sub-base. A temperature rise after this saturation, and traffic stresses can lead to significant void pressure when the voids are saturated (Kandhal 1994).

If the HMA is permeable, water could flow out from the voids under the pressure and relieve the developed pressure. If not, the tensile stresses developing can break the bond between the binder and the aggregate. This damage due to void water pressure is internal and the exterior sides of the specimen do not show any signs of stripping unless they are opened for visual examination.

Inadequate Compaction

Most agencies specify an air content in the HMA mat of about 8% during construction, which is further compacted by traffic to about 4-5%. Studies indicate that when the air content is about 4-5%, the pores are not interconnected, and thus almost impervious to water (Kandhal 1994). However, if good compaction control is not exercised, the pavement would have a higher air content, leading to the ingress of water, causing moisture damage to the pavement. Also, if the pavement remains pervious to water for a long period of time, moisture damage can also be caused due to the hydrostatic pore pressure caused by traffic.

Excessive Dust Coating on the Aggregate

The presence of dust and clay coating on the aggregate can inhibit the intimate contact between the binder film and the aggregate, thereby forming channels for penetrating water. The binder coats the dust coating and is not in contact with the aggregate surface.

Some very clayey material may cause stripping by emulsifying the binder in the presence of water.

Action of the Traffic

After any rain shower, the water in the pavement is pressed into the underlying layer by truck tires. This causes tremendous hydrostatic stresses, leading to the breaking of the bond between the binder and the aggregate. This is especially severe in the case of open graded friction courses due to the high air content.

Stripping can also be caused by the mechanism of hydraulic scouring; however, this is applicable only to the surface courses. Scouring starts at the surface and progresses downward. The water gets forced down into the pavement in the front of the tire, and it is immediately suctioned out of the pavement from behind the tire. This compression – tension cycle causes hydrostatic stresses leading to the stripping of the binder film from the aggregate surface.

Inadequate Drying of Aggregates

When the aggregate is coated with binder, a dry aggregate surface will better adhere to the binder than a wet surface. As the hot binder is introduced to the wet aggregate surface, the moisture on the surface of the aggregate vaporizes and does not allow the binder to coat the aggregate well.

Weak Aggregates

If weak and friable aggregates are used in the mix, degradation takes place during rolling and later under heavy traffic loads. Degradation and delamination exposes new uncoated aggregate surfaces that can absorb moisture and initiate stripping problems.

Water Proofing Membranes and Seal Coats

If the source of moisture is from below the pavement, which is usually the case, the application of a water proofing membrane or a seal coat can be detrimental. The moisture that reaches the bottom of the pavement from ground water, shoulders, median, etc., migrates through the pavement by capillary action. Above the capillary fringe, the water moves as vapor, and if its movement is obstructed by a seal coat or a water proofing membrane, the vapor condenses under the sealing layer. It is again converted to vapor, when heated by the sun light, causing significant vapor pressure and leads to stripping in the pavement.

Factors Affecting Stripping

Based on the Pedestal tests conducted by Graf (Graf 1986), the following factors were determined to affect the moisture susceptibility of the HMA.

Aggregate Type

Studies have shown that mixes with limestone show superior resistance to moisture induced damage (Graf 1986). Pure silicates show poor resistance, and granites range from poor to very good in their resistance to moisture damage. Aggregate shape is also an important factor. Angularity and heterogeneity promote mechanical interlocking and overall higher life cycle. Additionally, the surface texture of the aggregate is an important factor that relates to stripping. Rougher surfaces, allow for a stronger bond between the binder and the aggregate. This is one reason that uncrushed river gravel is not approved for asphalt in many instances – the surface is much smoother than crushed material.

Void Content

The overall performance of a pavement is also dependent on the void content of the HMA. The chance of stripping increases as the percentage of air voids increases, as there is more room for moisture to enter the mix and induce hydrostatic forces in the mix. Studies show that the Pedestal test life falls sharply as the void content in the HMA increases (Graf 1986).

Addition of ASA

There are many ASAs available and they all work differently in improving the bond between the aggregate and the binder film. Thus, the use of a particular type of ASA also affects stripping in HMA. Also, each ASA has a different effect on various aggregate sources. Thus, this variability also effects stripping in HMA relative to the type of ASA used.

Mixing Temperature

Sometimes, the aggregates are not heated for sufficient time in an asphalt plant, which can lead to lower mixing temperatures. At lower mixing temperatures, the viscosity of the binder is lower, and thus, the binder will not be able to form a uniform film thickness around the aggregate.

HMA Storage Time

Every time a truck is loaded, there is a possibility that air gets into the storage silos. This air oxidizes the binder, thereby making it hard and brittle. Thus, it can easily strip off the aggregate.

pH Instability

Studies by Kennedy, Scott, and others have indicated that the stripping is also effected by the pH of the water coming in contact with the HMA (Kiggundu and Roberts 1988). The pH of contact water can cause the value of the contact angle to shift, thereby affecting the wetting characteristics of the interface region. The results indicated that coating retention decreased as the pH increased. These results strongly suggest that stabilization of the pH sensitivity at the binder/aggregate interface would minimize the potential for bond breakage, providing strong durable bonds and hence reducing stripping.

Methods to Prevent Stripping

The best way to prevent stripping will be to test the mixture in the laboratory and to use an aggregate/binder combination that does not strip. However, this will not always be possible due to many reasons such as, lack of suitable aggregates, increased costs in the transportation of certain aggregates, political constraints, etc. Even in spite of having the mix not be susceptible to moisture in the laboratory, there is not much certainty that the mix will behave the same in the field. To make sure that a mix behaves the same in the field as in the lab, proper care should be taken in the construction of the pavement, such as providing proper drainage, especially sub-surface drainage, using proper compaction techniques and providing an adequate number of roller passes at the proper compaction temperature, etc.

Different types of aggregate pre-treatments have also shown to improve the moisture susceptibility of the mix. Some of the pre-treatments include pre-heating the aggregate to evaporate the moisture, weathering, washing to remove surface dirt, crushing, etc. It has also been shown that aggregates coated with asphalt or other recycled materials are better at resisting the moisture damage in the HMA than are virgin materials (Hunter and Ksaibati 2002).

However, even after taking all the above precautions, there is still a chance that a pavement will suffer damage due to moisture. One good way of increasing the resistance of the mix to moisture damage is to add an ASA to the mix. However, the addition of an ASA from an approved list of sources should not be considered as "insurance" as some ASAs are aggregate and binder specific, and therefore, may not be effective in all mixes; they could even be detrimental at times. Thus, a proper study of the mix should be done by systematically testing the mix for moisture susceptibility by tests such as Indirect Tension Testing (ITS), Lottman's Laboratory Test, the Boiling Water Test, etc. in the laboratory.

Anti-Stripping Agents

ASAs are substances designed to chemically improve the adhesion between the asphaltic binder and the aggregates. They are available in both liquid and solid forms. Hydrated lime has been widely used as an ASA for reducing the moisture susceptibility of HMA. Some other solid ASAs used are Portland cement, fly-ash, flue dust, etc. The liquid ASAs used include liquid amines and diamines, liquid polymers, etc.

Lime

Addition of lime is the most accepted way to reduce the moisture susceptibility of HMA in many parts of the country. The general practice is to add 1 to 1.5 percent of lime by the dry weight of the aggregate to the mix. If the aggregate contains more fines, more lime may be required to be added to the mix due to the increased surface area of the aggregate. Generally, three forms of lime are used in HMA: Hydrated Lime ($Ca(OH)_2$), Quick Lime (CaO), and Dolomitic Lime (Hunter and Ksaibati 2002).

It is assumed that the mechanism by which hydrated lime improves the moisture susceptibility of the HMA involves a chemical interaction between the calcium in the lime with the silicates in the aggregate (Selim 1997). Hydrated lime has proven to work effectively in a wide variety of aggregate sources.

Several methods exist for adding lime to a mixture. It may be added by sprinkling it over the pre-wetted coarse aggregate as it passes over the conveyer belt, or it may be added in the form of a slurry. Georgia DOT specifies the addition of dry lime just before the addition of the binder. However, there are problems with both techniques. When added in the dry form, the main concern is the coating of the aggregate. Also, adding the lime in a drum mix plant is ineffective as much of the lime is lost before the addition of the binder (Hunter and Ksaibati 2002). If lime is added in a slurry form, it will increase the amount of fuel needed to heat the aggregate, and thus increase the production cost. Also, some of the other concerns regarding the addition of the lime are health hazards due to inhalation and skin exposure (Selim 1997).

Liquid Anti-Stripping Agents

Recently, with the advent of new liquid ASAs in the market, and because of its 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 surface and the asphalt binder. When surface tension is reduced, increased adhesion of the binder to the aggregate is promoted. For this reason, they are also called surfactants. They are normally added in doses between 0.5 and 1.5 percent by weight of the binder (as recommended by the manufacturer).

The liquid ASA may be added either to the aggregate directly, 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.

Tests to Quantitatively Measure ASAs in Asphalt

In recent years methods have been developed to determine the quantity of ASAs present in HMA mixtures. Separate methods have been developed for lime and liquid ASAs.

Determination of Lime Content and Quality in HMA Mixtures

A recent study at the Turner Fairbank Highway Research Center was completed to identify a method or methods to quantitatively measure the presence of hydrated lime in an asphalt mixture. While there are current methods to determine the presence of hydrated lime, they are not able to measure the quantity or quality of the lime. From this study, two methods were identified that have the ability to measure not only the amount of hydrated lime present in a given mixture, but also to determine the quality of the lime. The first method uses Fourier Transform Infrared (FTIR) spectroscopy to identify the presence of the hydroxyl group in $Ca(OH)_2$ (hydrated lime). This is identified as a peak at a wave number of 3640 cm^{-1} in the FTIR spectrum. Either the area under this peak or the height of this peak, which produced slightly more accurate results, can be used to determine the quantity of hydrated lime present in the mix. The presence of a second and possibly third peak at a wave number of 1390 cm^{-1} and 866 cm^{-1}, respectively indicates the presence of calcium carbonate in the mix. Calcium carbonate, which is an impurity, forms as a result of the reaction of lime with carbon dioxide in the air resulting in poor quality lime (Arnold *et al* 2006).

The second method, which is more time consuming than FTIR, which takes only about 30 seconds to get a result, is a chemical analysis conducted on a sample of dust cored from a compacted specimen. The dust collected from drilling a hole in the sample is first boiled in a 4% acetic acid solution for 30 minutes and the resulting extract is analyzed by either Atomic Absorption Spectroscopy or Ion Exchange Chromatography to determine the amount of lime present in the sample. This method was more accurate than the FTIR method, but did require more time and labor to complete (Arnold *et al* 2006).

Determination of Liquid ASA in HMA Mixtures

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 cases 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).

To determine the amount of additive present in the mixture or binder, it is necessary to develop a calibration curve for a specific binder, aggregate, and/or ASA combination. The calibration curve can be generated by mixing the ASA at various contents and running each through the StripScan.

In 2004, an evaluation of the StripScan was completed by the Virginia Transportation Research Council (Maupin 2004). In this study, three binder grades, two binder sources, three aggregate sources, and four liquid ASAs were evaluated for a total of 24 binders and 36 mixtures tested. The results of this study indicated that the StripScan was able to predict the additive content within ± 0.2% for approximately 60% of the binders and mixtures tested. After minor modifications to the test method, the accuracy of the test results was further improved. Additionally, based on the requirement to establish calibration curves for each type of mixture, it would be difficult to accurately estimate the additive content of an old pavement due to the aging that the pavement endures. This would limit the use of the StripScan for forensic testing to simply determining the presence of a liquid ASA (Maupin 2004).

Tests to Evaluate Anti-Stripping Agents

Numerous studies have involved the development of indicator tests for stripping. These efforts have produced tests which use semi-subjective and subjective assessments to infer the stripping potential. The tests may be broadly classified into two categories: 1) qualitative and 2) quantitative or engineering based tests to evaluate stripping.

Qualitative Tests to Evaluate Stripping

Some of the tests in this category are:

- ASTM D 3625: **“**Standard Practice for Effect of Water on Bituminous Coated Aggregates using Boiled Water”
- The Texas Freeze-Thaw Pedestal Test
- Gagle procedure
- The Quick Bottle test
- The Rolling Bottle Method, and many others.

The l0-minute boil test (ASTM D 3625) is a field oriented test in which a mixture (plant or other) is boiled for l0-minutes and visually observed for coating retention. It is considered that 95 percent and higher retained coating indicates a “passing” mixture whereas below 95 percent denotes “failure”. The test is considered unfavorable because of the subjectivity of the rating pattern and rarity of users. Efforts are underway in ASTM D04.22 to revise this test (Kiggundu and Roberts 1988).

The Texas Freeze-Thaw Pedestal Test is conducted on an HMA mix with uniform aggregate sizes. Since a uniform aggregate size is used, the effects of mechanical properties of the aggregate are minimized in the test; thus, maximizing the effects of bonding. To perform the test, the asphalt and aggregate are mixed using the Texas Mixture Design Procedure. After initial mixing, the mixture is reheated and mixed two additional times. The specimens of height 19.05 mm (0.75 in.) and diameter 41.3 mm (1.6 in.) are then subjected to freeze-thaw cycles. The number of freeze thaw cycles to induce cracking indicates moisture susceptibility of the HMA. Studies indicate that mixtures that were not susceptible to moisture survived more than 20 cycles (Hunter and Ksaibati 2002).

The Gagle procedure was developed to test the finer portion of the grading for adhesion potential with binders. The amount of tanning a binder-aggregate mixture or pellet undergoes after 24 hour immersion in distilled water was reported to be indicative of the adhesion potential of the mixture. It has been a localized test and there is no evidence of continued use of this test (Kiggundu and Roberts 1988).

The Quick Bottle Test is used to judge coating ability of a binder-additive blend on Ottawa sand. The mixture is vigorously shaken under water after which the supernatant is drained and the sand-binder mixture emptied on a paper towel for coating observation. The results are usually reported as pass or fail. This test has been conducted by a number of state highway departments.

The Rolling Bottle Method test, used in Sweden, has been reported as a predictor for percent coating. A single coated aggregate particle is dropped in a half-filled bottle of distilled water until the required sample size is obtained. The distilled water is maintained at 41°F (5°C) in order to inhibit agglomeration potential of the coated aggregates. Bottles containing the sample are placed in a rolling machine which turns at 40 rpm if the asphalt mixture is additive free, otherwise 60 rpm. This test runs for three days with two independent evaluations of the coating recommended at 5, 24, 48, and 72 hours after the start of the test.

These evaluations are used to determine the mean degree of coverage as the test statistic. Other tests include Dye Adsorption, Mechanical Integration Method, Radioactive Isotope Tracer Technique, Tracer-Salt with Flame Photometer Analysis, Light-Reflection Method, A Chemical Immersion Test by Reidel and Weber, Abrasion Displacement, Briquette Soaking, Swell, Peeling, Detachment, and Stripping Coefficient Measurement (Kiggundu and Roberts 1988). The general relative use of these methods is fairly low.

Quantitative or Engineering Based Tests to Evaluate Stripping

This group of tests is directed for making quantitative predictions, developing criteria for assessing failure, and applying or interpreting laboratory test results to predict field performance. These tests include:

- Lottman Test,
- Tunnicliff/Root Test,
- Modified Lottman Test,
- Immersion Compression Test,
- Resilient Modulus,
- The Double Punch Method,
- Dynamic Strip Method (Nevada),
- Cold Water Abrasion Test (Minnesota)

The Lottman Laboratory Test predicts the susceptibility of asphalt concrete mixtures to moisture damage. The test was developed by Lottman at the University of Idaho. The laboratory procedure that was developed was field tested in a research project (NCHRP 246). Nine specimens are used in this procedure. They are compacted to field air void content. The nine cores are split into three groups. Group one is the control group in which no conditioning is done. The second group cores are vacuum saturated with water for 30 minutes at 660 mmHg. These cores reflect field performance of the HMA mix for the first four years. The third group also is vacuum saturated, but then the cores are put through a freeze-thaw cycle. The cores are frozen at 0°F (-18°C) for 15 hours, and then thawed at 140°F (60°C) for 24 hours. These cores reflect field performance from the fourth to the twelfth year.

The Tunnicliff/Root Test was developed by modifying the test conditions of the Lottman test as follows:

- Load rate (2 in/min) compared to 0.065 in/min
- Test temperature 77°F (25°C) compared to 55°F (12.8°C)
- Presaturation of 55 to 80 percent compared to an unlimited level in the Lottman test
- Absence of a freeze cycle

This test is more preferred, by many states, to the Lottman test as it is faster than the Lottman test. However, it lacks the severity of the Lottman test, and also allows a number of stripping binder/aggregate systems to pass as non – stripping systems.

AASHTO accepted the Modified Lottman Test (AASHTO T-283) in 1985. It is a combination of the Lottman and the Tunnicliff and Root Tests. Six specimens are produced with air voids between six percent and eight percent. The specimens are then split into two groups. The first group is the control group. The second group is saturated between 70 and 80 percent with water and is placed in the freezer (0°F or -18°C) for 16 to 18 hours. The frozen cores then are moved to a water bath at 140°F (60°C) for 24 hours. After conditioning, the resilient modulus test and/or the indirect tensile strength (ITS) tests are performed. The ITS test is performed at 77°F (25°C) with a loading rate of 2 in/min. The ratio of the average tensile strengths of the wet cores and the dry cores is known as the tensile strength ratio (TSR). The minimum acceptable TSR as per AASHTO is 70% (AASHTO 2004).

The Immersion-Compression Test (AASHTO T-165) utilizes six cores. Each core is four inches in diameter and four inches in height. The cores are compacted with a double plunger at 3,000 psi for two minutes. An air void content of 6 percent is attained. The six cores are split into two groups. The first group is a control group. The second group is conditioned in a water bath at 120°F (49°C) for four days or at 140°F (60°C) for one day. After conditioning, the unconfined compressive strength of each core is found. A testing temperature of 77°F (25°C) and a loading rate of 0.2 in/min are used. The retained compressive strength is calculated. A retained strength of 70 percent is specified by AASHTO (AASHTO 2004).

The Immersion-Compression Test has produced retained strengths close to 100 percent even when stripping is visually evident in the cores. Thus, this test is not sensitive enough to measure damage induced by moisture (Hunter and Ksaibati 2002).

To test the resilient modulus, compacted specimens are tested along the diametrical plane by using a pulsating stress wave while deformations are recorded along the ends by linear-variable differential transducers (LVDTs). Both, moisture conditioned and dry sets, are evaluated and the mean wet modulus is divided by the mean dry modulus yielding a resilient modulus ratio. The suggested minimum ratio is 70 percent (Kiggundu and Roberts 1988).

In the Double Punch Method, compacted samples are tested by means of steel rods placed at either end of the specimen in a punching configuration. Tensile strength is computed from the peak load values. A strength ratio is determined between the wet and dry strengths as the test statistic. The double punch method was reported to produce lower retained strength ratios and hence considered to be more severe than the immersion compression test.

The Dynamic Strip Method is used predominantly by the Nevada DOT. Hveem specimens are soaked in a 140°F (60°C) water bath for six days, rapidly cooled to 41°F (5°C) by packing with ice, and tumbled through 1000 revolutions at 33 rpm. The conditioning and tumbling processes result in a durability index expressed by the amount of weight loss of the specimens, in percent. The maximum value of this index is 25 percent, above which severe stripping is considered likely to occur.

The Cold Water Abrasion Test is used by the Minnesota DOT for evaluating compacted briquettes for moisture damage susceptibility. A set of six briquettes is first conditioned in 140°F (60°C) oven for 24 hours. The set is then immersed in a 120°F (48.9°C) water bath for six days, cooled to room temperature followed by further cooling at 33°F (0.8°C) for one hour. Then the set is abraded in a tumbling machine at 33°F for 1000 revolutions in 34.5 minutes. The amount of abrasion loss, expressed as a percent of the original weight, is an indication of the moisture susceptibility of the set of briquettes. A maximum value of 25 percent is desirable (Kiggundu and Roberts 1988).

ASAs in the Southeastern U.S.

A review of six departments of transportation in the Southeastern U.S. was conducted to identify the usage of ASAs in HMA and any associated issues or concerns in the states surrounding South Carolina (Alabama, Florida, Georgia, North Carolina, Tennessee, and Virginia). All of the states surveyed allow the use of liquid ASAs for all asphalt mixes except for Georgia. The Georgia DOT only allows the use of liquid ASAs on off system roads. Hydrated lime (1% by weight of aggregate) is required in all other mixes. For the other states, it is the contractor's decision whether to use hydrated lime or liquid ASA. The contractor almost always selects the liquid ASA due to the reduced cost of the liquid ASA and the simplicity of incorporating it into the mix as compared to the hydrated lime. At the time this project began (2004), Virginia, Tennessee, and North Carolina 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 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, as well as TSR, to evaluate moisture susceptibility.

CHAPTER III: EXPERIMENTAL MATERIALS AND METHODS

In this study, the effects of liquid ASAs on HMA were evaluated in the laboratory. The research evaluated various materials (i.e., aggregates, binders, and ASAs) using multiple test methods and conditioning procedures. Figure 1 illustrates the experimental design for the binder source I portion of the study. The same design was used for binder source II. Figure 2 shows the experimental design for the binder testing phase of the project. Again, binder II was tested in the same manner.

Materials

Since the main objective of the study was to investigate the performance of different types of ASAs with respect to moisture susceptibility of various mixtures, it was important to evaluate not only different types of ASAs, but also various aggregate and binder sources. In South Carolina, certain aggregates have historically performed better than others with regard to moisture susceptibility. For this reason, three aggregates having various degrees of stripping were included in this study. The first aggregate (source A) was a crushed micaceous granite from upstate South Carolina. Aggregate A has historically had stripping problems when used in HMA mixtures without the use of some type of ASA. The second aggregate source (source B), also from upstate South Carolina, was a crushed marble schist having favorable performance with regard to moisture susceptibility. The final source of aggregate included in this study (source C) was crushed granite from the midlands of South Carolina, also not historically prone to stripping. Table 1 summarizes the properties of the three aggregate sources included in this study.

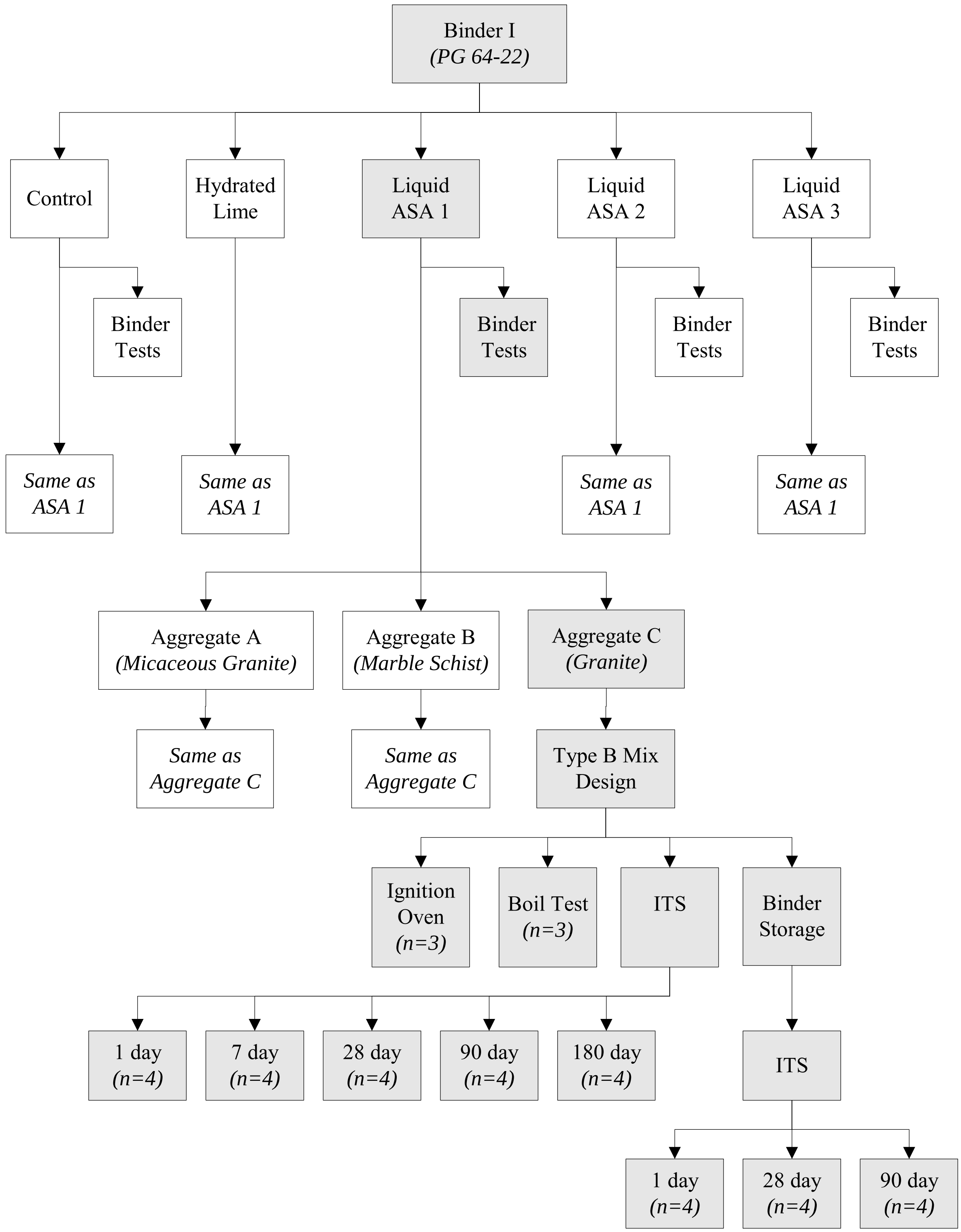


Figure 1: Flowchart of experimental design.

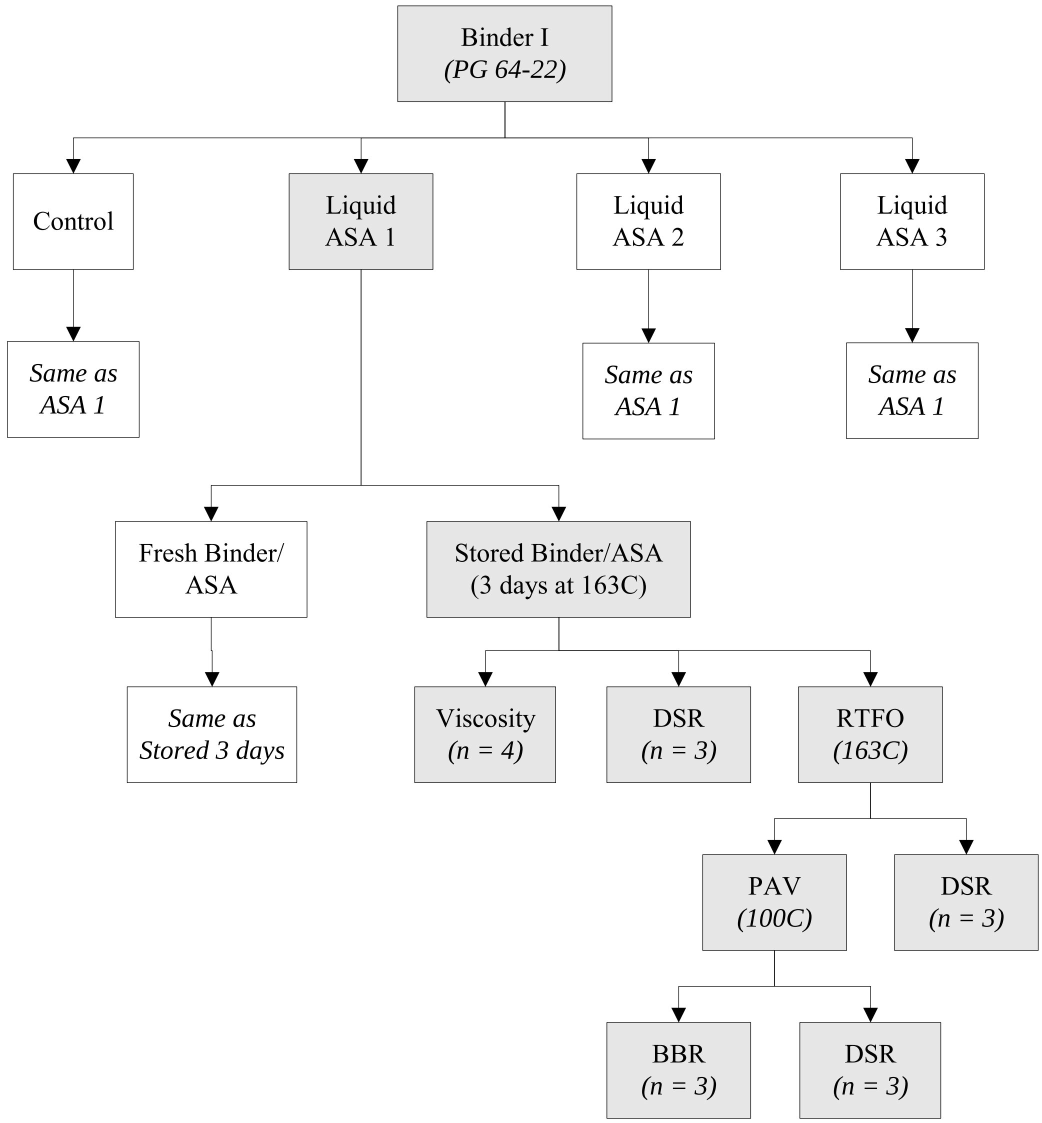


Figure 2: Flowchart for binder testing.

Table 1: Properties of aggregate sources.

Property		Aggregate A	Aggregate B	Aggregate C	Specification
Geology*		Micaceous Granite	Marble Schist	Granite	n/a
Bulk Specific Gravity*		2.67	2.82	2.61	n/a
Absorption* , *%*		0.6	0.1	0.5	n/a
L.A. Abrasion* , *% Loss*		51	41	21	≤ 60
Sand Equivalent*		67	47	60	≥ 40
Gradation, *% Passing*					
25.0 mm	*(1 in.)*	100	100	100	100
19.0 mm	*(3/4 in.)*	99	100	100	98 - 100
12.5 mm	*(1/2 in.)*	94	94	94	90 - 100
9.5 mm	*(3/8 in.)*	89	84	85	72 - 90
4.75 mm	*(No. 4)*	49	49	51	44 - 62
2.36 mm	*(No. 8)*	30	39	32	23 - 43
0.600 mm	*(No. 30)*	18	18	17	9 - 23
0.150 mm	*(No. 100)*	7	8	8	4 - 12
0.075 mm	*(No. 200)*	3.3	5.1	5.0	2 - 8

* *Information from SCDOT coarse aggregate approval sheet (2/12/06)*

In addition to the aggregate source, the binder source will also affect the ability of ASAs to prevent or minimize moisture induced damage of asphalt pavements. To study this variable, asphalt binders, having the same Performance Grade (PG 64-22), from two different crude sources were included in the study. Binder source I was from an unidentified mixture of sources and source II was a Venezuelan crude source. Both of these sources are commonly used to produce HMA in South Carolina. The properties of these binders are included in Table 2.

The major variable evaluated in this study was the ASA used in the HMA mixtures. Four different additives were included: hydrated lime and three liquid ASAs. Table 3 includes the properties of the three liquid ASAs included in the study. These three liquid ASAs were selected for this study based on a survey of departments of transportation in the Southeastern US, the suggestions of the suppliers, and the approval of the SCDOT steering committee for this specific study. Each liquid ASA was added to the asphalt binder at a dosage rate of 0.5% by weight of binder. This dosage rate was selected based on the manufacturers' recommended ranges. While each asphalt mix design is unique and would typically require a specific liquid ASA dosage, depending on the aggregate source and binder source and grade, a single dosage rate was selected for this study to limit the variables and to complete the work in the allotted duration.

Table 2: Properties of asphalt binders evaluated in this study.

Property		Binder I	Binder II
Original			
Viscosity, *Pa-s*	*(135 °C)*	0.405	0.626
G*/sinδ, *kPa*	*(64 °C)*	1.207	1.801
RTFO Residue			
Mass Change, *%*	*(163 °C)*	-0.02	-0.24
G*/sinδ, *kPa*	*(64 °C)*	2.815	4.608
PAV Residue			
G*sinδ, *kPa*	*(25 °C)*	2970	2420
Stiffness (60), *MPa*	*(-12 °C)*	183	129
m-value (60)	*(-12 °C)*	0.311	0.354
PG Grade		***64-22***	***64-22***
Mixing Temperature*, *°C*		150 - 155	163 - 170
Compaction Temperature*, *°C*		139 - 144	150 - 155

* *Information provided by supplier*

Table 3: Properties of liquid anti-strip additives.

Property*		Liquid ASA 1	Liquid ASA 2	Liquid ASA 3
Specific Gravity	*(25 °C)*	1.06	0.97	0.94
Viscosity, *cP*	*(25 °C)*	2000 - 4500	900	575
Flash Point, *°C*		170	> 148	> 200
Dosage, *%*		0.3 - 0.5	0.25 - 1.0	0.25 - 1.0

* *Information provided by supplier*

Methods

As indicated in Figures 1 and 2, there was a significant amount of testing conducted throughout the course of this study and, as such, there were several procedures followed for mix design, sample preparation, sample conditioning, and physical testing.

Asphalt Mix Design

To complete this project, eighteen (18) separate mix designs were conducted following SCDOT procedures and specifications for a Surface Type B mix (Tables 1 and 4) (SCDOT 2006). While there were thirty (30) total mix combinations, it was decided that the different liquid ASAs would not significantly alter the optimum binder content (OBC) of the mixes, so a mix design was conducted for ASA 1 and that OBC was used for the mixes containing ASAs 2 and 3. The mix design procedure is illustrated in Figure 3.

Table 4: Specifications for a SCDOT Surface Type B mixture.

Property	Specification
Dust/asphalt ratio	0.6 - 1.2
Void filled with asphalt (VFA), %	70 - 77
Voids in mineral aggregate (VMA), %	≥ 14.5

Storage of Asphalt Binders

The effects of storing binders containing liquid ASAs at high temperatures, as would be encountered when HMA production is delayed due to many factors (e.g., inclement weather), was also evaluated in this study. To simulate the storage of the binder in a tank at an asphalt plant, the liquid ASAs (0.5% by binder weight) were mixed with the binders in 1 quart steel paint cans at the appropriate mixing temperature (Table 2), sealed, and placed in a 163^{o}C oven for three (3) days before mixing with each aggregate source to produce samples for testing. It should be noted that the design OBC, as determined with the original binders, was also used for the stored binders.

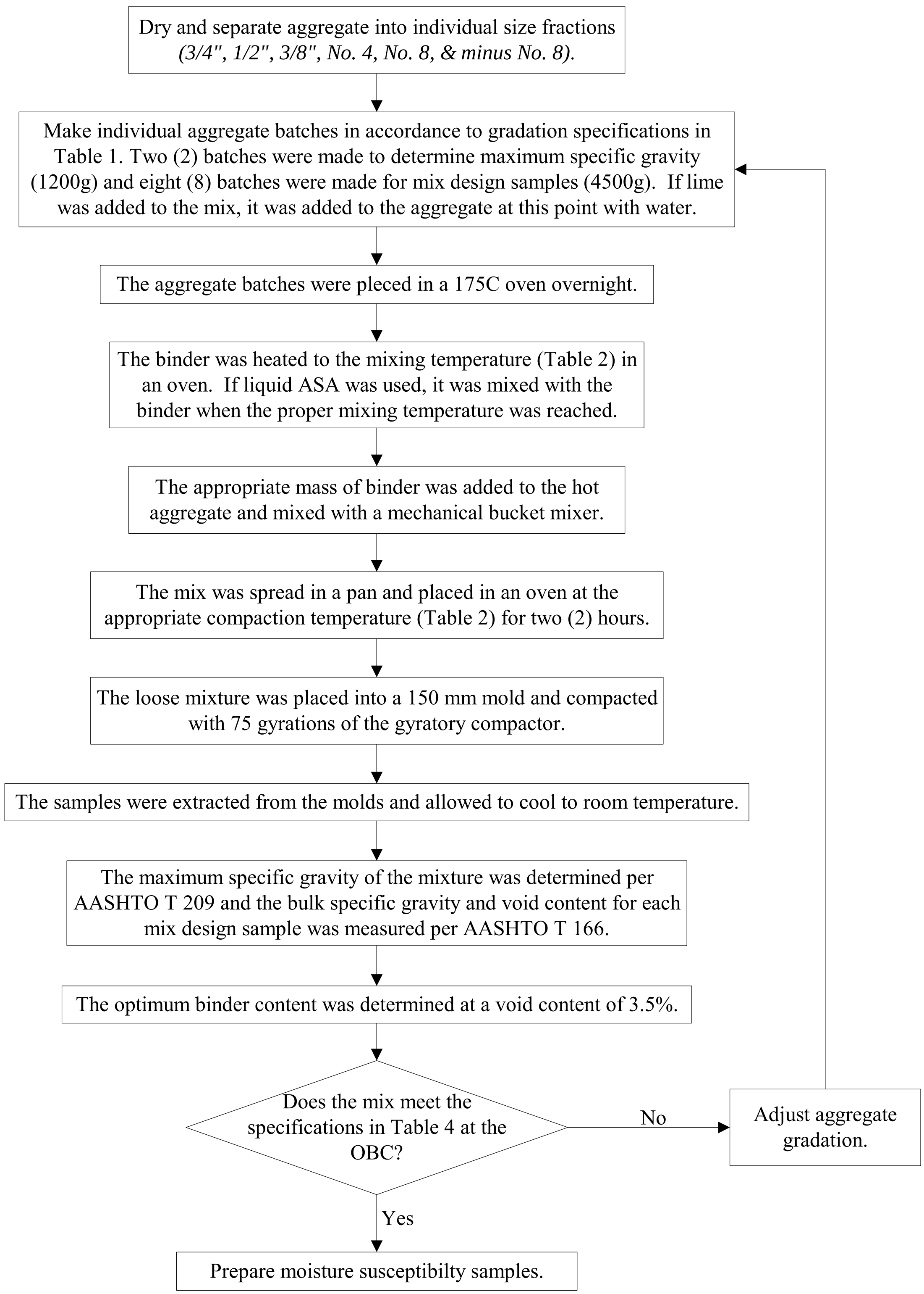


Figure 3: Flowchart of the asphalt mix design procedure.

Moisture Susceptibility Testing

Two test methods were employed to evaluate the susceptibility of the 30 different mixtures to moisture induced damage (i.e., stripping). The two test methods included the determination of the tensile strength ratio (TSR) per SC-T-70 and the boil test per ASTM D 3625.

Tensile Strength Ratio

The tensile strength ratio (TSR) of each mixture was evaluated using SC-T-70. For each mix design, twenty (20) 150 mm diameter by 95 mm tall samples were made using a gyratory compactor. The number of gyrations necessary to reach a sample height of 95 mm and a void content of 7 ± 1% was unique for each sample. The 20 samples were divided into groups of four (4), where two (2) were conditioned in air at 25 ± 1^{o}C for the appropriate duration and two (2) were conditioned in water for the appropriate duration. Of the five groups, one was conditioned for 1 day, one for 7 days, one for 28 days, one for 90 days, and one for 180 days. For the wet samples that were conditioned for 1 day, each sample was saturated to a level of 70 to 80% with 25 ± 1^{o}C water and then placed in a 60 ± 1^{o}C water bath for 24 hours followed by 2 hours in a 25 ± 1^{o}C water bath prior to testing. For the wet samples conditioned for longer durations, they were also saturated to 70 to 80% with 25 ± 1^{o}C, but they were then placed in a 25 ± 1^{o}C water bath for a duration that was one day short of the test duration. For example, if the conditioning period was to be 28 days, then the samples were removed from the 25 ± 1^{o}C water bath after 27 days. For the last day of conditioning, the samples were placed in a 60 ± 1^{o}C for 24 hours followed by 2 hours in a 25 ± 1^{o}C water bath prior to testing. Testing of each sample consisted of measuring the indirect tensile strength (ITS). The ratio of the average wet ITS and average dry ITS of each group was calculated as the TSR for that group of samples. The SCDOT requirement for TSR is a minimum of 85% (SCDOT 2006).

The TSR of the mixes made with the stored binders were also determined for conditioning durations of 1, 28, and 90 days using practices identical to the unaged binder samples. A total of 960 ITS samples were prepared and tested during the course of this study.

Boil Test

The adhesion of the binders to aggregates was evaluated in accordance with ASTM D 3625. In this test, three 250g loose HMA samples were prepared in the lab for each of the 30 mix designs evaluated in this study. The samples were then brought to a temperature between 85 and 100^{o}C and placed in a container of boiling water for 10 minutes. After 10 minutes, the container was removed from the heat source and allowed to cool to room temperature. The water was decanted and the mixture was transferred onto a white paper towel, where it was observed for stripping by the same person for all samples to reduce the variability of using various operators. A mixture was considered to experience stripping if more than 5% the binder coating had stripped off of the aggregate in the sample.

Binder Content Determination

The binder content of each of the thirty (30) mixtures was determined using an asphalt ignition oven in accordance with SC-T-75. This procedure was included in the test program to determine if the different ASAs had an impact on the asphalt binder content results from the ignition oven test. Prior to testing any mixtures, a calibration factor was first determined for each aggregate source, which was then used in the determination of the binder content for mixtures made from each individual aggregate source. For each mixture, four (4) 1500 g specimens were mixed (one butter mix and three test samples). The average of the three test samples was reported as the binder content and compared to the actual binder content added to prepare the samples.

CHAPTER IV: RESULTS & DISCUSSION

Mix Design Data

The optimum binder content (OBC) and volumetric properties of each of the Surface Type B mixtures are included in Table 5. It can be seen that the addition of liquid ASAs did not significantly alter the properties of the mixes with respect to the OBC or volumetric properties. In all cases, the addition of hydrated lime to the mixture reduced the OBC. It should be noted, however, that these findings are based on a single mix design for each combination of materials. Repeating the mix design process would most likely add some variability to the results and, therefore, alter the statistical significance of the differences.

Each of the mixes was given a unique code containing three parts. The first part was the aggregate (A, B or C); the second part was the binder source; (I or II), and the third part for the ASAs; (0, 1, 2, 3 or L). For example, AIIL denotes a sample prepared by mixing aggregate A with binder II and hydrated lime as the ASA treatment.

Table 5: Mix design properties.

Mix Design	OBC, %	VMA, %	VFA, %	Air Voids, %
AI0	5.8	17.5	76	4.0
AI1	5.9	17.7	77	3.9
AI2	5.9	17.7	77	3.9
AI3	5.9	17.7	77	3.9
AIL	5.7	16.8	77	3.8
AII0	5.8	17.3	77	3.9
AII1	5.8	17.6	77	3.9
AII2	5.8	17.6	77	3.9
AII3	5.8	17.6	77	3.9
AIIL	5.4	16.2	76	3.4
BI0	4.6	15.1	74	3.4
BI1	4.6	15.2	72	3.7
BI2	4.6	15.2	72	3.7
BI3	4.6	15.2	72	3.7
BIL	4.4	14.5	76	3.5
BII0	4.6	15.0	73	3.4
BII1	4.5	14.8	73	3.5
BII2	4.5	14.8	73	3.5
BII3	4.5	14.8	73	3.5
BIIL	4.4	14.5	73	3.5
CI0	5.8	17.2	76	3.9
CI1	5.8	16.8	77	3.9
CI2	5.8	16.8	77	3.9
CI3	5.8	16.8	77	3.9
CIL	5.2	14.6	76	3.3
CII0	5.8	17.1	76	4.0
CII1	5.7	16.6	77	3.6
CII2	5.7	16.6	77	3.6
CII3	5.7	16.6	77	3.6
CIIL	5.3	15.2	76	3.4

Moisture Susceptibility of Fresh Binders

The results of the moisture susceptibility testing (i.e., tensile strength ratio and boil test) of mixtures made with fresh binder are presented in the following sections.

Indirect Tensile Strength & Tensile Strength Ratio

Effects of ASA

Based on the analysis of variance (ANOVA) results of the wet ITS (Tables A-1 through A-4), it was found that hydrated lime was the most effective ASA. In most cases, the three liquid ASA followed with no significant differences in their effectiveness, as seen in Figures 4 through 8. The control treatment (no ASA) was the least effective. However, in mixes containing aggregate sources B and C, the liquid ASAs were not significantly different from the control treatment. Thus, the liquid ASAs did not work effectively with aggregate sources B and C in improving the wet ITS at an early age. This was observed with samples conditioned in water for 1 day and 7 days. At 28 days, no general trend was observed. It was observed that certain aggregate/ASA or binder/ASA or aggregate/binder/ASA combinations work better than others. In general, hydrated lime seemed to be the most effective ASA. For longer durations of conditioning, namely 90 days and 180 days, mixes with lime and the liquid were equally effective, and performed better than mixes with no ASA treatment.

A similar set of ANOVA tests were performed on the TSR values of the samples. Based on these results, it was observed that again in most cases, hydrated lime was most effective at one day. Hydrated lime was followed with the three liquid ASAs and then by the control treatment. At 7 days, the TSR for the mixes with lime and the three liquid ASAs were not significantly different from each other. The same trend was observed for samples conditioned for 28, 90 and 180 days, in water. Thus, one may note that mixes with hydrated lime and the liquid ASAs have similar TSR values, for the mixtures tested in this research project, when conditioned in water for durations beyond 1 day.

Effects of Aggregate Source

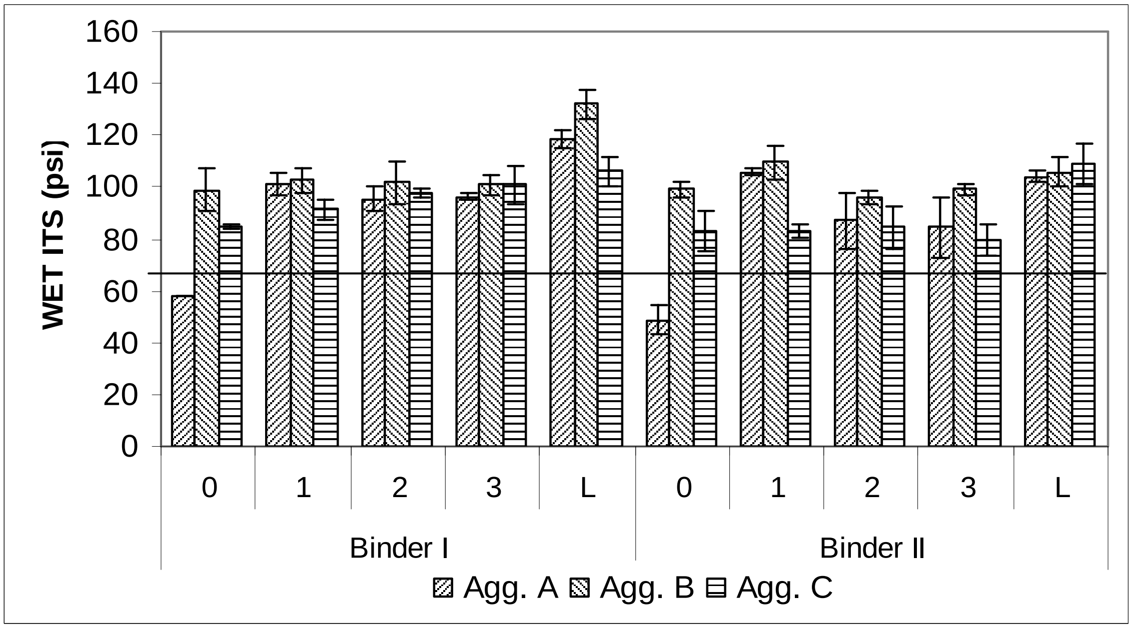
In all cases, the mixes containing aggregate source B gave the highest wet ITS after conditioning for 1 day. Aggregate source B was followed by aggregate source C and A, with significantly similar wet ITS. However, for samples conditioned in water for 7 days, there was no significant difference in the mean wet ITS of mixes with aggregate sources B and C. Again, at 28 days, aggregate source B seemed to show significantly higher wet ITS only when mixed with binder II. The wet ITS of samples made with aggregate sources A and C were significantly the same after 28 days of conditioning. Aggregate B also showed higher wet ITS after 90 days and 180 days of conditioning in water. The high tensile strength of mixes with aggregate B may be explained due to its higher toughness and density. Figures 4(a) through 8(a) show the effects of aggregate sources on the wet ITS of the mixes after different conditioning durations.

As far as the effect of the aggregate source on the TSR of mixes was concerned, there was no significant difference in the values of the mean TSR for mixes with different aggregate sources. This was the case at 1 day as well as 7 days. However, at 28 days, mixes with aggregate source B showed significantly lower TSR values compared to the other aggregate sources. This may be explained by the fact that mixes with aggregate source B showed exceptionally higher dry ITS compared to the mixes with other aggregate sources, whereas their wet ITS values were significantly similar. Figures 4(b) through 8(b) show the effect of aggregate source on the TSR at 1 day, 7 days, 28 days, 90 days, and 180 days, respectively.

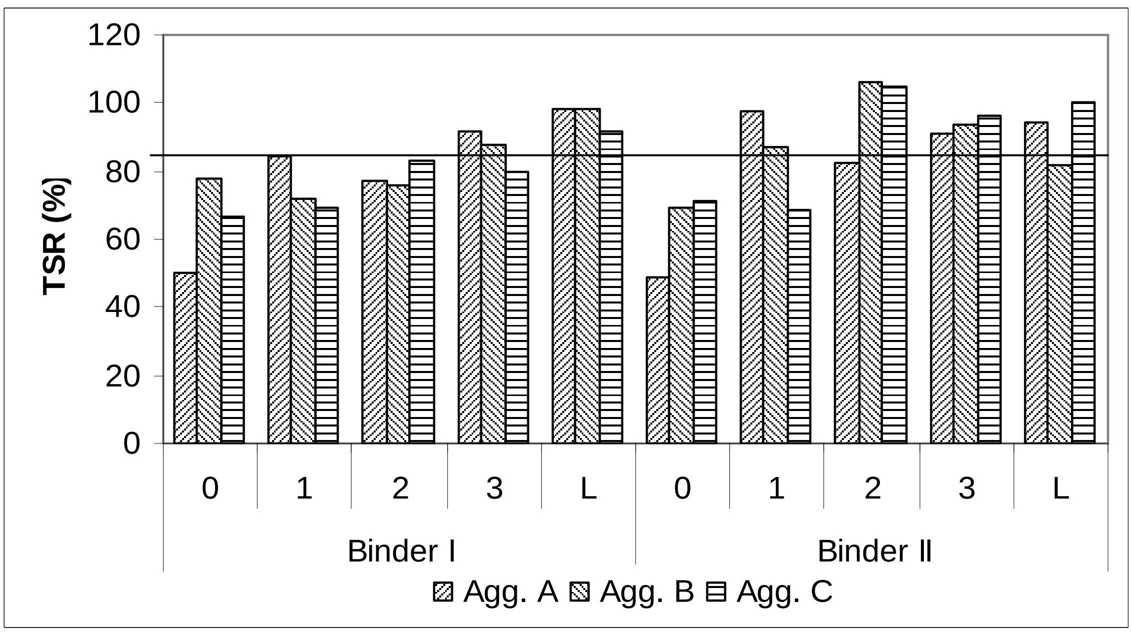
Effects of Binder Source

The ANOVA performed to check the effect of binder source on the wet ITS showed that the mixes with binder I generally gave higher wet ITS at 1 day, except in the case of mixes with aggregate source B, where the mean strengths of mixes with both binders were not significantly different. Again, at 7 and 28 days, the mean wet ITS of the mixes with both the binders were not significantly different from each other. This was also the case with long term conditioning of 90 and 180 days. Thus, the binder source did not seem to significantly affect the wet ITS of the mixes at conditioning durations over 1 day. Figures 4(a) through 8(a) show the effects of binder source on the wet ITS of the mixes.

The ANOVA for the TSR values showed that the binder source did not have any significant affect on the TSR values of the mixes. Figures 4(b) through 8(b) show the effects of binder source on the TSR.

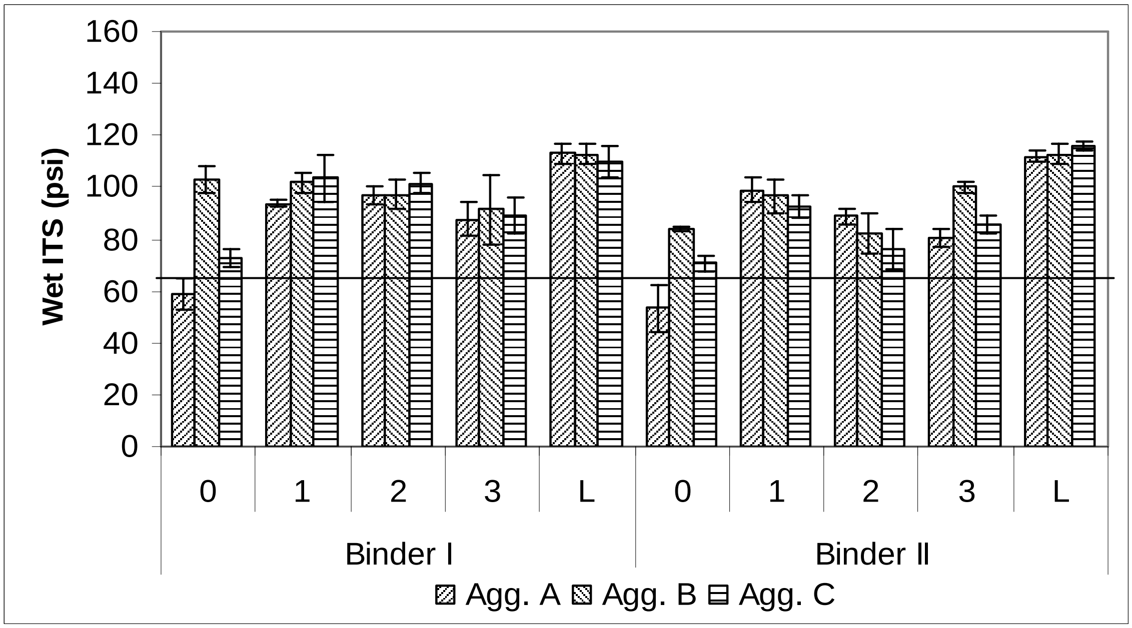


(a)

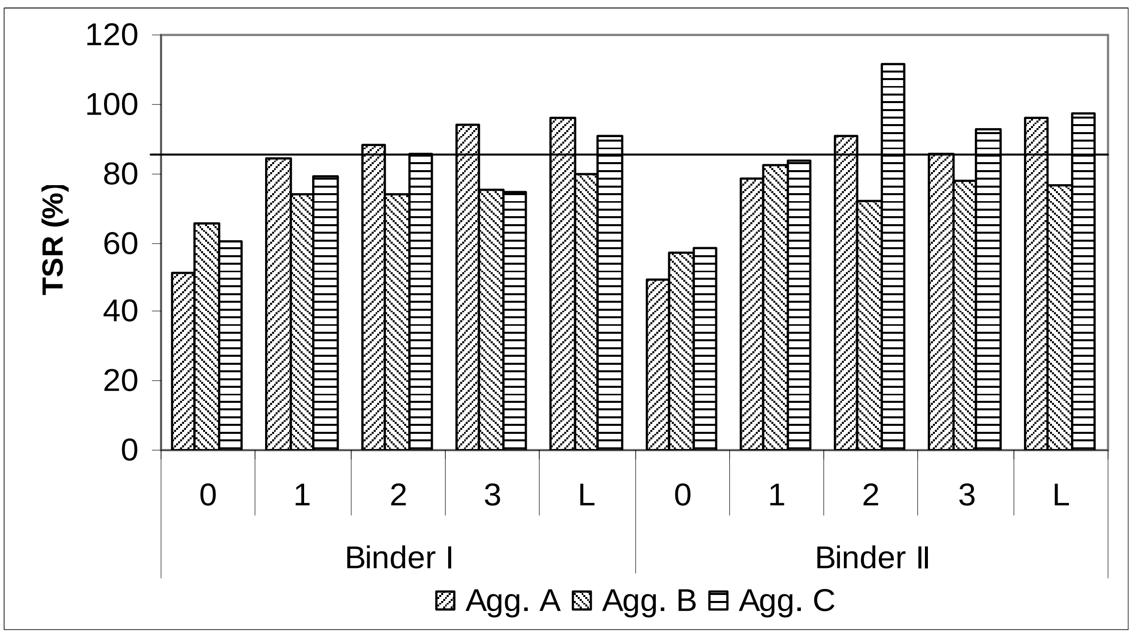


(b)

Figure 4: (a) Wet ITS and (b) TSR of mixes made with fresh binders after conditioning for 1 day.

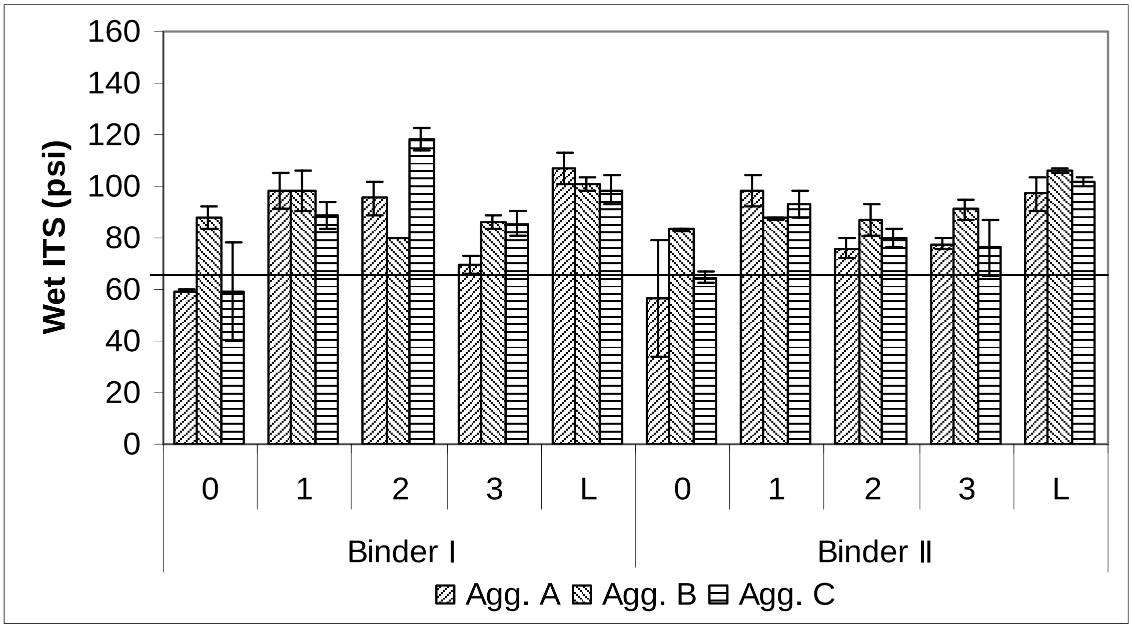


(a)

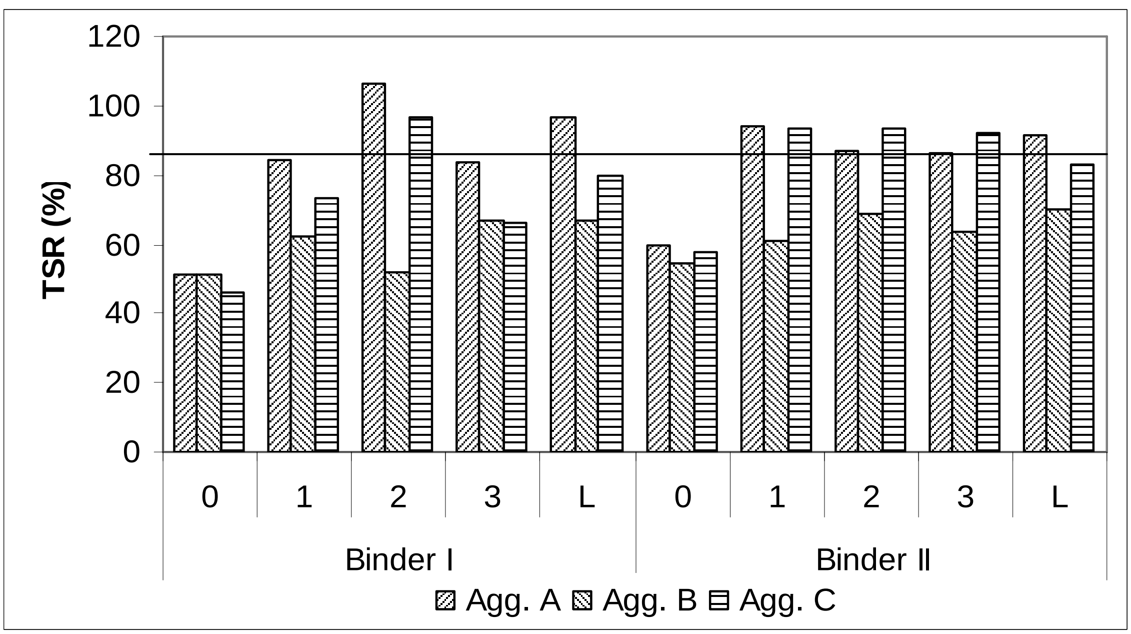


(b)

Figure 5: (a) Wet ITS and (b) TSR of mixes made with fresh binders after conditioning for 7 days.

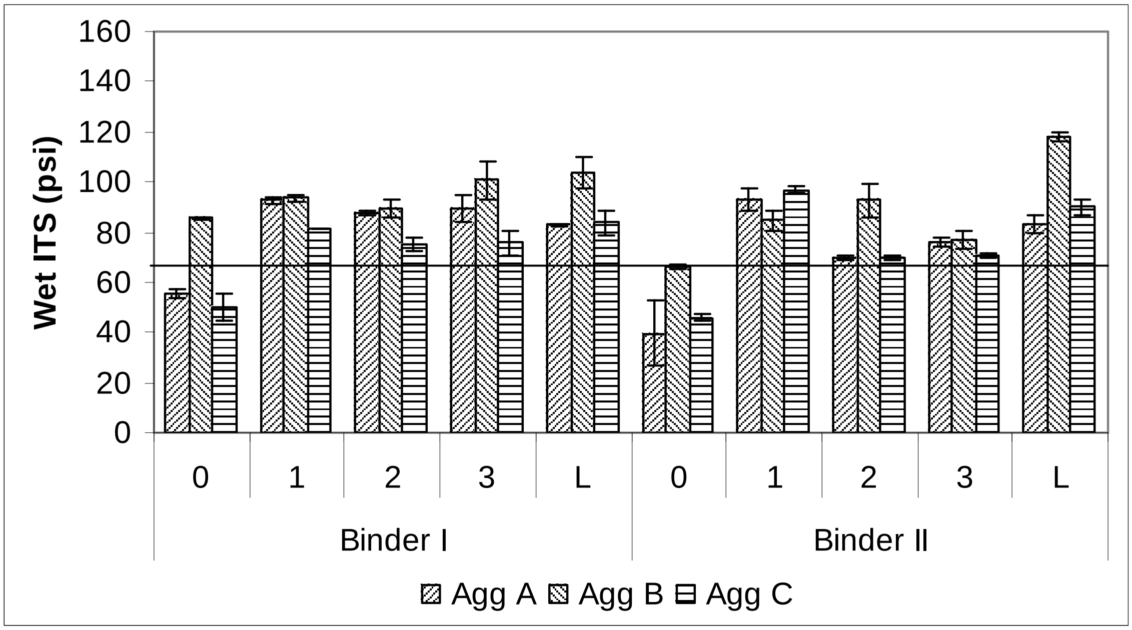


(a)

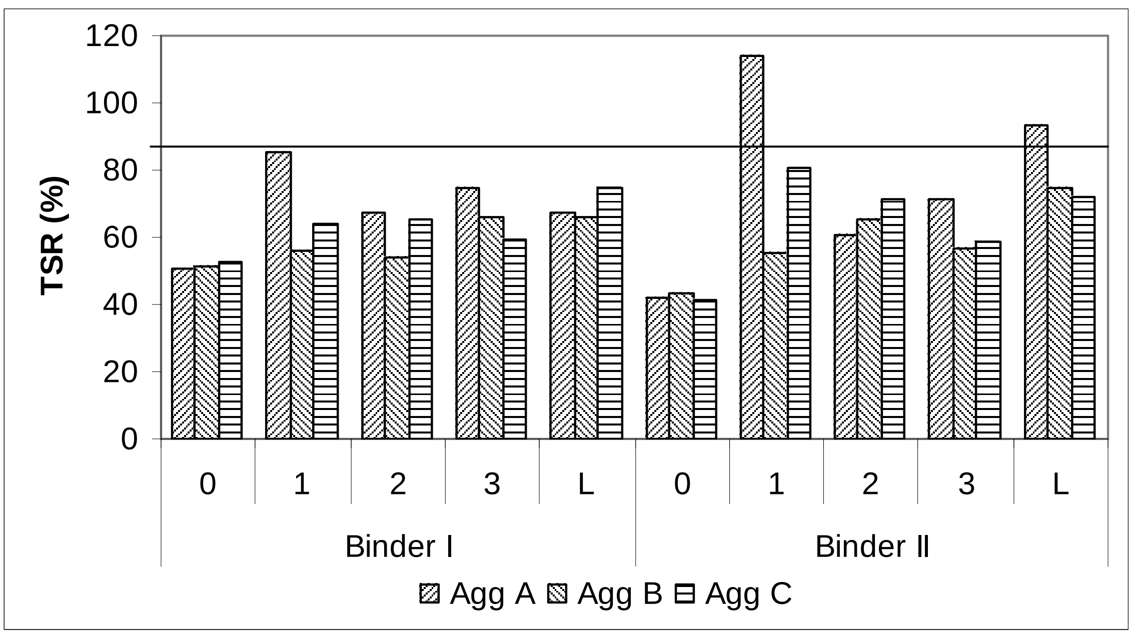


(b)

Figure 6: (a) Wet ITS and (b) TSR of mixes made with fresh binders after conditioning for 28 days.

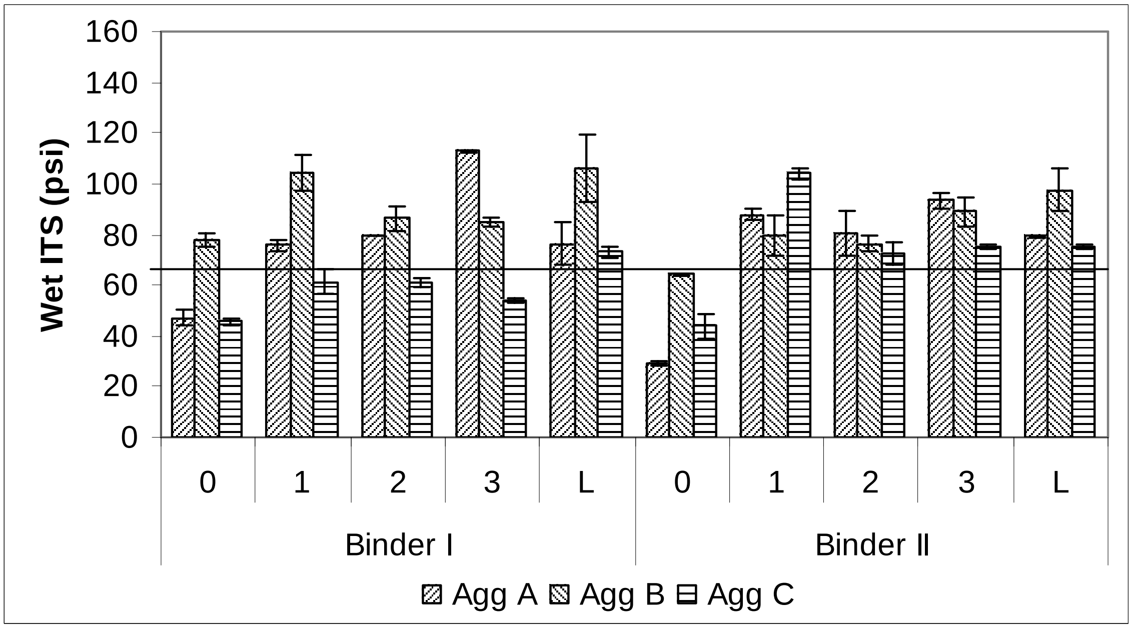


(a)

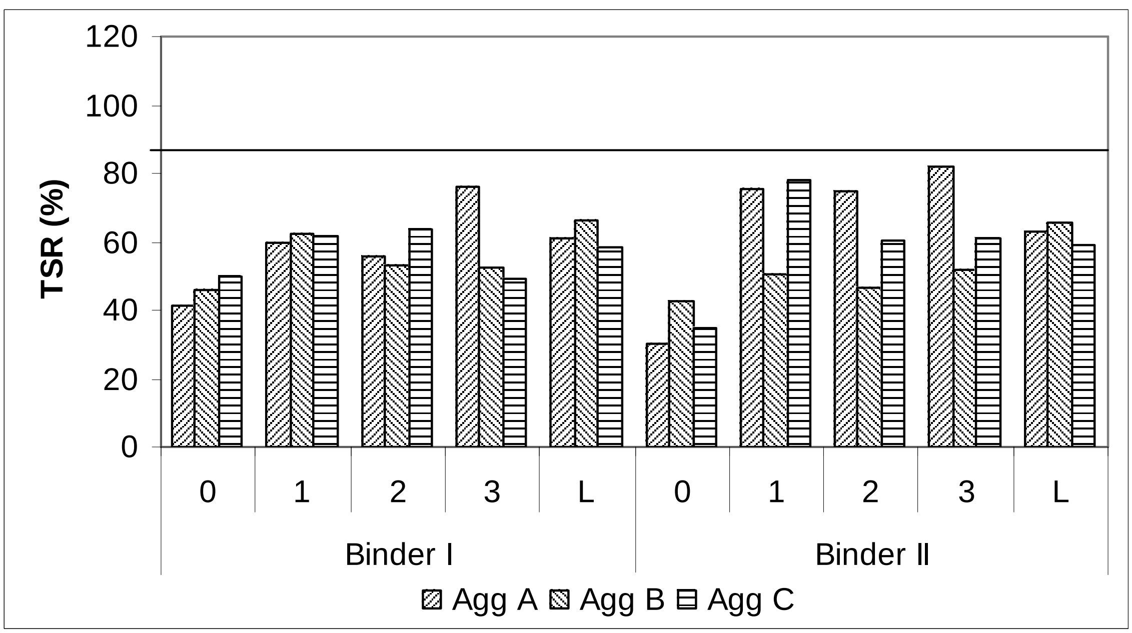


(b)

Figure 7: (a) Wet ITS and (b) TSR of mixes made with fresh binders after conditioning for 90 days.



(a)



(b)

Figure 8: (a) Wet ITS and (b) TSR of mixes made with fresh binders after conditioning for 180 days.

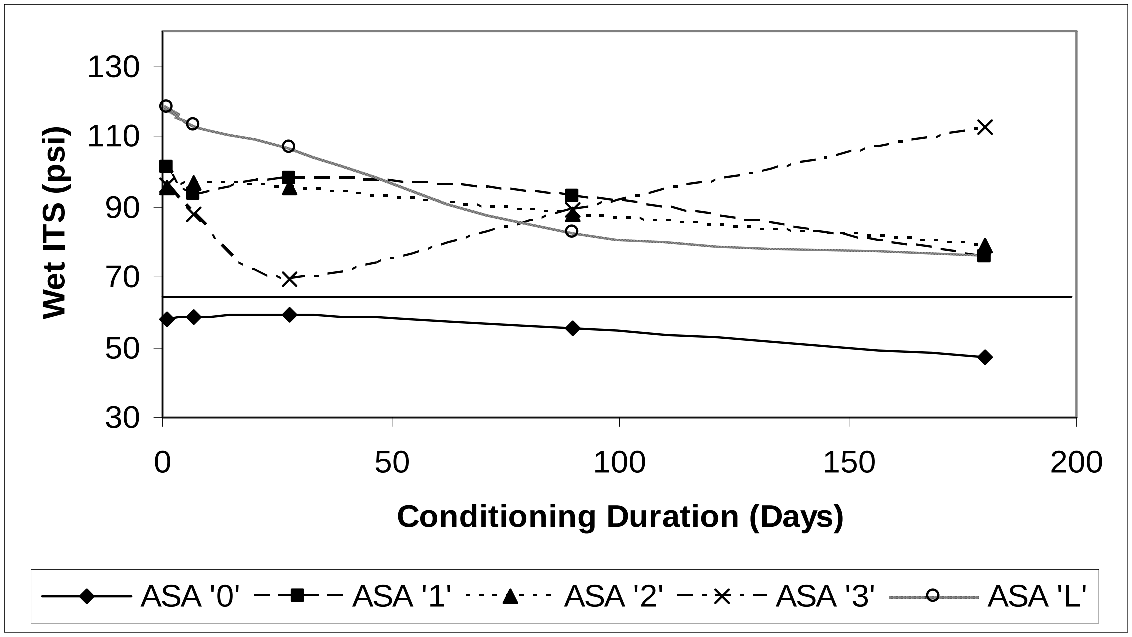
Effects of Conditioning Durations

To study the effects of conditioning durations on the wet ITS and TSR of the mixes, wet ITS and TSR values of samples for each mix after 1, 7, 28, 90, and 180 days were compared. From the comparison, for most of the mixes with aggregate source A the wet ITS and TSR values were significantly similar for 1, 7, 28, and 90 days of conditioning. For some of the mixes, the wet ITS after 180 days of conditioning were also significantly similar to the other durations, and for some, it was different. Figures 9 and 10 compare the effects of conditioning durations on the wet ITS and TSR for mixes with aggregate source A.

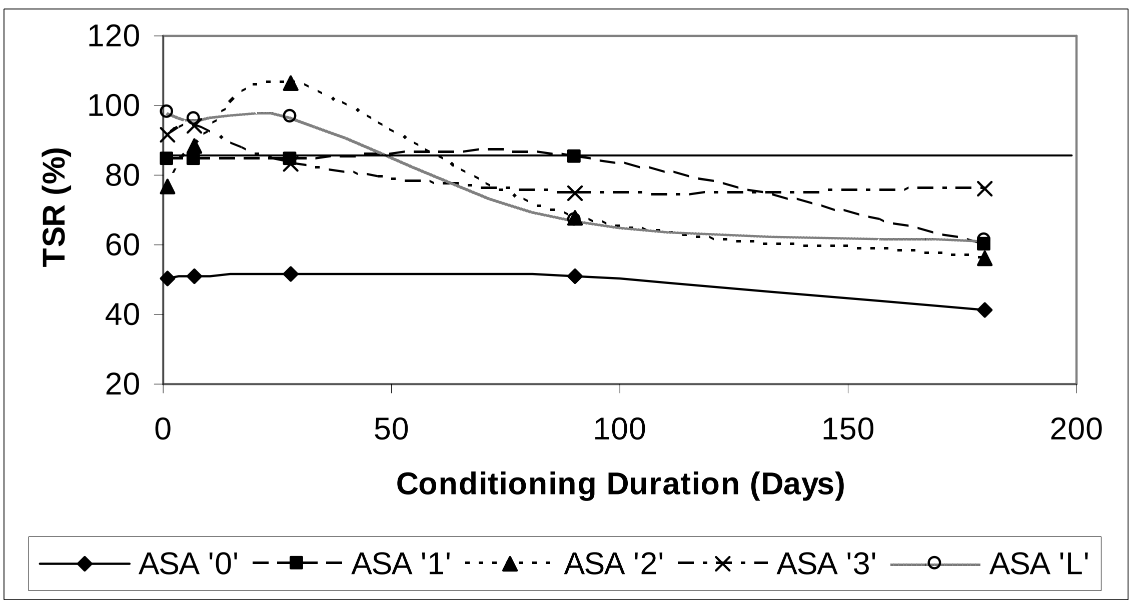
In the case of mixes with aggregate source B, most mixes exhibited significantly similar wet ITS after longer durations of conditioning (90 days and 180 days) and shorter durations of conditioning (1 day, 7 and 28 days). The TSR values were significantly similar after 28, 90 and 180 days of conditioning and lower than the TSR values after 1 and 7 days of conditioning. Figures 11 and 12 show the effects of conditioning durations on the wet ITS and TSR for aggregate source B.

The conditioning duration seemed to have some effect on the wet ITS of mixes with aggregate source C. When conditioned for longer durations (90 and 180 days), majority of the mixes with aggregate source C showed significantly lower wet ITS when compared to the wet ITS after shorter durations of conditioning (1 day, 7 days and 28 days). Figures 13 and 14 show the effects on conditioning durations on the wet ITS of mixes with aggregate source C. Mixes with aggregate C followed similar trends with TSR values, as they did with wet ITS values, except for a few exceptions.

The swell of each sample was measured after removal from the water, prior to testing (Figures 15 through 17). The results indicate that the samples did swell over time, but the trends were inconsistent for each aggregate/binder combination. In addition, since some of the samples showed signs of deterioration due to being submerged in water for long durations, it was not appropriate to compare the data to each other, since the calculation for swell is based on the mass of the sample.

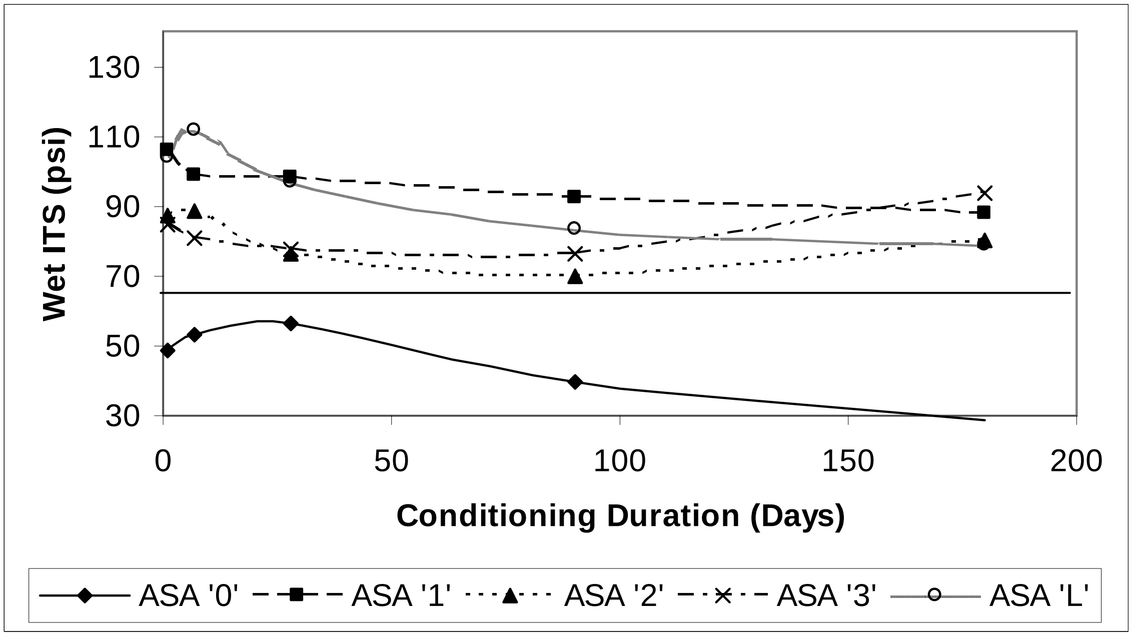


(a)

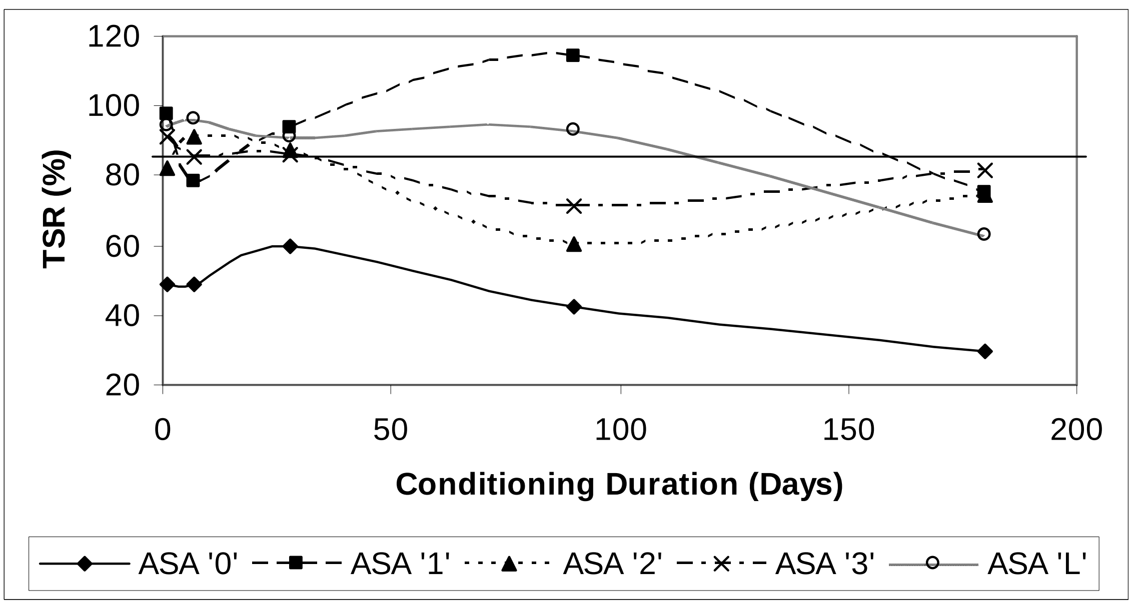


(b)

Figure 9: Moisture susceptibility results of mixes made with aggregate A and fresh binder I with respect to time: (a) wet ITS and (b) TSR.

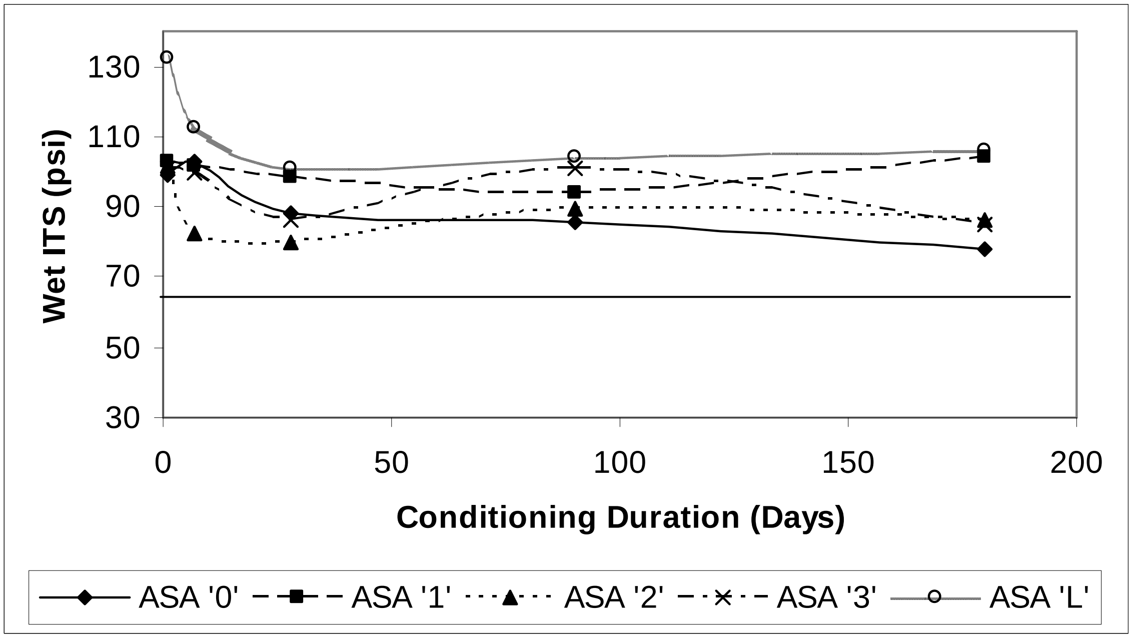


(a)

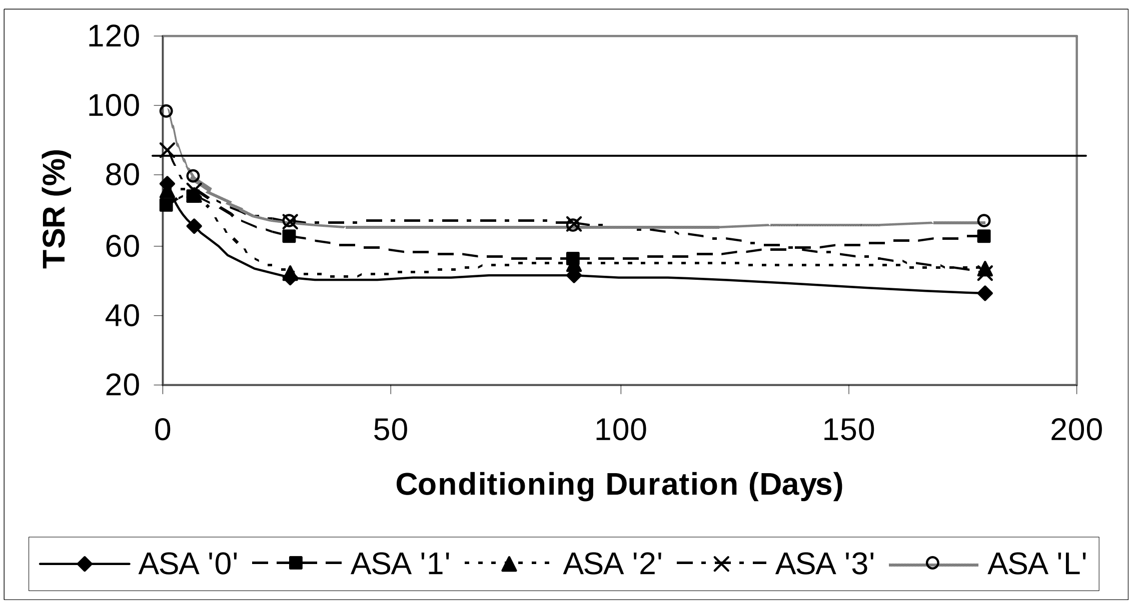


(b)

Figure 10: Moisture susceptibility results of mixes made with aggregate A and fresh binder II with respect to time: (a) wet ITS and (b) TSR.

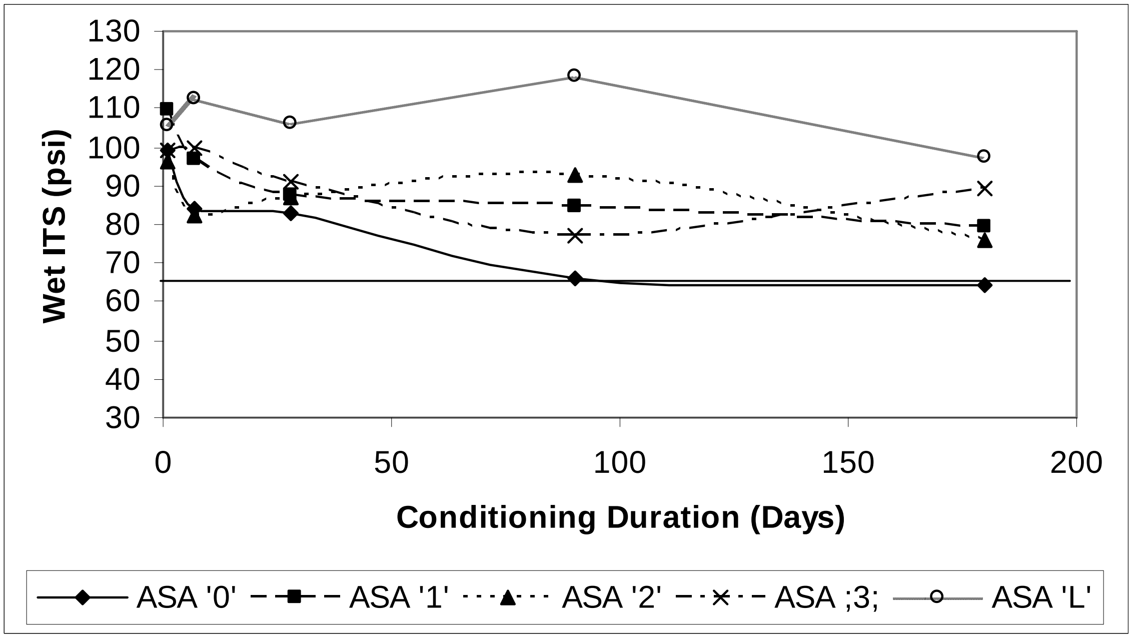


(a)



(b)

Figure 11: Moisture susceptibility results of mixes made with aggregate B and fresh binder I with respect to time: (a) wet ITS and (b) TSR.



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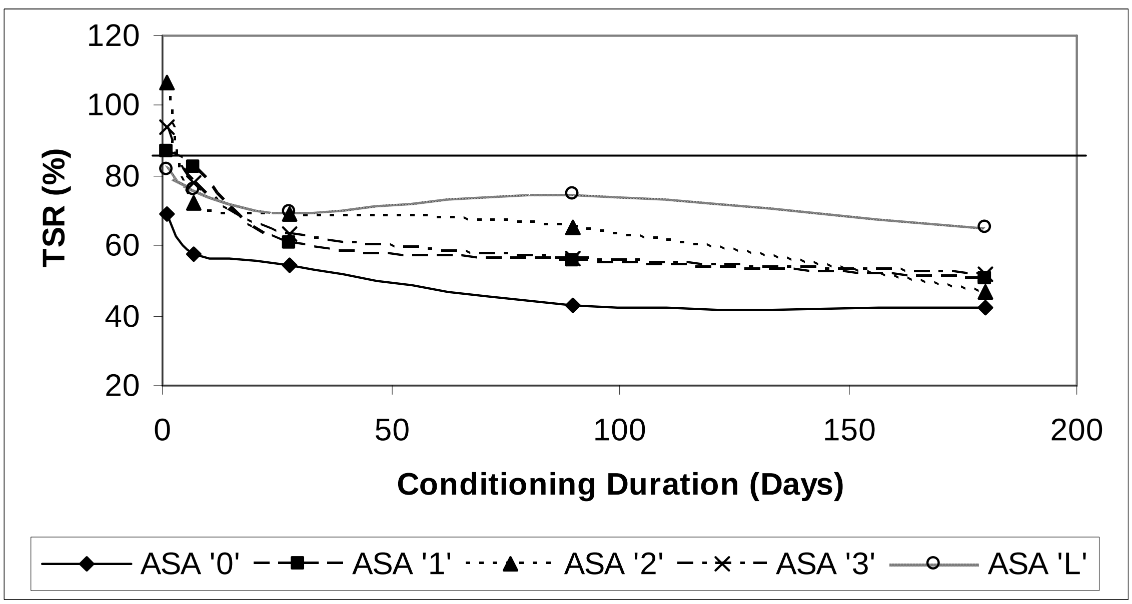
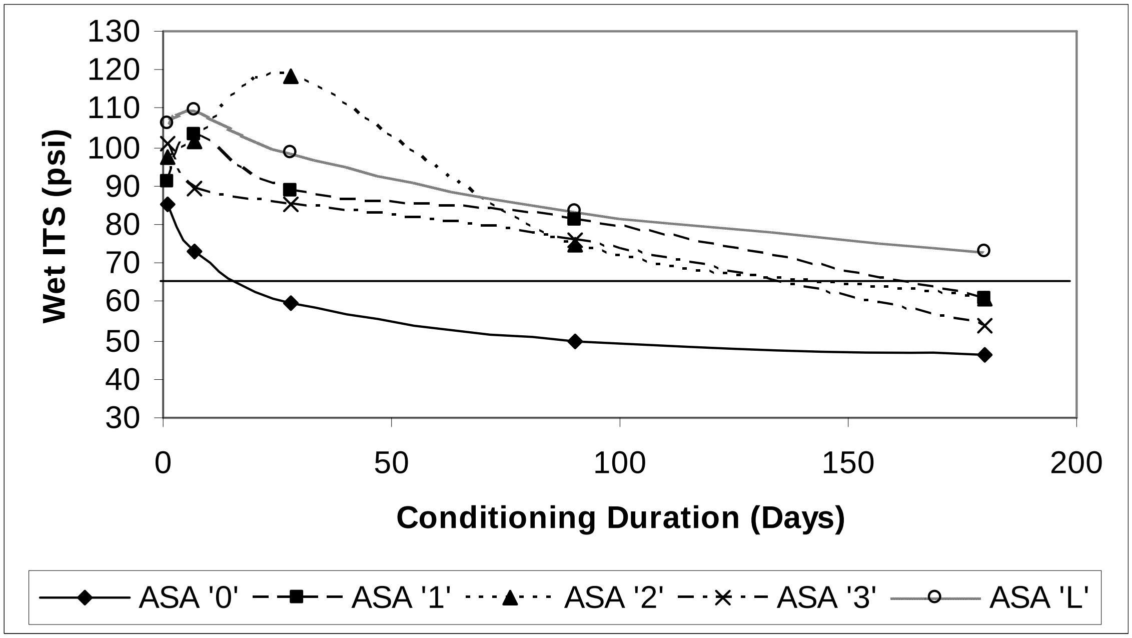
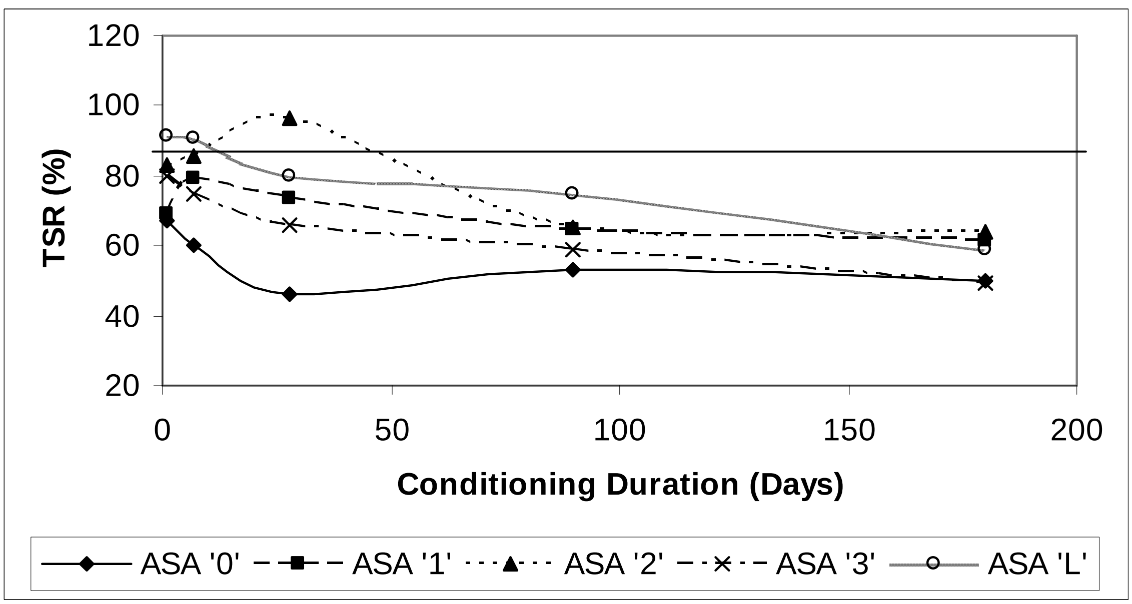


(b)

Figure 12: Moisture susceptibility results of mixes made with aggregate B and fresh binder II with respect to time: (a) wet ITS and (b) TSR.

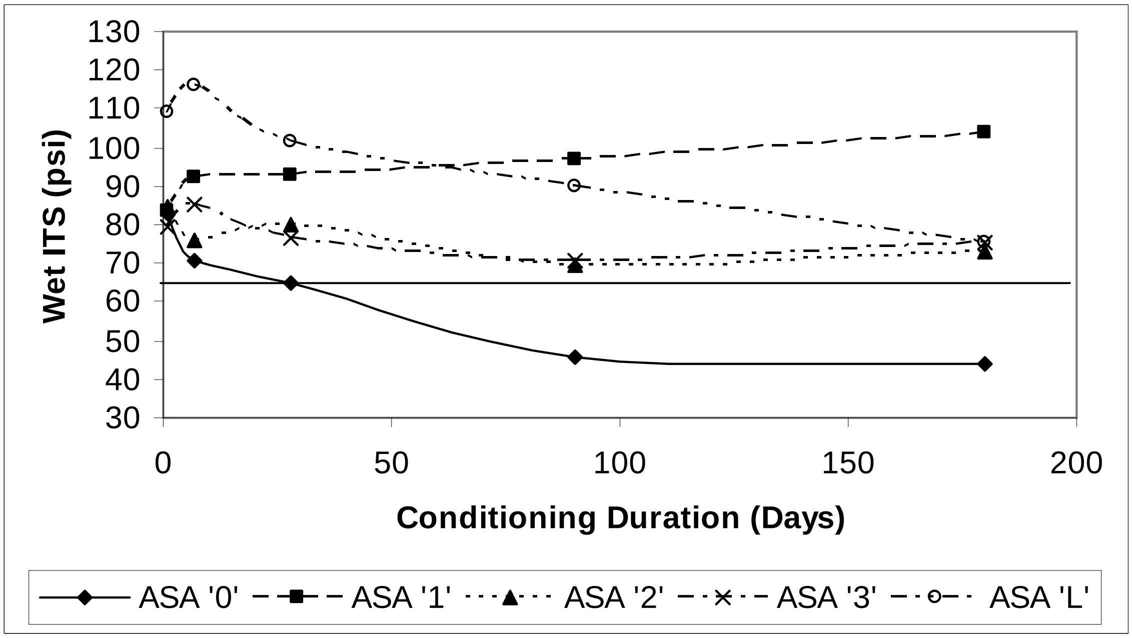


(a)

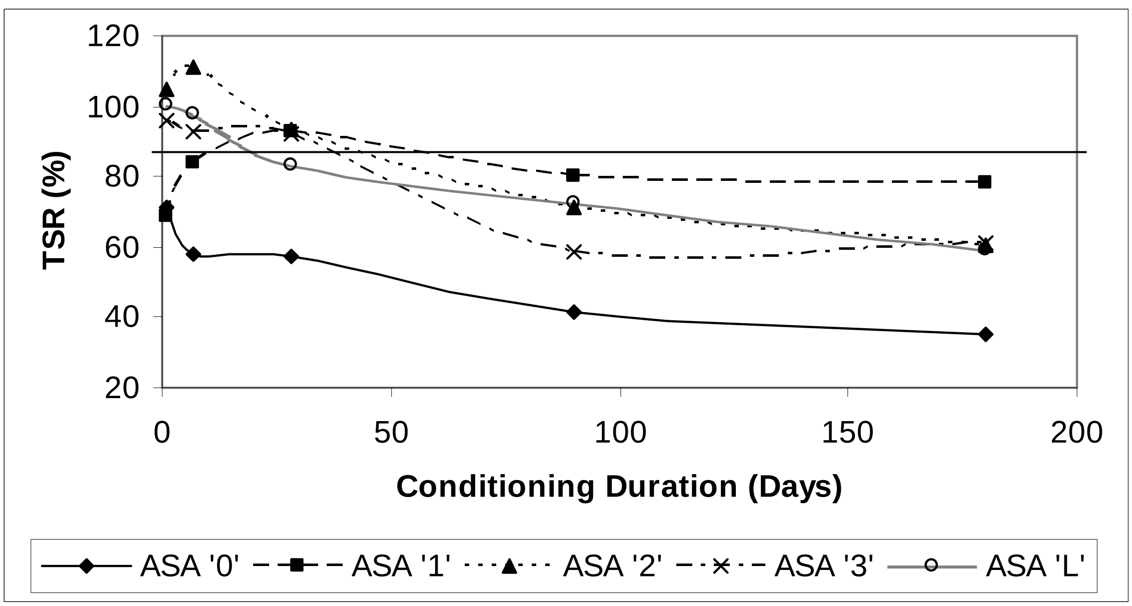


(b)

Figure 13: Moisture susceptibility results of mixes made with aggregate C and fresh binder I with respect to time: (a) wet ITS and (b) TSR.

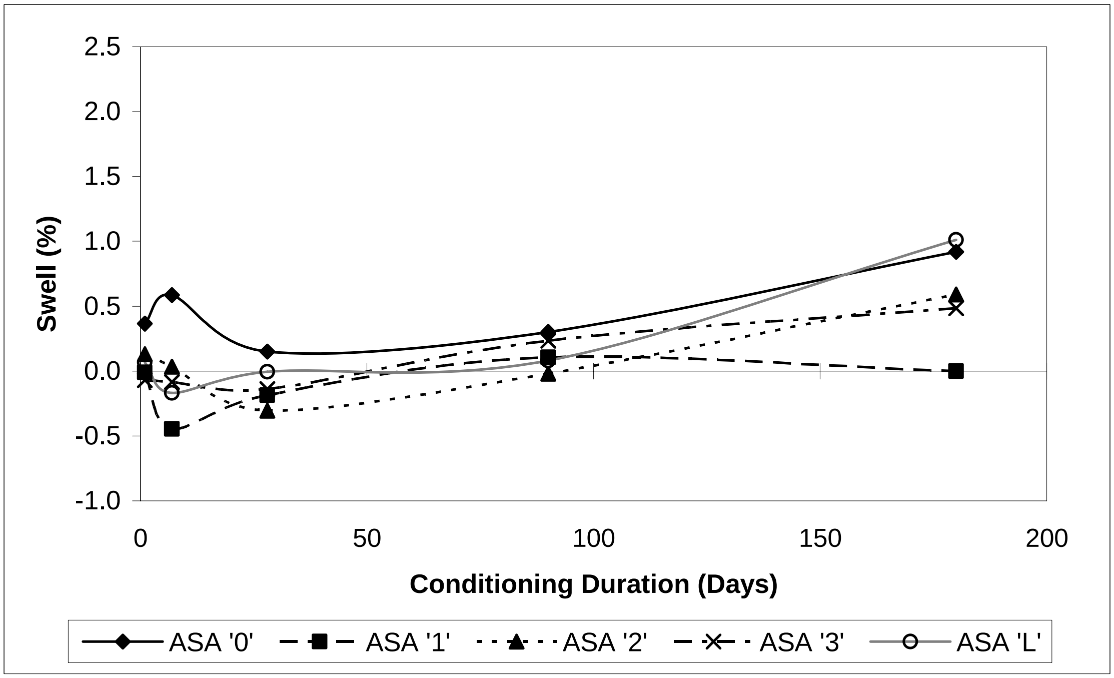


(a)

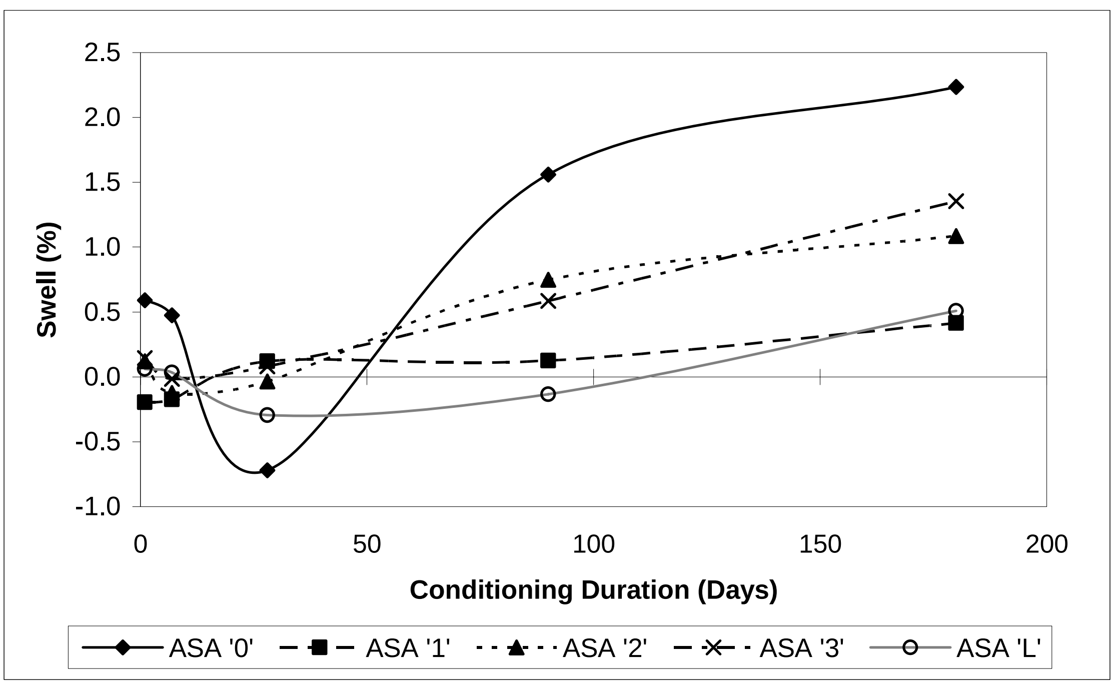


(b)

Figure 14: Moisture susceptibility results of mixes made with aggregate C and fresh binder II with respect to time: (a) wet ITS and (b) TSR.

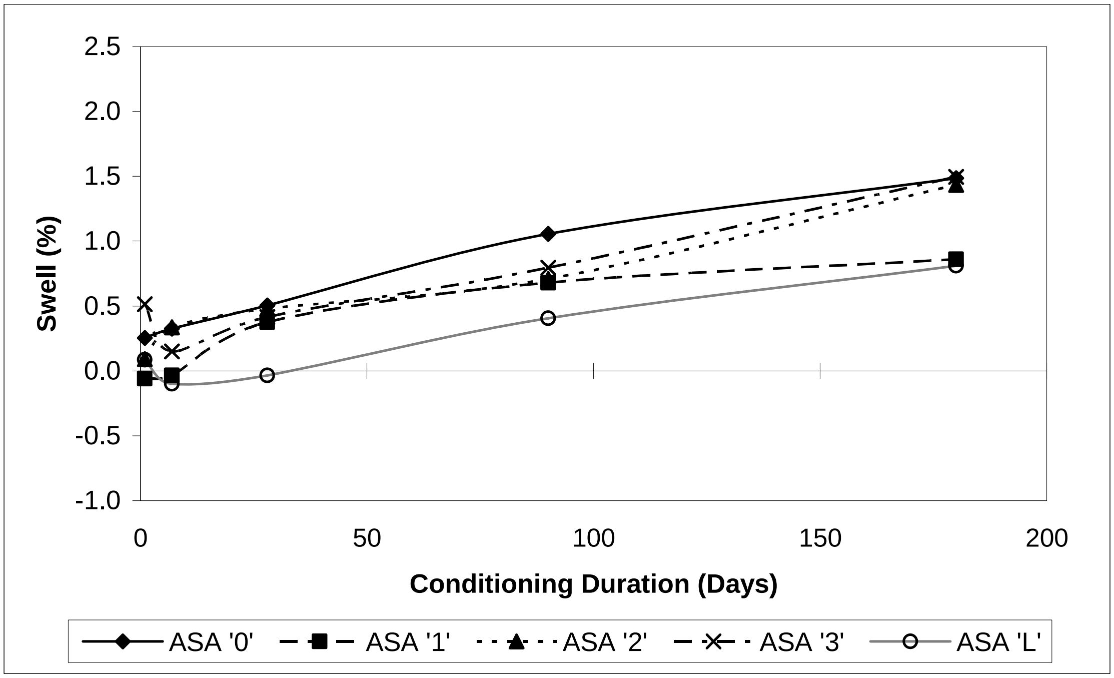


(a)

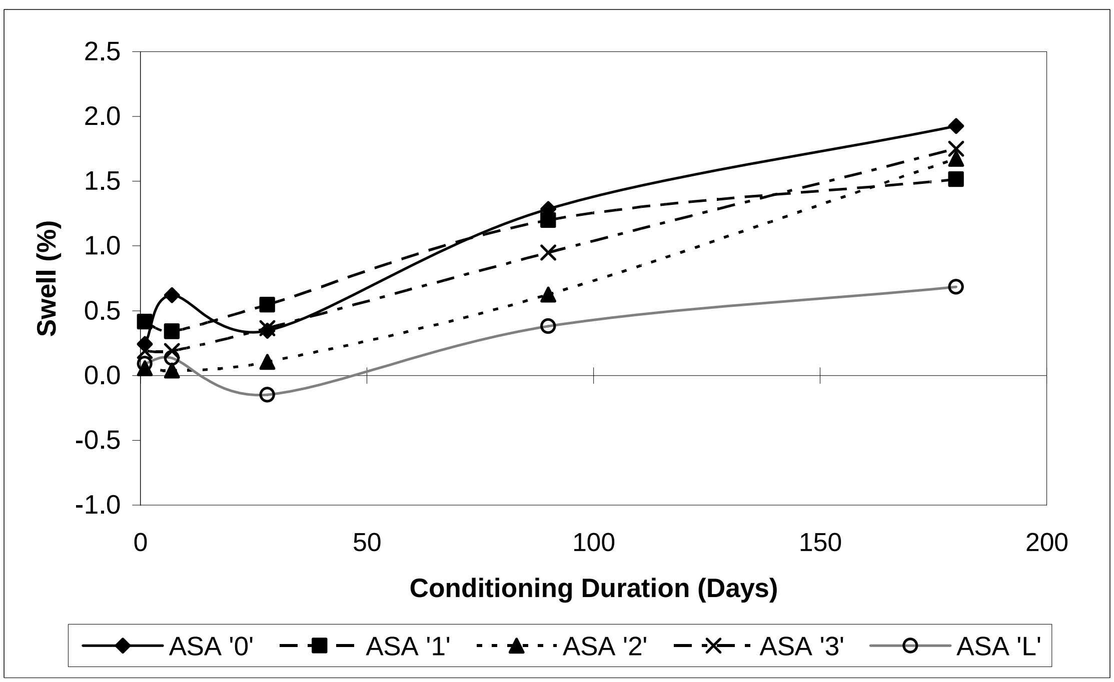


(b)

Figure 15: Swell results of mixes made with aggregate A and (a) binder I and (b) binder II.

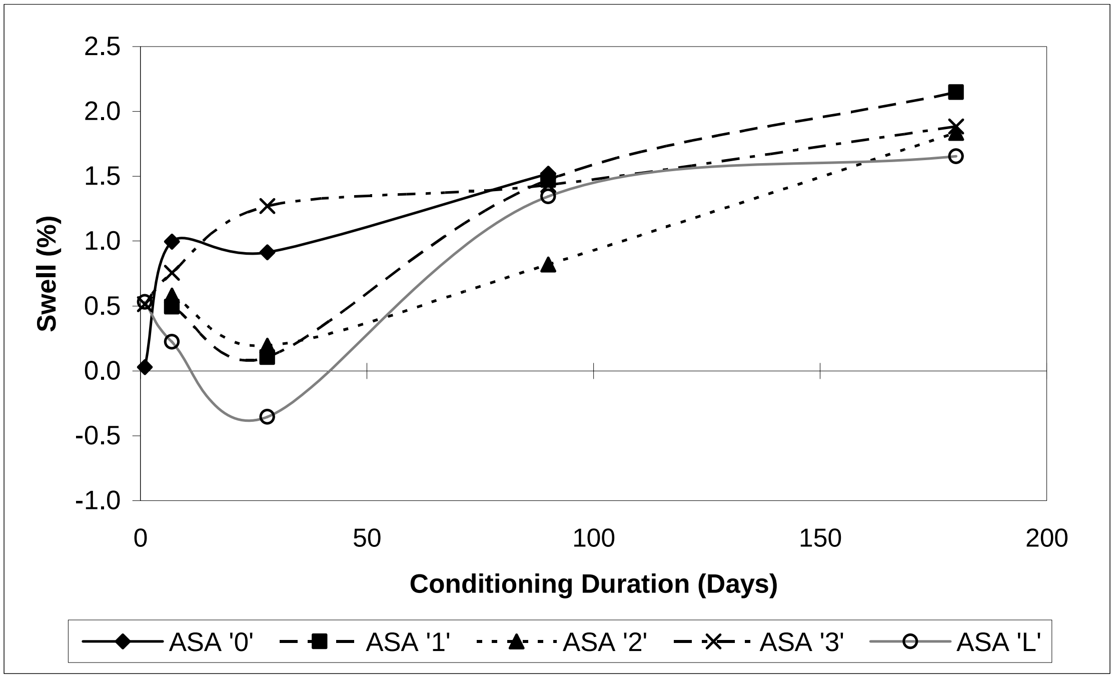


(a)

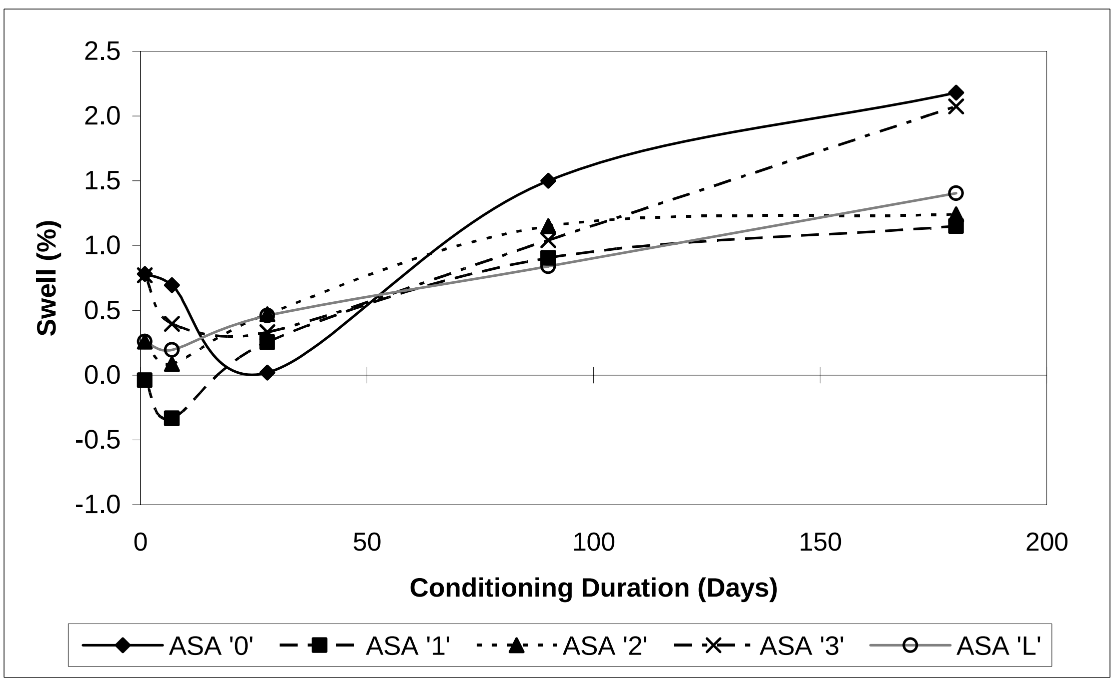


(b)

Figure 16: Swell results of mixes made with aggregate B and (a) binder I and (b) binder II.



(a)



(b)

Figure 17: Swell results of mixes made with aggregate C and (a) binder I and (b) binder II.

Boil Test

The Boil Test did not provide any conclusive results about the moisture susceptibility of the mixtures evaluated in this study. Only two samples out of 90 showed any signs of stripping in this test. Both samples were of mixtures that did not contain any ASA and were from different aggregate sources.

Moisture Susceptibility of Stored Binders

The results of the moisture susceptibility testing (i.e., tensile strength ratio) of mixtures made with stored binder are presented in the following sections.

Indirect Tensile Strength & Tensile Strength Ratio

To study the heat storage capacity of the liquid ASAs, the liquid ASAs were mixed with the binder and stored in the oven for three days at 325°F, and then the binder was used to prepare samples. Twelve samples were prepared for each mix and two were conditioned for 1 day, 28 and 90 days in water each, and their wet ITS were determined. The other samples were stored dry, and their dry ITS values were determined after 1 day, 28 and 90 days. The TSR was then calculated.

Effect of ASA

For mixes prepared with stored binder, there was no significant difference in the ITS values of mixes with different ASA treatments (Tables A-5 through A-8). This was observed at 1 day, 28 and 90 days of conditioning. The only exception was mixes with binder source II after 90 days of conditioning, where hydrated lime seemed to be significantly effective in improving the wet ITS.

The TSR values also showed a similar trend, where none of the ASA treatments performed significantly different from the others after 1 day, 28 and 90 days of conditioning. It could be concluded that storing the binders with the liquid ASA reduces the effectiveness of the liquid ASA. However, hydrated lime also did not perform well in case of the stored binders. Thus, the increase in the stripping tendency of the mixes could be due to the aging of the binders when stored in the oven for 3 days at 325°F.

Effects of Aggregate Source

Based on the statistical analysis, it was observed that aggregate source B gave the highest wet ITS at 1 day. However, at 28 and 90 days, the wet ITS values of mixes with all aggregates were significantly similar. Figures 18(a) through 20(a) show the wet ITS of mixes with different aggregate sources after 1, 28 and 90 days of conditioning.

Similarly, the effects of aggregate source on the TSR values of the mixes were studied and, in general, it was observed that aggregate source did not have a significant effect on TSR. This was the case after 1 day and 90 days of conditioning. After 28 days of conditioning, mixes with aggregate source B seemed to show lower TSR values. Figures 18(b) through 20(b) show the effect of aggregate sources on the TSR values after 1 day, 28 days and 90 days of conditioning.

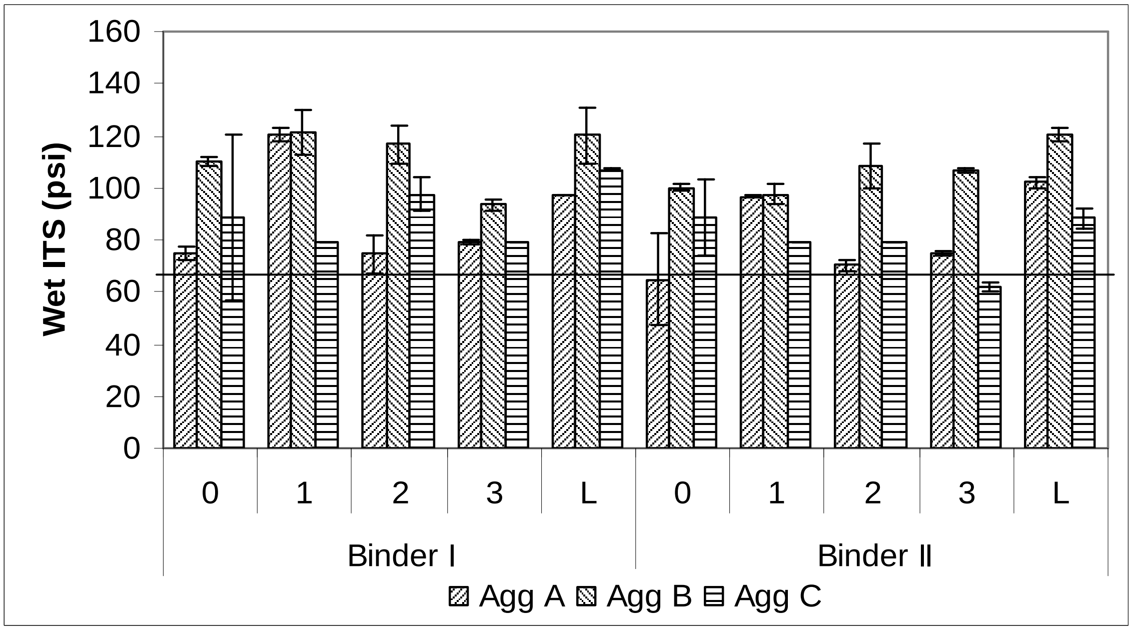
Effect of Binder Source

The binder source did not seem to have any influence on the wet ITS values of the mixes after 1 day, 28 days and 90 days of conditioning. Figures 18(a) through 20(b) show the effect of binder source on the wet ITS of the mixes.

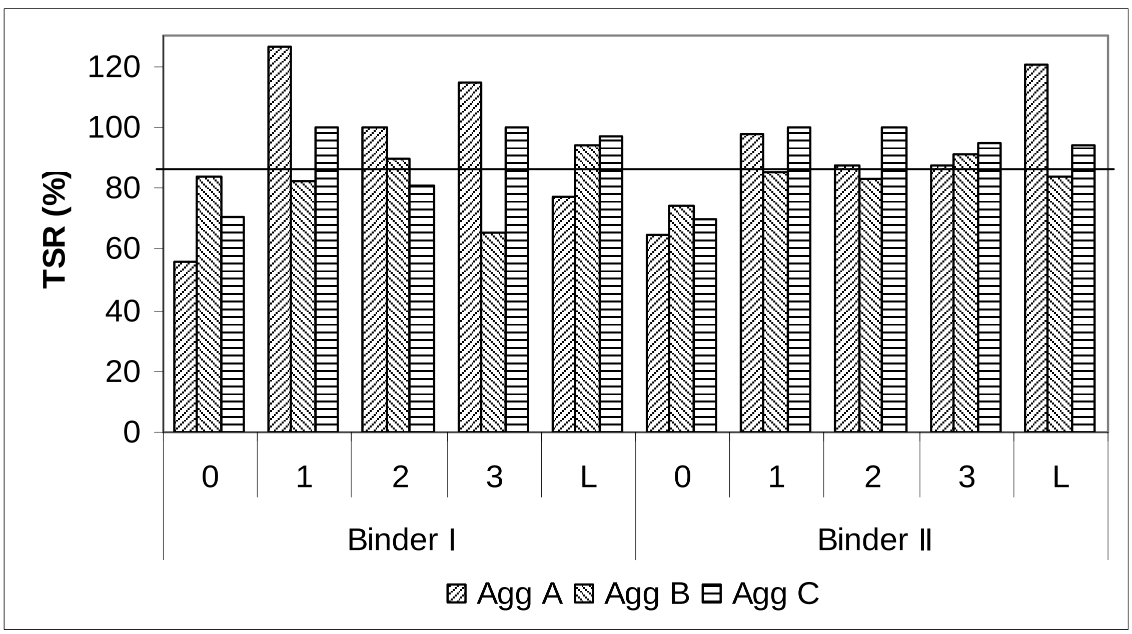
A similar analysis was performed to check the effect of binder source on the TSR values of the samples prepared from stored binder. The binder source did not seem to have any effect on the TSR values of the mixes either. Figures 18(a) through 20(b) show the effect of the binder source on the TSR values of the mixes at 1 day, 28 and 90 days respectively.

Effects of Conditioning Duration

The wet ITS and the TSR values of all the mixes after 1 day, 28 and 90 days of conditioning were compared and the effects of conditioning durations of the mixes were evaluated. However, no particular trend could be seen. While some of the mixes' wet ITS and TSR values decreased over longer conditioning, some increased, and some peaked at 28 days of conditioning. Figures 21 through 26 show the effect of the conditioning durations on the wet ITS and TSR values of the mixes.

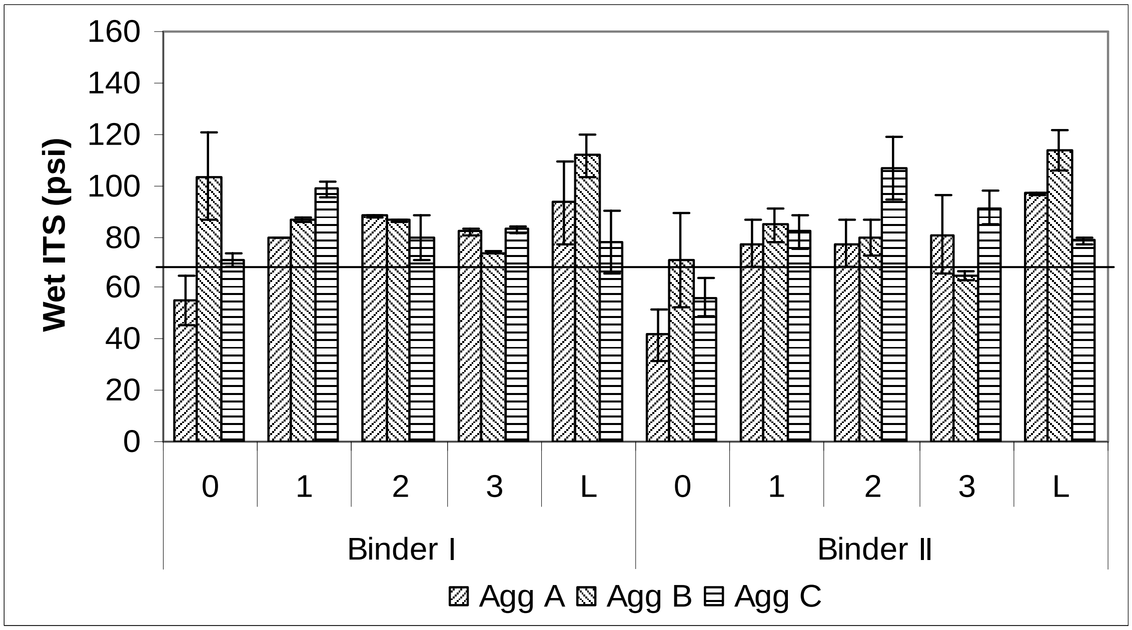


(a)

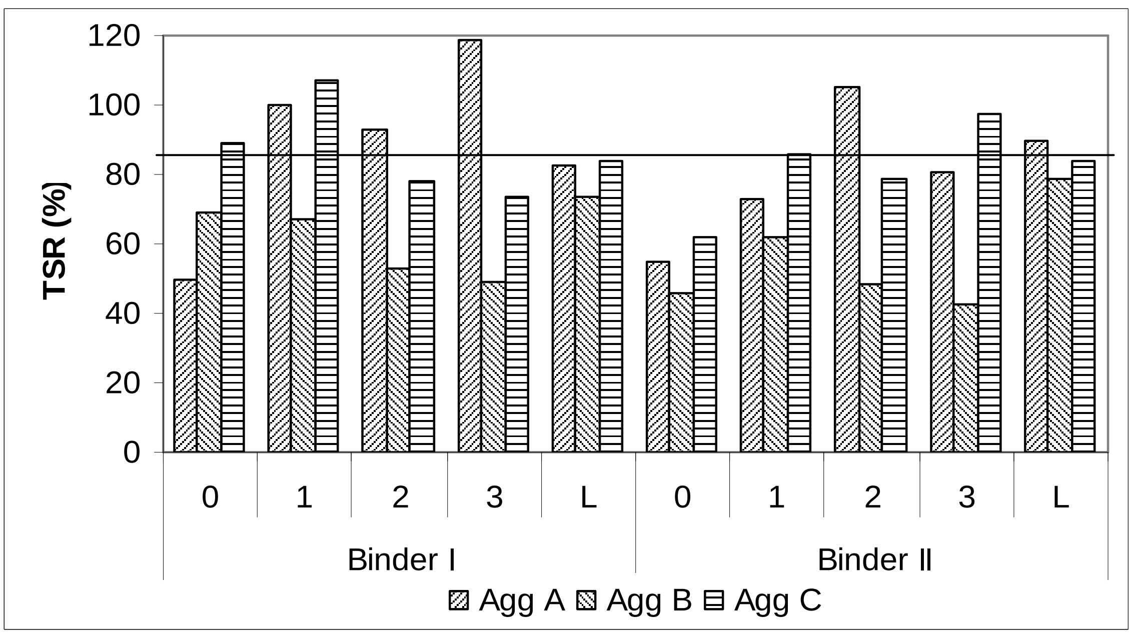


(b)

Figure 18: (a) Wet ITS and (b) TSR of mixes made with stored binders after conditioning for 1 day.

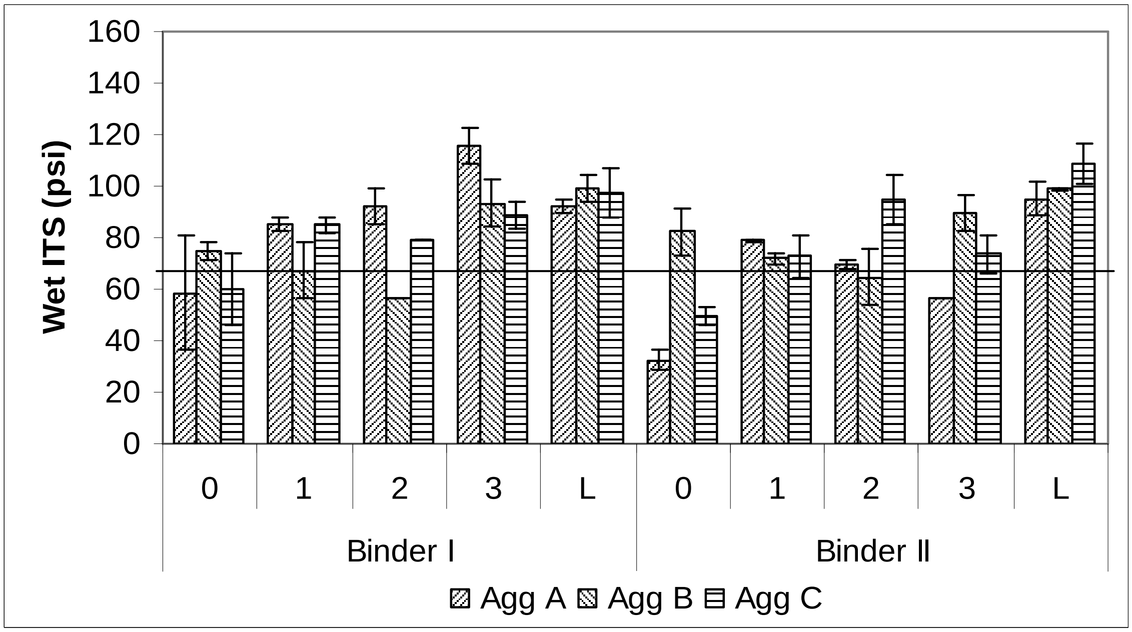


(a)

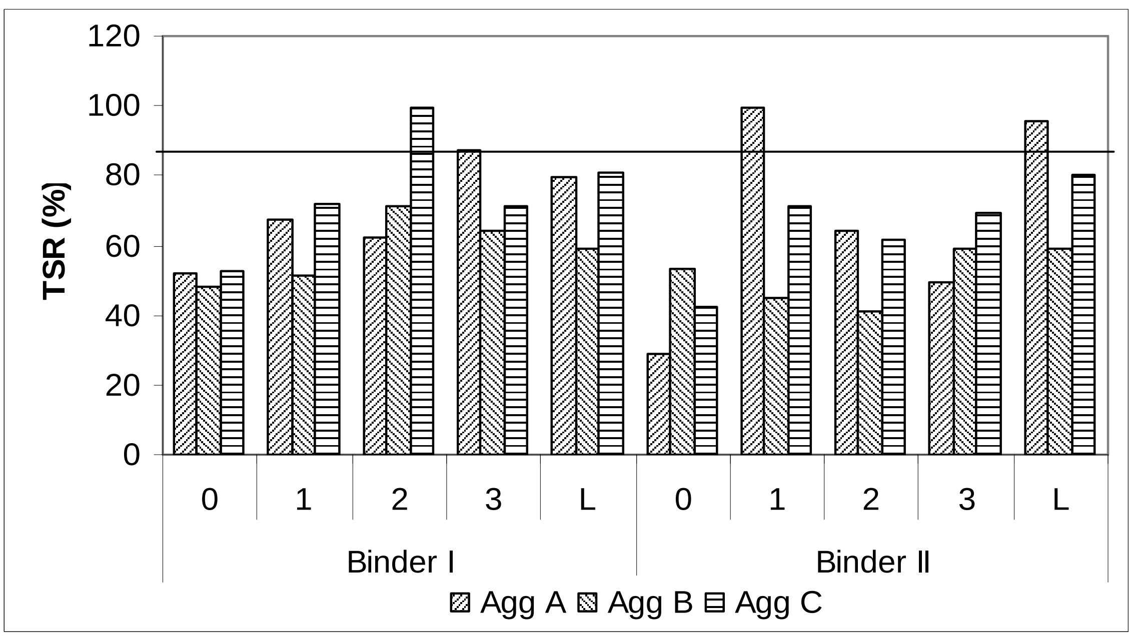


(b)

Figure 19: (a) Wet ITS and (b) TSR of mixes made with stored binders after conditioning for 28 days.

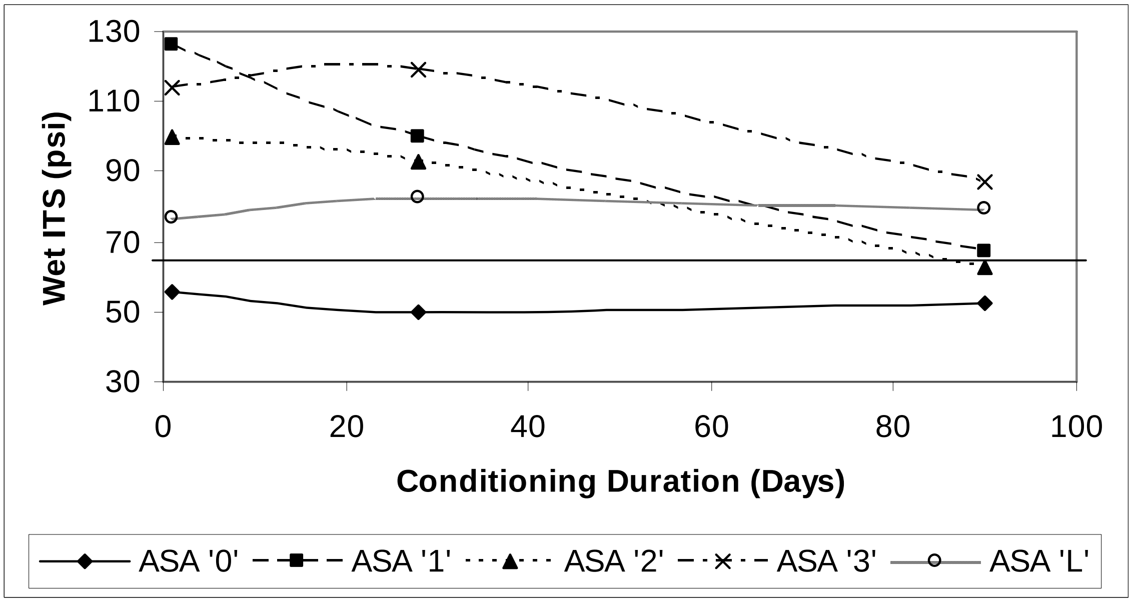


(a)

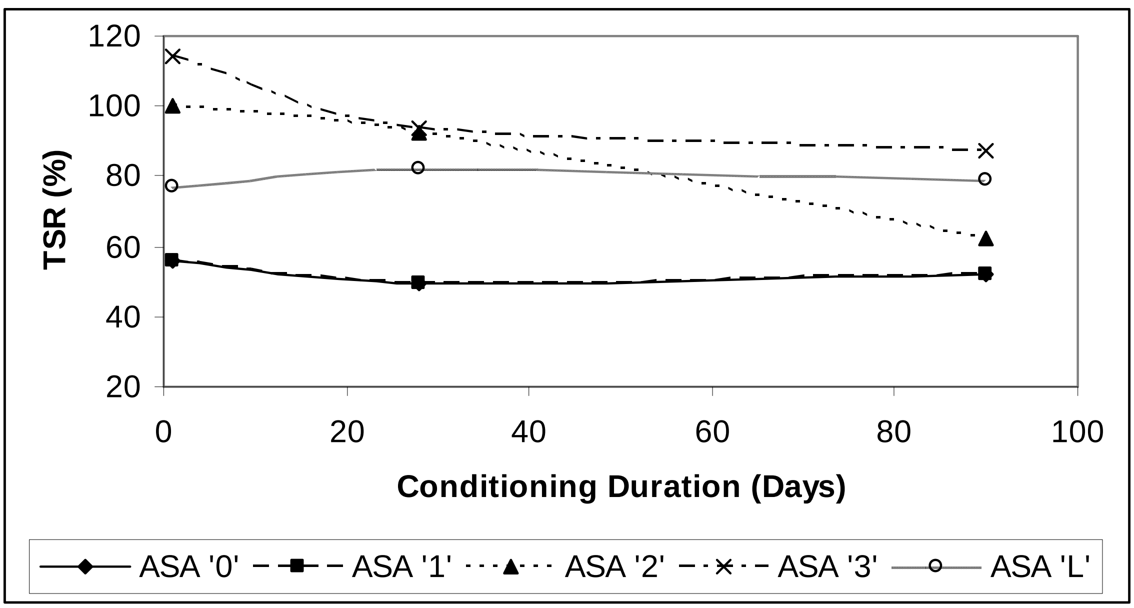


(b)

Figure 20: (a) Wet ITS and (b) TSR of mixes made with stored binders after conditioning for 90 days.

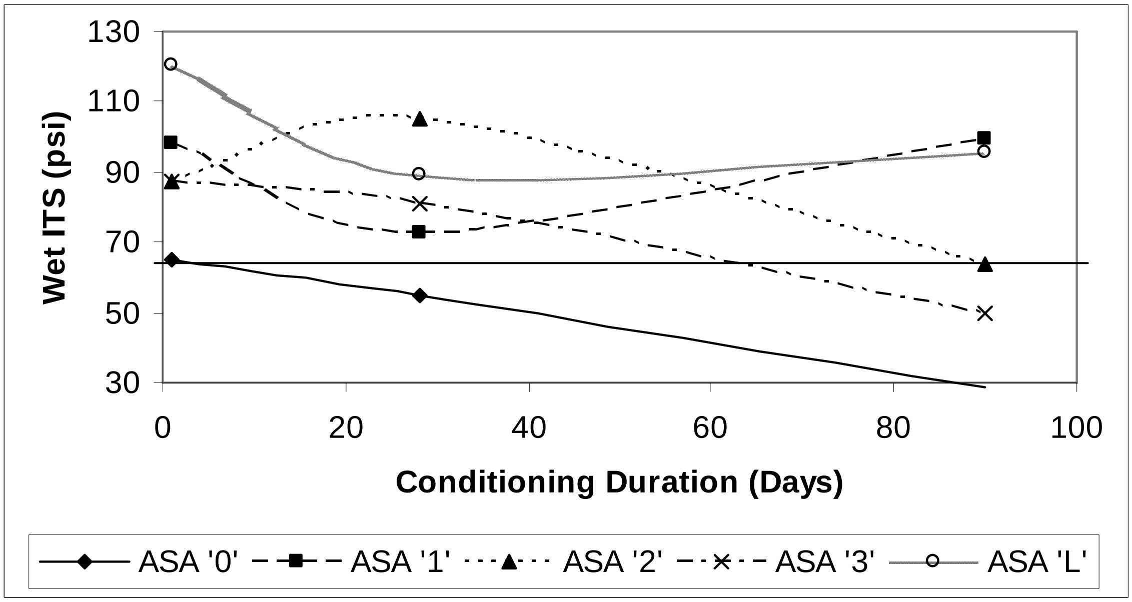


(a)

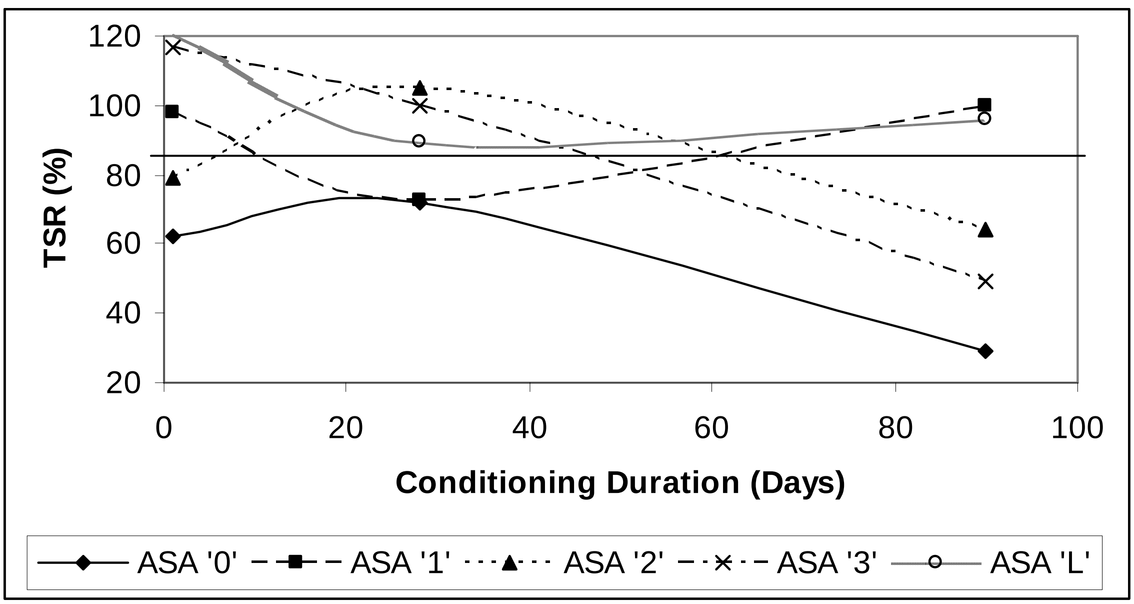


(b)

Figure 21: Moisture susceptibility results of mixes made with aggregate A and stored binder I with respect to time: (a) wet ITS and (b) TSR.

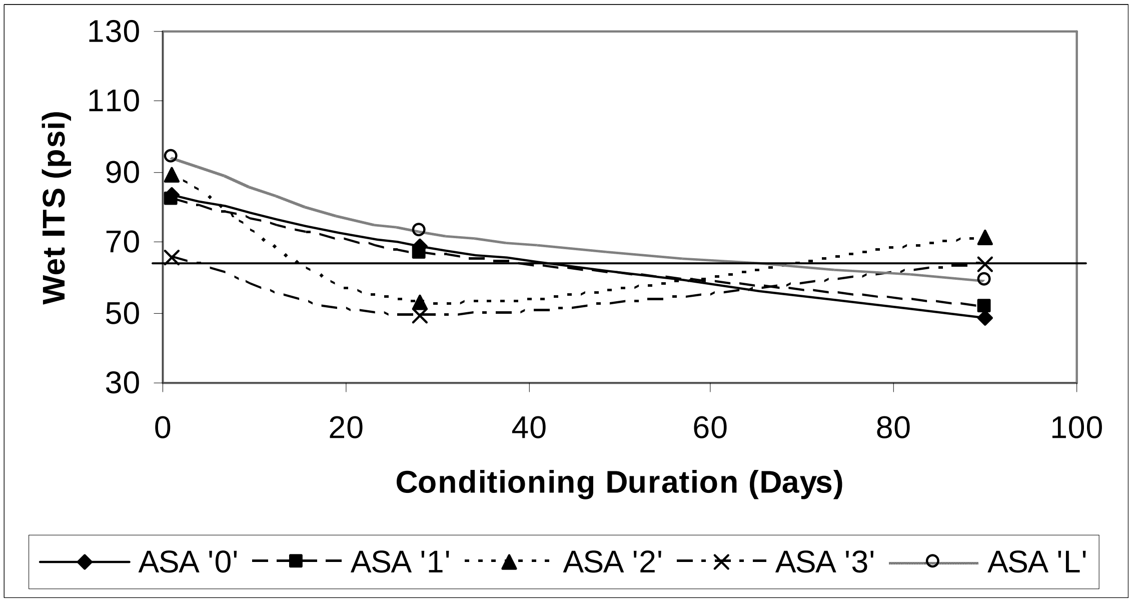


(a)

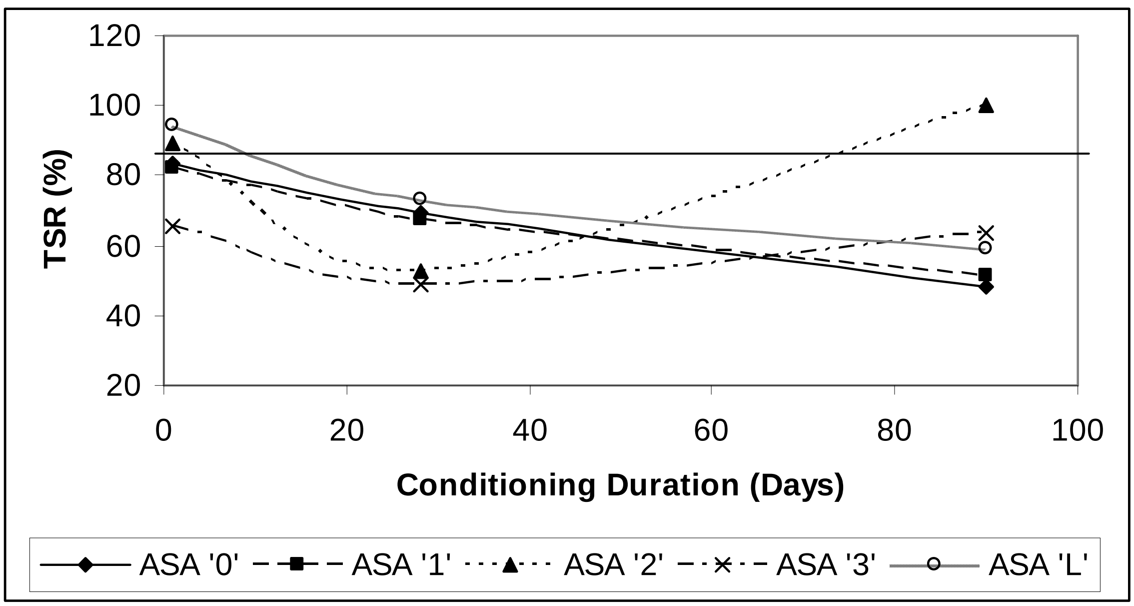


(b)

Figure 22: Moisture susceptibility results of mixes made with aggregate A and fresh binder II with respect to time: (a) wet ITS and (b) TSR.

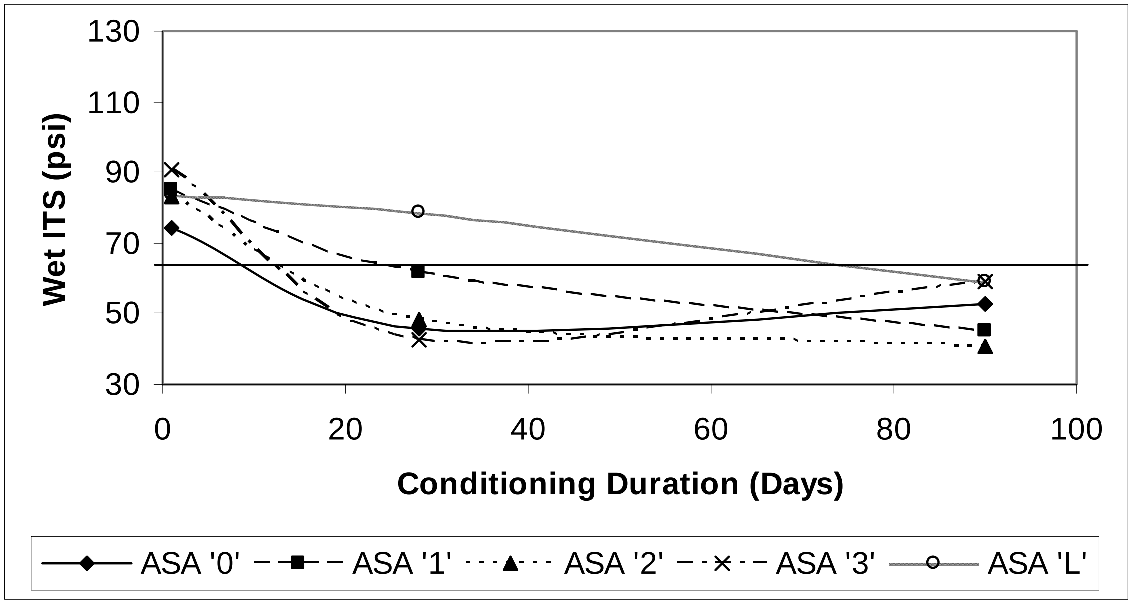


(a)

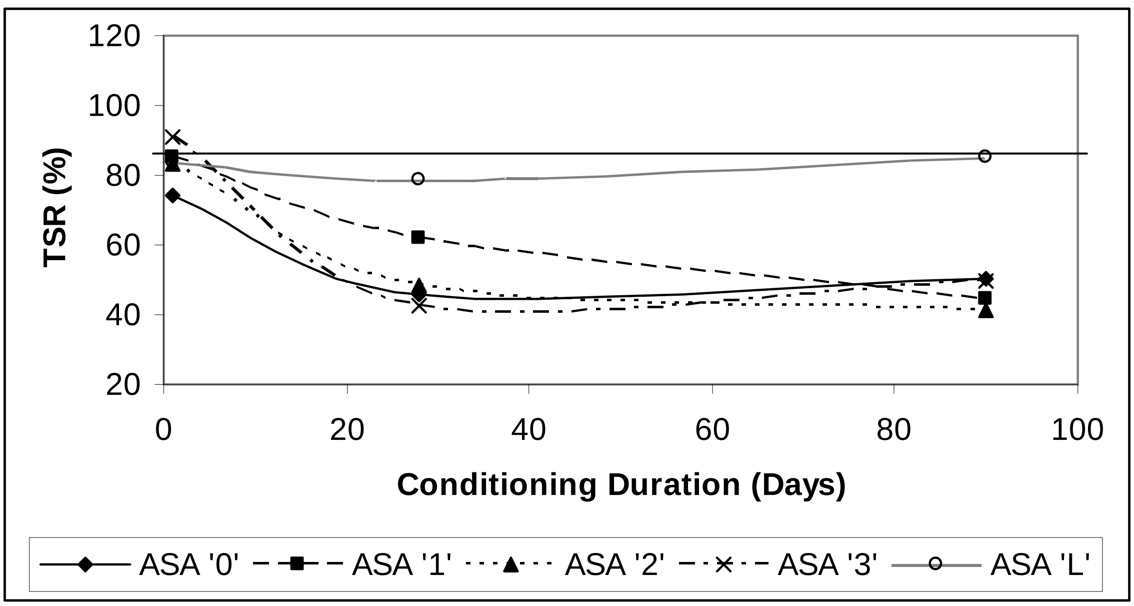


(b)

Figure 23: Moisture susceptibility results of mixes made with aggregate B and fresh binder I with respect to time: (a) wet ITS and (b) TSR.

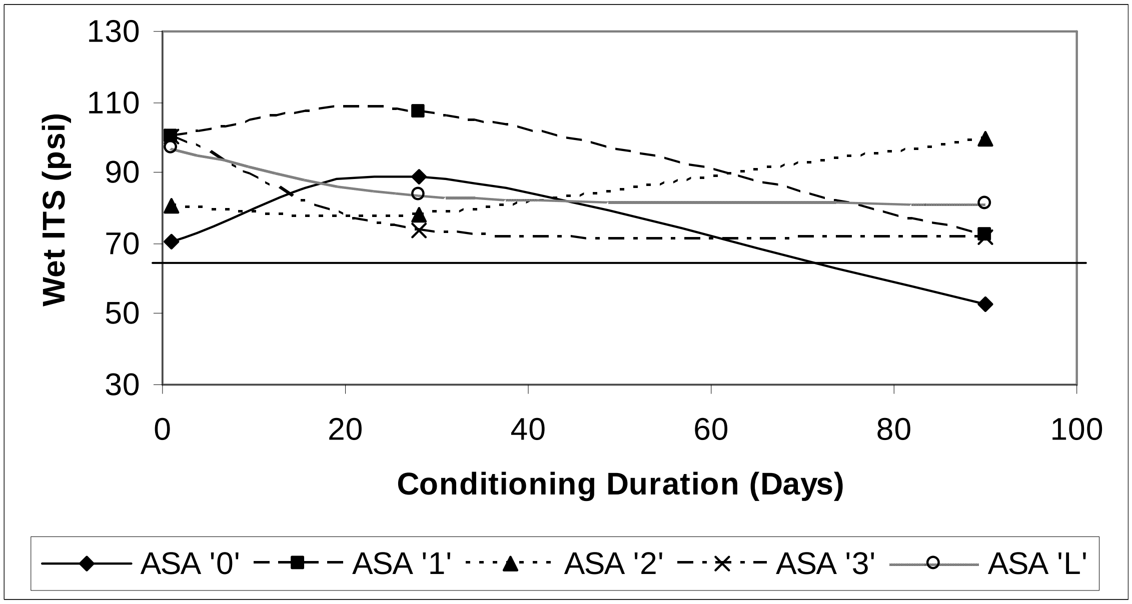


(a)

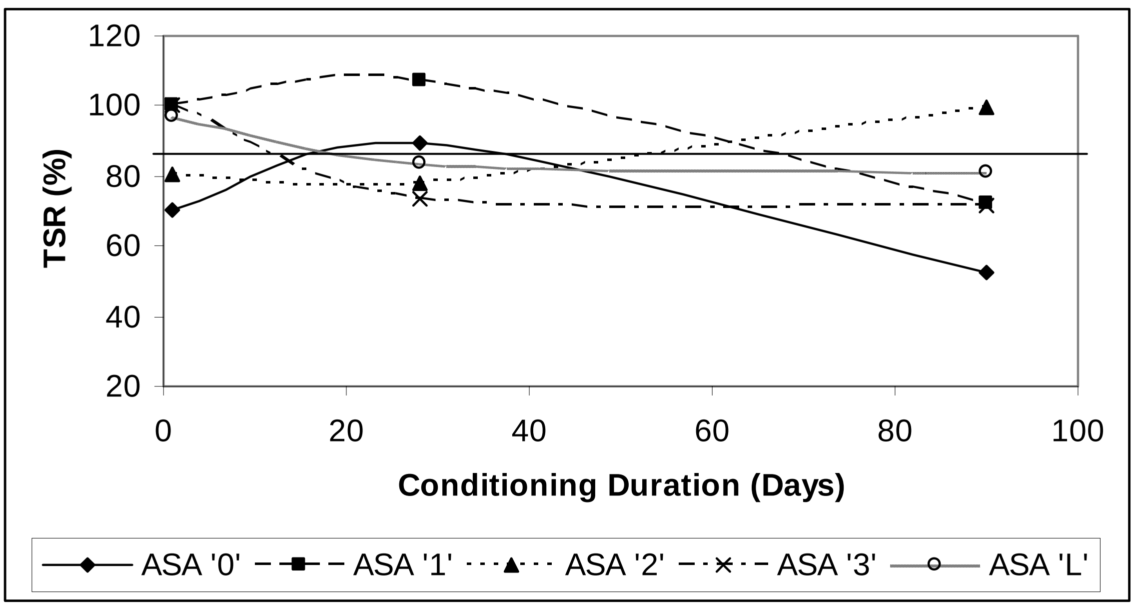


(b)

Figure 24: Moisture susceptibility results of mixes made with aggregate B and fresh binder II with respect to time: (a) wet ITS and (b) TSR.

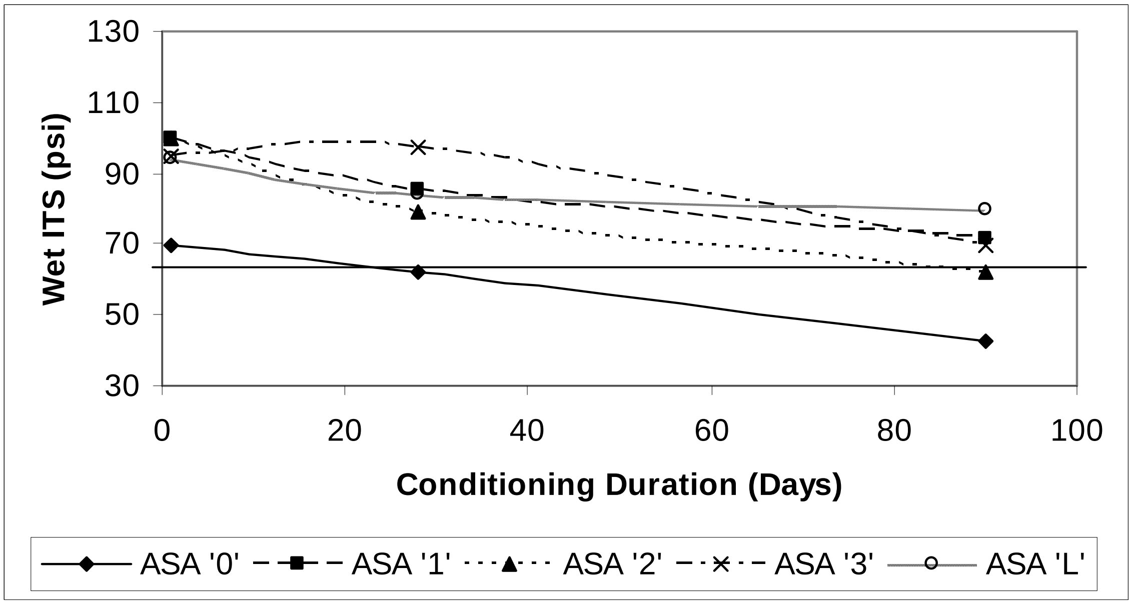


(a)

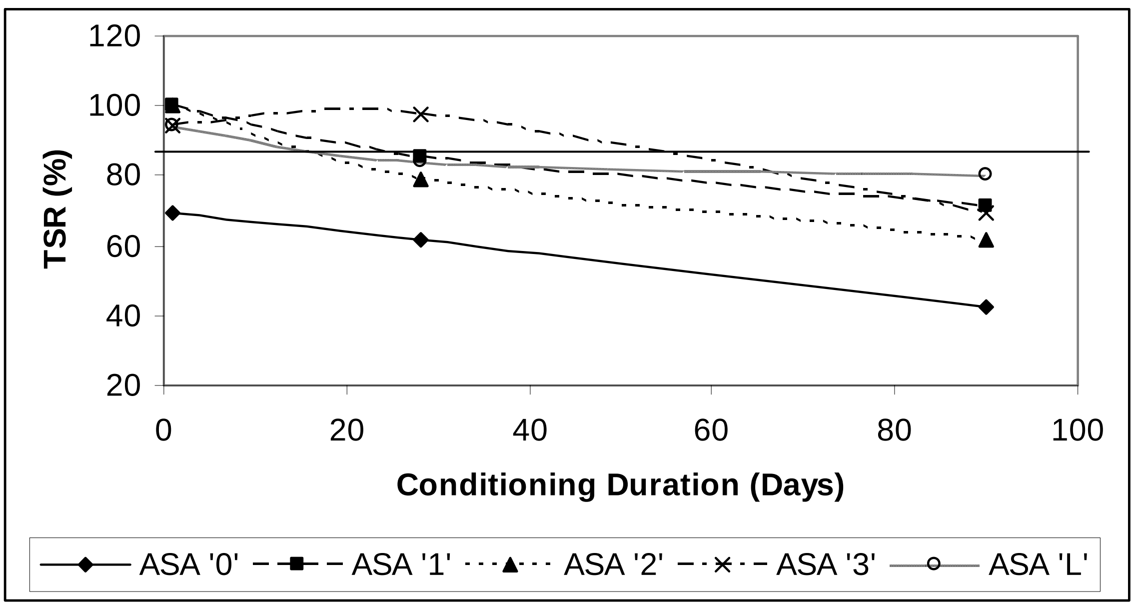


(b)

Figure 25: Moisture susceptibility results of mixes made with aggregate C and fresh binder I with respect to time: (a) wet ITS and (b) TSR.



(a)



(b)

Figure 26: Moisture susceptibility results of mixes made with aggregate C and fresh binder II with respect to time: (a) wet ITS and (b) TSR.

Asphalt Binder Content Determined by the Ignition Oven

The ignition oven test was performed on all the mixes to determine how the ASAs affected the results of the binder content test. First, the results of each mix were compared to the actual amount of binder added to the mix. It was observed that in almost all cases, except for a few exceptions, the binder content determined from the ignition oven was significantly similar to the amount of binder actually added. Among those mixes where the difference was significant, no particular trend was observed.

Next, the difference between the ignition oven binder content and the actual binder content for each ASA treatment within each aggregate/binder combination was compared. From the comparison, within each aggregate/binder combination, the difference between the binder contents was significantly similar for each ASA treatment. Figure 27 shows the difference in the binder contents for each mix.

From the comparison, it could be concluded that the ASA treatments do not affect the results of the ignition oven test. However, it should be noted that the variability in the results is high, and that could be misleading.

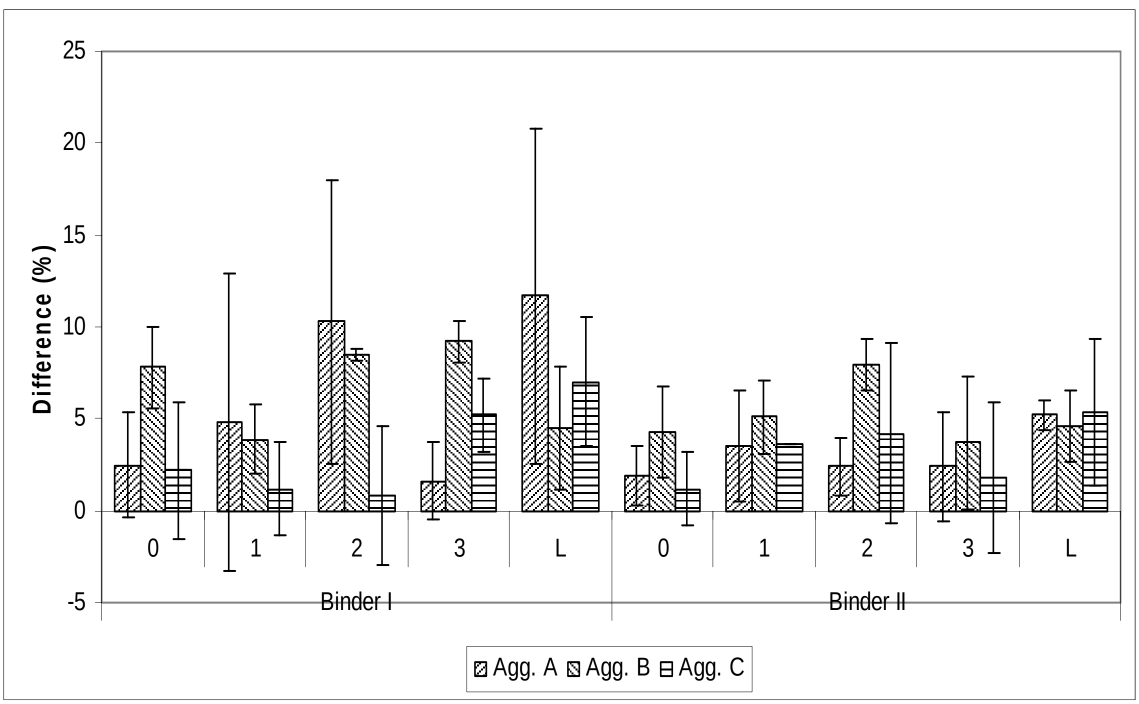


Figure 27 : Ignition oven results (percent difference of measured to actual).

Asphalt Binder Properties

Viscosity

Based on the results in Figure 28 and Tables B-1 and B-2 it can be seen that the viscosity of the binders containing the liquid ASAs were not significantly different from each other. This indicates that the addition of either of these ASAs did not greatly affect the viscosity of the two binder sources. The storage stability of the binders, with respect to viscosity, was more affected by the liquid ASAs with binder II than for binder I. The differences between the fresh and stored binders containing liquid ASAs were not significant for binder I, but were significant for two of the three liquid ASAs (ASA 2 and 3) combined with binder II.

Original G*/sinδ

Figure 29 presents the results of the original G*/sinδ results for the binders evaluated in this study. It is evident that the G*/sinδ value is more significantly affected by the addition of different liquid ASAs than the viscosity (Tables B-1 and B-2). For binder I, the addition of liquid ASA 1 increases the value compared to the control, while the addition of ASAs 2 and 3 both reduce the G*/sinδ, with ASA 3 showing the greatest reduction. It should be noted, however, that all of the values exceeded the minimum G*/sinδ value of 1.00 kPa. Binder II showed a slightly different trend. Only the addition of ASA 2 increased the G*/sinδ over the control, while the others produced similar results.

The effect of binder storage on the performance showed a different trend, with respect to the liquid ASAs, however. All of the stored binders containing liquid ASAs had significantly lower G*/sinδ values than the control. This could potentially be the result of the storage stability of these ASA/binder combinations.

RTFO G*/sinδ

The results of the DSR testing on the RTFO residue for the binders studied are included in Figure 30. Again, the addition of liquid ASAs to the binder affected the G*/sinδ. For both fresh binders, ASAs 2 and 3 resulted in lower values than the control, while ASA 1 had no effect on binder I and increased the G*/sinδ of binder II. Again, binder storage generally had a negative effect on the binders containing ASAs compared to the control as the binders containing ASAs had lower G*/sinδ values after storage than the control, with the exception of ASA 3 combined with binder II, which was similar to the control. Again, none of the binders had G*/sinδ values below the minimum value of 2.20 kPa.

PAV G*sinδ

Figure 31 summarizes the results of the DSR testing on the PAV residue of the binders included in this study. The data shows that the addition of liquid ASA reduced the value of G*sinδ for both binders. A reduction in the G*sinδ value is desirable as it shows that the binder is more flexible to withstand repetitive traffic loading that could potentially result in fatigue cracking. The effect of storage on this property generally did not have an effect on the G*sinδ value of the binders, with the exception of the ASA 2/binder I combination.

Stiffness

The effect of liquid ASA on the stiffness of the binders as measured with a BBR are illustrated in Figure 32. The results indicate that the addition of the liquid ASAs do not have a significant effect on the binders. The storage of the binders, however, did show some differences in stiffness compared to the control. The addition of ASA 3 to binder I reduced the stiffness, while ASAs 1 and 2 increased the stiffness of binder II. As with the G*sinδ, a reduction in stiffness is desirable for performance at low temperatures. It should be noted that none of the binders exceeded the maximum stiffness value of 300 MPa.

m-value

Figure 33 presents the m-value data from the BBR test. The results indicate that the addition of the liquid ASAs to binder I increased the m-value in all cases, which is a positive effect. For binder II, however, only the addition of ASA 1 increased the m-value, while the others reduced the value compared to the control, with ASA 2 having a larger reduction than ASA 3. The effect of storage on the ASAs was not significant as each of the ASA/binder combinations had higher m-values than the controls after storage. None of the liquid ASAs reduced the m-value below the minimum value of 0.300.

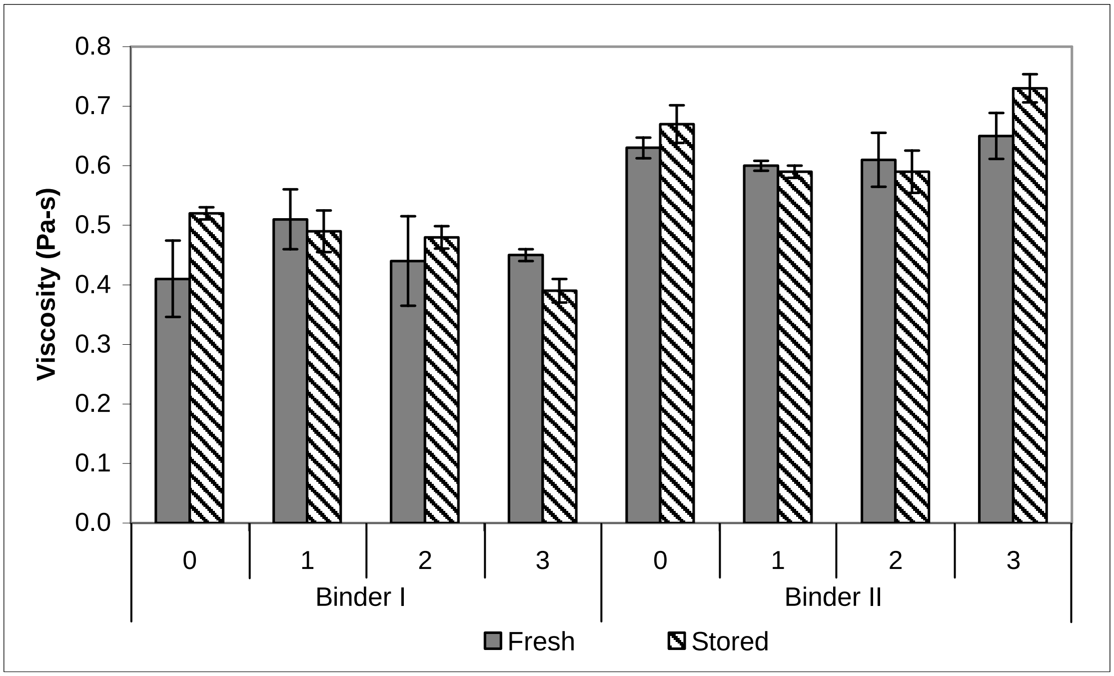


Figure 28 : Viscosity of fresh and stored asphalt binders tested at 135°C.

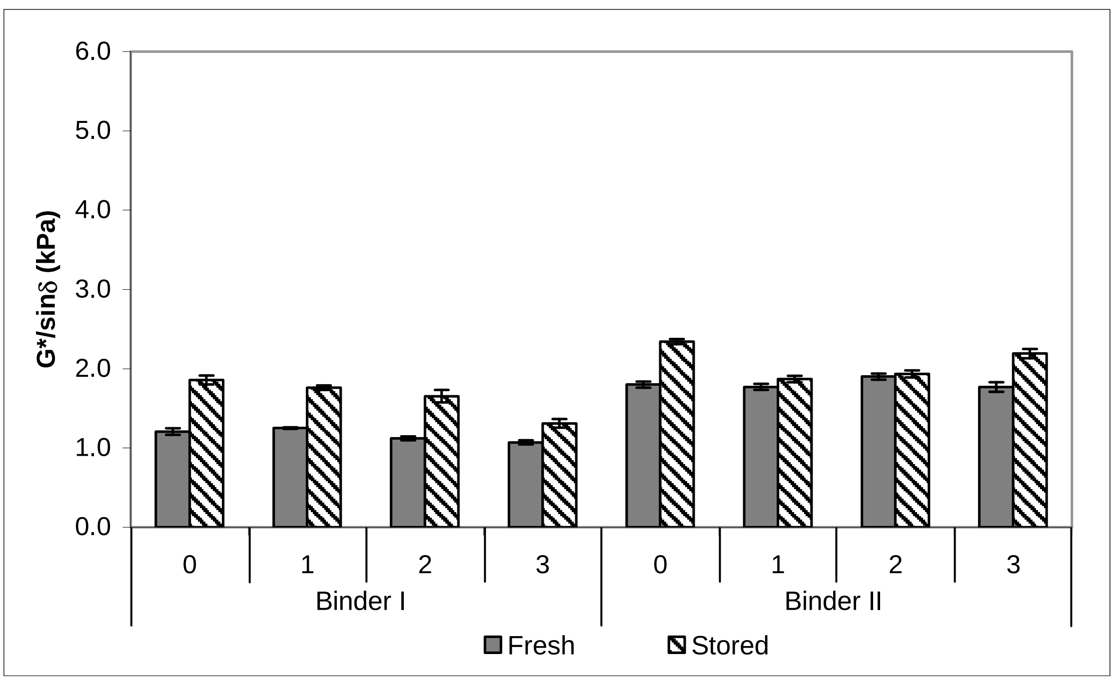


Figure 29 : Original G*/sinδ of fresh and stored binders tested at 64°C.

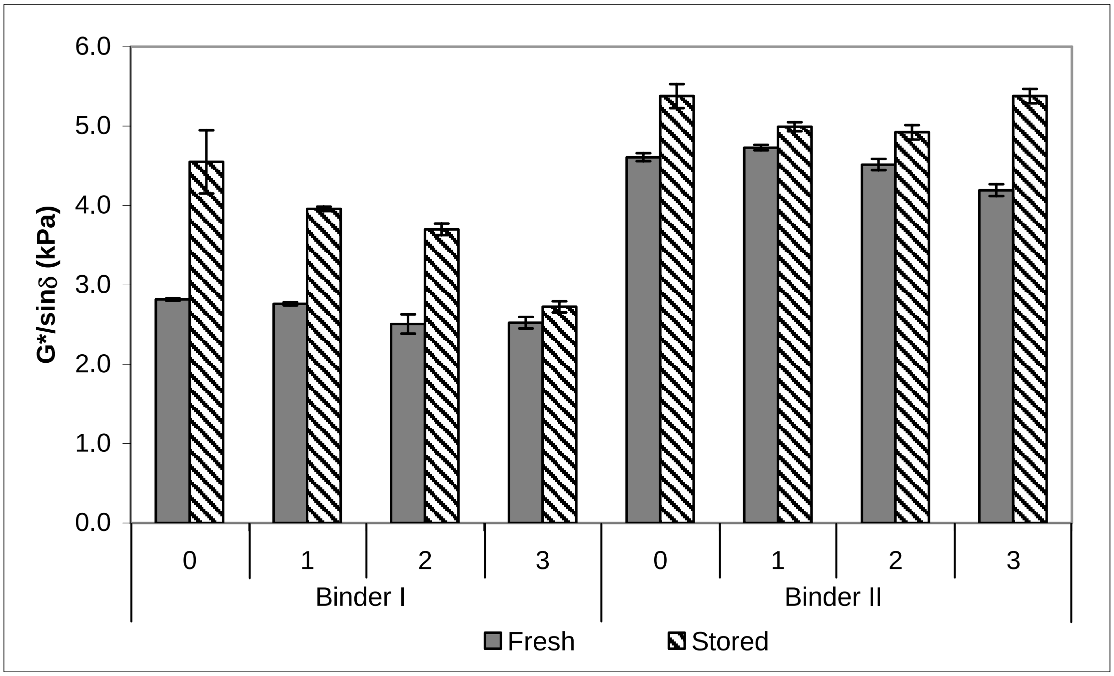


Figure 30: G*/sinδ of fresh and stored binders tested at 64^{o}C (RTFO residue).

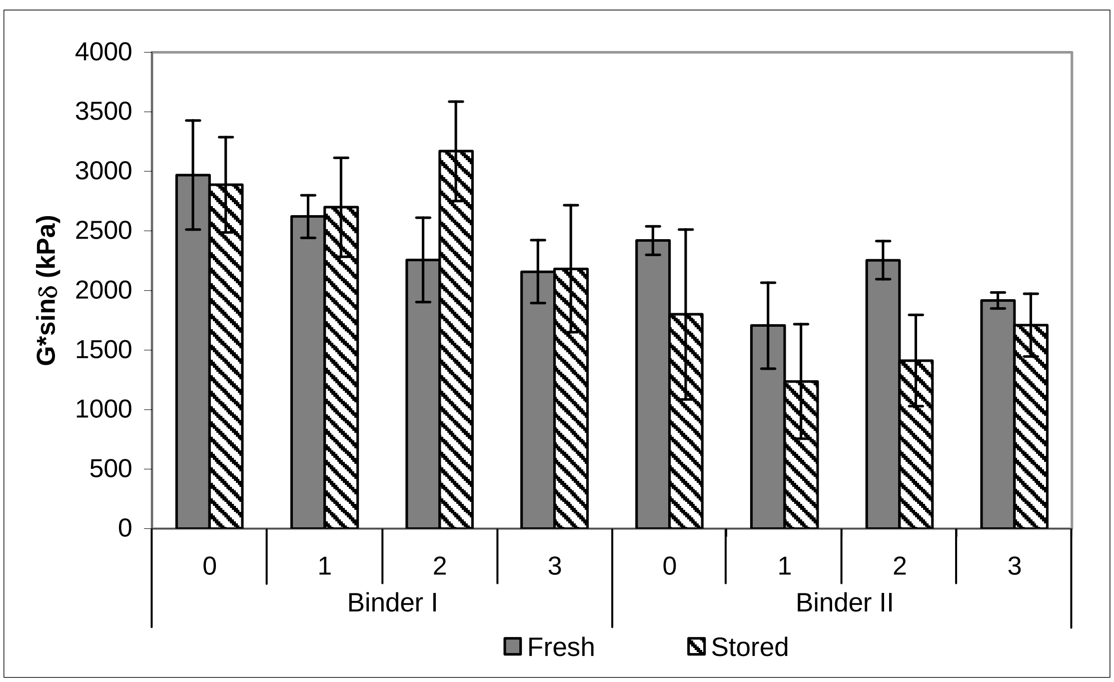


Figure 31: G*sinδ of fresh and stored binders tested at 25^{o}C (PAV residue).

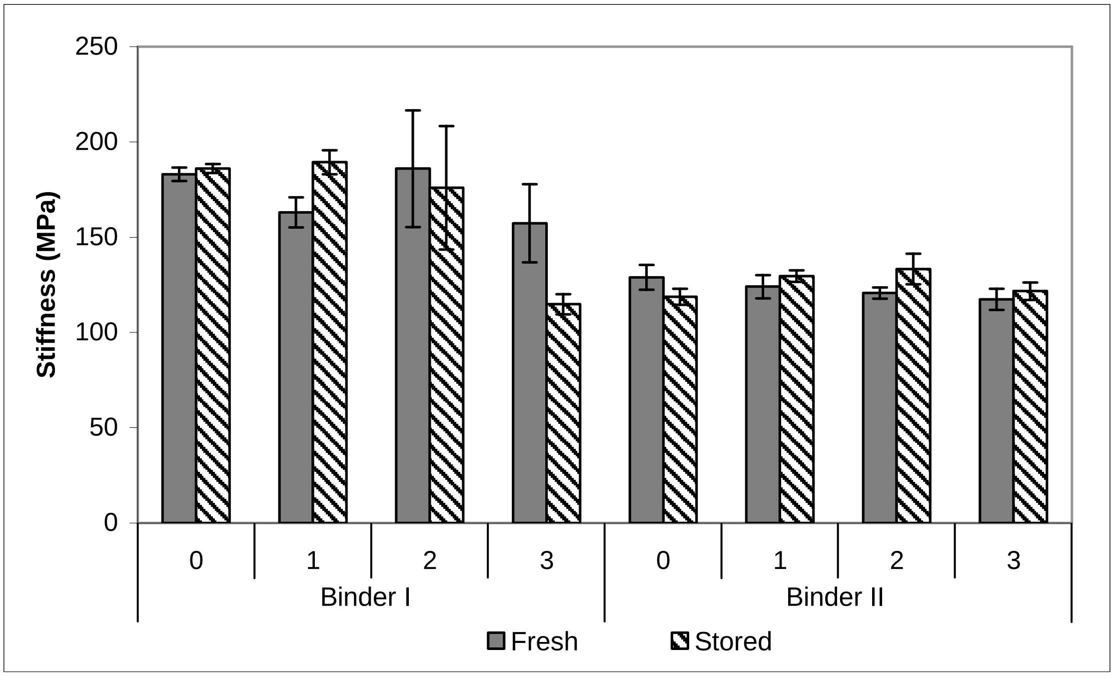


Figure 32: Stiffness (60 seconds) of fresh and stored binders tested at -12^{o}C.

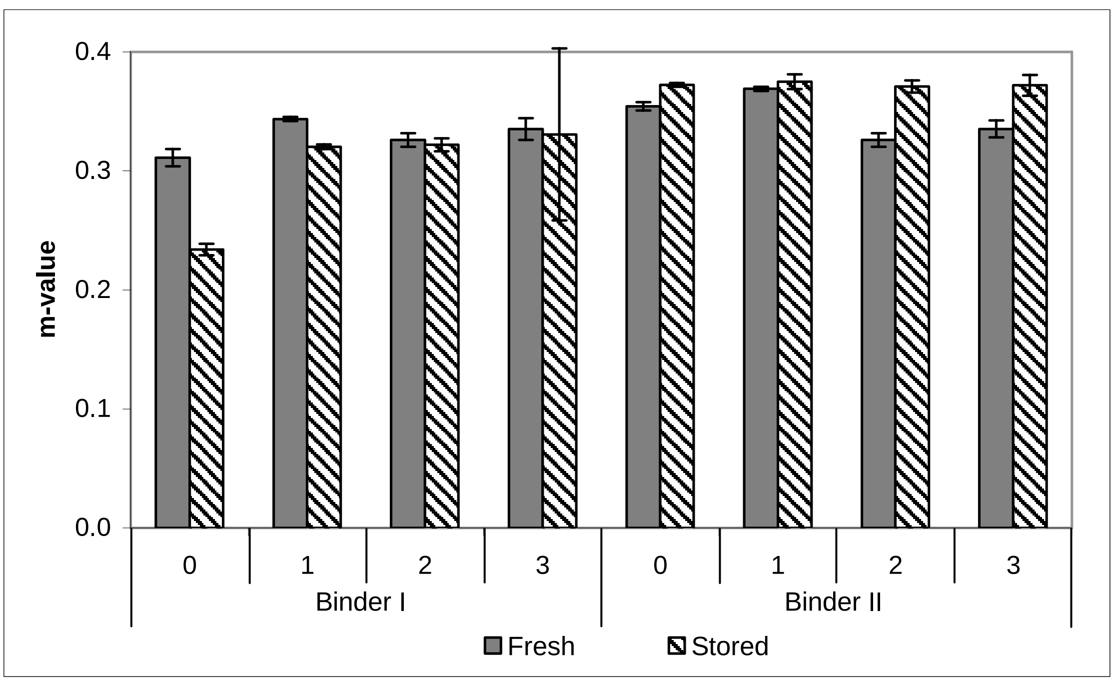


Figure 33: m-value (60 seconds) of fresh and stored binders tested at -12^{o}C.

Characterization of Binders & ASAs Using HP-GPC

A limited investigation was conducted to assess the capability of high pressure gel permeation chromatography (HP-GPC) to identify the presence of liquid ASAs in asphalt binders. Table 6 summarizes the molecular size distributions of binder II with no ASA and with each of the three liquid ASAs. Typical HP-GPC chromatograms are included in Figure 34. Based on the limited amount of information gathered from this portion of the study, it is not reasonable to draw any conclusions about the HP-GPC analysis. If, however, this analytical method was used to characterize binders from mixtures exposed to long durations of moisture exposure, changes in the molecular size distributions could potentially indicate loss of liquid ASA over time.

Table 6: Molecular size distribution of binder/ASA combinations *(LMS – large molecular size, MMS – medium molecular size, and SMS – small molecular size).*

ASA Treatment	LMS, %	MMS, %	SMS, %
0	14.32	50.06	35.61
1	15.67	52.29	32.05
2	15.02	51.83	33.14
3	14.65	53.94	31.4

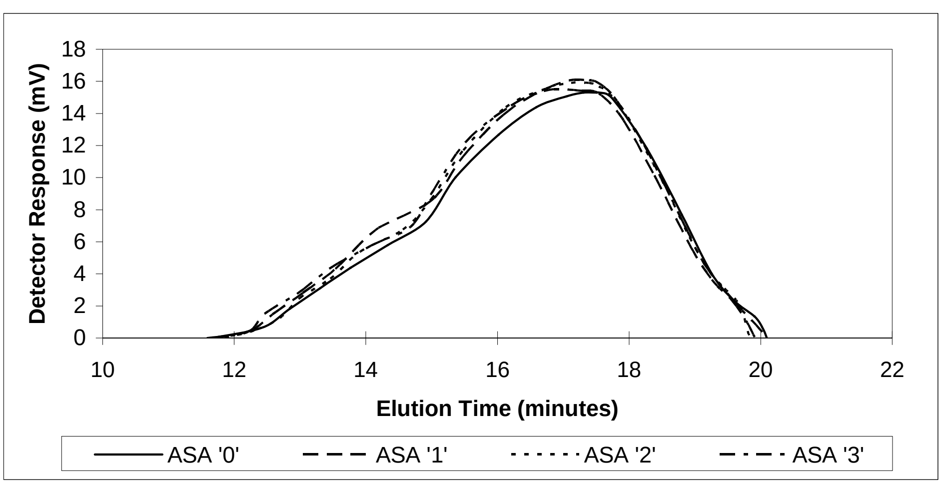


Figure 34: Typical HP-GPC chromatograms for binder I.

CHAPTER V: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Based on the results of this study, the following conclusions were made regarding the use of anti-strip additives (ASAs) in hot mix asphalt (HMA) mixtures used for this research project:

- 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 value of 85% for the ASA percentages evaluated in this study.
- All of the ASAs were effective in producing mixtures with wet ITS values above the SCDOT minimum value of 65 psi. This was not always the case with the control mixes.
- The aggregate and binder sources have an effect on the effectiveness of a particular ASA treatment.
- No particular trend regarding the effectiveness of the different ASAs over extended conditioning durations could be identified. All of the mixes had lower wet ITS and TSR values as the conditioning duration increased.
- 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.
- 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 M320.
- The boil test proved to be ineffective to identify stripping in all cases, when compared to SC-T-70.

Recommendations

Based on the results and conclusions of this study, the authors recommend two possible courses of action for the SCDOT regarding the use of liquid ASAs: field implementation and future considerations.

Field Implementation

Based on the findings of this study, it is recommended that the SCDOT conduct some field investigations incorporating liquid ASAs in the mix designs. In doing so, the following should be considered:

- Conduct the field evaluations on lower volume routes to develop a "comfort level" when using these products.
- The effectiveness of many liquid ASAs is dependent upon the binder/aggregate combination. Additional testing may have to be performed during mix design to determine the proper dosage of liquid ASA to achieve the minimum wet ITS and TSR.
- Field TSR testing should be conducted to assure that the wet ITS and TSR requirements are being met.

Future Considerations

Based on the findings of this study, the following are recommended to the SCDOT for consideration:

- Future research to determine the fatigue performance of HMA containing different ASAs exposed to similar conditioning evaluated in this study.
- Re-evaluate the TSR requirement of 85% for all situations. In some cases, a mixture having a TSR of 80% and a wet ITS of 120 psi. may perform better than a mix having a TSR of 85% and a wet ITS of 65 psi.
- Evaluate the effect on the life-cycle cost of pavements constructed with HMA containing liquid ASAs compared to hydrated lime.

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APPENDIX A: ANOVA RESULTS FOR WET ITS AND TSR

Table A-1: Results of t-tests for wet ITS of mixes made with fresh binders and (a) Aggregate A, (b) Aggregate B, and (c) Aggregate C. Treatments with at least one common letter are not significantly different at α = 0.05.

(a)

	t - Grouping				
ASA	**1 Day**	**7 Days**	**28 Days**	**90 Days**	**180 Days**
L	a	a	a	b	b
1	a	b	a b	a	b
2	b	b	b c	b	b
3	b	c	c	b	a
0	c	d	d	c	c

(b)

	t - Grouping				
ASA	**1 Day**	**7 Days**	**28 Days**	**90 Days**	**180 Days**
L	a	a	a	a	a
1	b	b	b	b c	a b
2	b	b	b c	b	b c
3	b	b	c	b c	b
0	b	b	b c	c	c

(c)

	t - Grouping				
ASA	**1 Day**	**7 Days**	**28 Days**	**90 Days**	**180 Days**
L	a	a	a	a	a b
1	b	b	a	a	a
2	b	c	a b	b	b
3	b	b c	b	b	b
0	b	d	c	c	c

Table A-2: Results of t-tests for wet ITS of mixes made with fresh binders and (a) Binder I and (b) Binder II. Treatments with at least one common letter are not significantly different at $\alpha = 0.05$.

(a)

	t - Grouping				
ASA	**1 Day**	**7 Days**	**28 Days**	**90 Days**	**180 Days**
L	a	a	a	a	a
1	b	b	a b	a	a
2	b	b	a	a	a
3	b	b c	b c	a	a
0	c	c	c	b	b

(b)

	t - Grouping				
ASA	**1 Day**	**7 Days**	**28 Days**	**90 Days**	**180 Days**
L	a	a	a	a	a b
1	a b	b	a	a	a
2	b c	c	b	b	b
3	b c	b c	b	b	a b
0	c	d	c	c	c

Table A-3: Results of t-tests for TSR of mixes made with fresh binders and (a) Aggregate A, (b) Aggregate B, and (c) Aggregate C. Treatments with at least one common letter are not significantly different at $\alpha = 0.05$.

(a)

	t - Grouping				
ASA	**1 Day**	**7 Days**	**28 Days**	**90 Days**	**180 Days**
L	a	a	a	a b	a
1	a b	b	a	a	a
2	b	a b	a	a b	a
3	a b	a b	a	a b	a
0	c	c	b	b	b

(b)

	t - Grouping				
ASA	**1 Day**	**7 Days**	**28 Days**	**90 Days**	**180 Days**
L	a	a	a	a	a
1	a	a	a b	a b	b
2	a	a b	a b	a b	b c
3	a	a	a b	a b	b c
0	a	b	b	b	c

(c)

	t - Grouping				
ASA	**1 Day**	**7 Days**	**28 Days**	**90 Days**	**180 Days**
L	a	a	a	a	a b
1	b	a	a	a	a
2	a	a	a	a	a b
3	a	a	a	a b	a b
0	b	b	b	b	b

Table A-4: Results of t-tests for TSR of mixes made with fresh binders and (a) Binder I and (b) Binder II. Treatments with at least one common letter are not significantly different at $\alpha = 0.05$.

(a)

	t - Grouping				
ASA	**1 Day**	**7 Days**	**28 Days**	**90 Days**	**180 Days**
L	a	a	a	a	a
1	b c	a	a	a	a b
2	b c	a	a	a b	a b
3	a b	a	a	a	a b
0	c	b	b	b	b

(b)

	t - Grouping				
ASA	**1 Day**	**7 Days**	**28 Days**	**90 Days**	**180 Days**
L	a	a	a	a	a
1	a b	a	a	a	a
2	a	a	a	a b	a
3	a	a	a	a b	a
0	b	b	b	b	b

Table A-5: Results of t-tests for wet ITS of mixes made with stored binders and (a) Aggregate A, (b) Aggregate B, and (c) Aggregate C. Treatments with at least one common letter are not significantly different at $\alpha = 0.05$.

(a)

ASA	t - Grouping 1 Day	28 Days	90 Days
L	a b	a	a
1	a	b	a
2	c d	a b	a
3	b c	b	a
0	d	c	b

(b)

ASA	t - Grouping 1 Day	28 Days	90 Days
L	a	a	a
1	a b	b	c
2	a b	b c	c
3	b	c	b
0	b	b	b c

(c)

ASA	t - Grouping 1 Day	28 Days	90 Days
L	a	a b	a
1	b c	a	b
2	a b	a	b
3	c	a	b
0	a b	b	c

Table A-6: Results of t-tests for wet ITS of mixes made with stored binders and (a) Binder I and (b) Binder II. Treatments with at least one common letter are not significantly different at $\alpha = 0.05$.

(a)

ASA	t - Grouping		
	1 Day	**28 Days**	**90 Days**
L	a	a	a b
1	a b	a b	c
2	a b c	a b	b c
3	c	a b	a
0	b c	b	d

(b)

ASA	t - Grouping		
	1 Day	**28 Days**	**90 Days**
L	a	a	a
1	a b	a b	b
2	a b	a b	b
3	b	b	b
0	b	c	c

Table A-7: Results of t-tests for TSR of mixes made with stored binders and (a) Aggregate A, (b) Aggregate B, and (c) Aggregate C. Treatments with at least one common letter are not significantly different at α = 0.05.

(a)

ASA	t - Grouping 1 Day		28 Days		90 Days
L	a	b	a	b	a
1	a		a	b	a
2	a	b	a		a
3	a		a	b	a
0		b		b	a

(b)

ASA	t - Grouping 1 Day	28 Days		90 Days
L	a	a		a
1	a	a	b	a
2	a		b	a
3	a		b	a
0	a	a	b	a

(c)

ASA	t - Grouping 1 Day		28 Days	90 Days	
L	a		a	a	
1	a		a	a	b
2	a		a	a	
3	a		a	a	b
0		b	a		b

Table A-8: Results of t-tests for TSR of mixes made with stored binders and (a) Binder I and (b) Binder II. Treatments with at least one common letter are not significantly different at $\alpha = 0.05$.

(a)

ASA	t - Grouping 1 Day		28 Days	90 Days	
L	a		a	a	b
1	a		a	a	b
2	a		a	a	
3	a		a	a	b
0	a		a		b

(b)

ASA	t - Grouping 1 Day		28 Days	90 Days		
L	a		a	a		
1	a		a	a	b	
2	a	b	a		b	c
3	a		a		b	c
0		b	a			c

APPENDIX B: ANOVA RESULTS FOR BINDER TESTS

Table B- 1: Results of t-tests for binder tests on Binder I in the (a) fresh and (b) stored condition. Treatments with at least one common letter are not significantly different at $\alpha = 0.05$.

(a)

	t - Grouping					
ASA	Viscosity	Original G*/sinδ	RTFO G*/sinδ	PAV G*sinδ	Stiffness	m-value
1	a	a	a	a b	a	a
2	a b	c	b	b	a	b
3	a b	d	b	b	a	a b
0	b	b	a	a	a	c

(b)

	t - Grouping					
ASA	Viscosity	Original G*/sinδ	RTFO G*/sinδ	PAV G*sinδ	Stiffness	m-value
1	b	b	b	a b	a	a
2	b	c	b	a	a	a
3	c	d	c	b	b	a
0	a	a	a	a	a	b

Table B- 2: Results of t-tests for binder tests on Binder II in the (a) fresh and (b) stored condition. Treatments with at least one common letter are not significantly different at $\alpha = 0.05$.

(a)

	t - Grouping					
ASA	**Viscosity**	**Original $G^*/\sin\delta$**	**RTFO $G^*/\sin\delta$**	**PAV $G^*\sin\delta$**	**Stiffness**	**m-value**
1	a	b	a	b	a b	a
2	a	a	c	a	a b	d
3	a	b	d	b	b	c
0	a	b	b	a	a	b

(b)

	t - Grouping					
ASA	**Viscosity**	**Original $G^*/\sin\delta$**	**RTFO $G^*/\sin\delta$**	**PAV $G^*\sin\delta$**	**Stiffness**	**m-value**
1	c	c	b	a	a b	a
2	c	c	b	a	a	a
3	a	b	a	a	b c	a
0	b	a	a	a	c	a